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Research Paper

Application of Universal Thermal Climate Index (UTCI) for microclimatic analysis in urban thermal environments

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HIGHLIGHTS

- Universal Thermal Climate Index (UTCI) works well for outdoor thermal environments.
- Human bioclimatic maps are useful representations of outdoor thermal conditions.
- ENVI-met for wind speeds and HURES model for radiation simulation can be used.
- Direct beam solar radiation was the dominant summertime UTCI control.

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ABSTRACT

Microclimatic effects were investigated for human thermal sensation on human bioclimatic maps in summer, 2009 using the Universal Thermal Climate Index (UTCI). Study locations were downtown Nanaimo, BC, Canada and Changwon, Republic of Korea. Air temperatures and humidities of several sites were collected at the two locations. Mean radiant temperatures of outdoor study areas in high resolution were simulated with the HURES human-urban radiation exchange simulation model. Wind speeds estimated using the ENVI-met model were corrected using collected wind speed data and adjusted from one to ten meters above the surface via UTCI's wind speed converting formula. Greatest heat stress was around mid-afternoon. Sunny areas had moderate to strong heat stress, 28–38 °C UTCI. Shady areas had no thermal stress to moderate heat stress, 20–27 °C UTCI. Narrow streets had lower UTCI's than open spaces in both areas. A 1 m s^{-1} reduction in 10 m height wind speed (u) increased UTCI by 1 °C. In this study, u varied by up to 3.3 m s^{-1}. Observed direct beam solar radiation variations changed UTCI by three heat stress levels, diffuse and reflected solar radiation and longwave radiation changed it by 1.5 levels and u altered UTCI by half a level. UTCI is an accepted, easy to determine human thermal index whose results can be mapped as human bioclimatic maps and should be a useful tool for analyzing possible outdoor human thermal effects of urban and landscape planning and design.

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1. Introduction

Human thermal sensation and comfort studies have been conducted since the 1910s in a variety of indoor and outdoor environments (Benedict & Carpenter, 1910; Söderström & DuBois, 1917; Winslow, Herrington, & Gagge, 1937; Yaglou & Miller, 1925). A great deal of recent attention has been devoted to outdoor urban areas by both urban climatologists and human biometeorologists/bioclimatologists. They have studied the urban heat island phenomenon (Arnfield, 2003; Landsberg, 1981; Oke, 1982; Roth, 2007; Stewart, 2011), vegetation and park cooling effects (Alexandri & Jones, 2008; Ali-Toudert & Mayer, 2007; Bowler, Buyung-Ali, Knight, & Pullin, 2010; Ca, Asaeda, & Abu, 1998; Chow, Pope, Martin, & Brazel, 2011; Dimoudi & Nikolopoulou, 2003; Georgi & Dimitriou, 2010; Oke, 1989; Picot, 2004; Rosenfeld, Akbari, Romm, & Pomerantz, 1998; Shashua-Bar & Hoffman, 2000; Shashua-Bar, Pearlmutter, & Erell, 2011), mortality and morbidity related to heat and cold stresses (Antics et al., 2013; Davis, Knappenberger, Novicoff, & Michaels, 2003; Dessai, 2002; Díaz

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et al., 2005; Golden, Hartz, Brazel, Luber, & Phelan, 2008; Gosling, McGregor, & Páldy, 2007; Nakai, Itoh, & Morimoto, 1999; Raatikka, Rytkönen, Näyhä, & Hassi, 2007; Smoyer, Rainham, & Hewko, 2000; Tan et al., 2007), heat-health watch/warning systems (de Freitas, Scott, & McBoyle, 2008; Kalkstein & Sheridan, 2007; Lin & Matzarakis, 2008; Matzarakis, Rudel, Zygmuntowski, & Koch, 2005; Matzarakis, 2007a, 2007b; Nicholls, Skinner, Loughnan, & Tapper, 2008; Pascal et al., 2006, 2013; Shiue & Matzarakis, 2011; Tan et al., 2004), tourism (de Freitas, 2003) and methods to adopt climatic knowledge to urban/landscape planning and design (Alcoforado, Andrade, Lopes, & Vasconcelos, 2009; Bonan, 2000; Brown, 2011; Chen, Ooka, & Kato, 2008; Corbella & Magalhães, 2008; Eliasson, Knez, Westerberg, Thorsson, & Lindberg, 2007; Eliasson, 2000; Fahmy & Sharples, 2009; Gulyás, Unger, & Matzarakis, 2006; Harlan, Brazel, Prashad, Stefanov, & Larsen, 2006; Kántor & Unger, 2010; Lin, 2009; Mahmoud, 2011; Ng, 2012; Shashua-Bar, Pearlmutter, & Erell, 2009; Wong, Jusuf, & Tan, 2011).

One method of analyzing outdoor thermal environments is using human thermal sensation/comfort indices such as PMV (Predicted Mean Vote; Fanger, 1972; Fountain & Huizenga, 1995), Burt model (Burt, 1979 modified by Tuller, 1990), COMFA (COMfort FormulA; Brown & Gillespie, 1986, 1995), MENEX (Man-ENvironment heat EXchange; Blazejczyk, 1994, 2004, 2005), PET (Physiological Equivalent Temperature; Höppe, 1993, 1999; Mayer & Höppe, 1987), PT (Perceived Temperature; Jendritzky, Schirmer, Menz, and Schmidt-Kessen (1990); Staiger, Bucher, & Jendritzky, 1997; Staiger, Laschewski, & Grätz, 2012), SET* (Standard Effective Temperature; Gagge, Stolwijk, & Nishi, 1971; Gagge, Fobelets, & Berglund, 1986) which was later adapted to OUT-SET* (Pickup & de Dear, 2000), Sultriness model (Steadman, 1979, 1984), CS (Cold Stress) and HS (Heat Stress) models (Auliciems & Kalma, 1979) and STEBIDEX (Skin Temperature Energy Balance Index) and HEBIDEX (Heat Budget Index) models (de Freitas, 1985). For landscape planning and design, four climatic variables [air temperature, humidity, wind speed and radiation (or mean radiant temperature)] should be considered together. However, some but not all indices use all four climatic variables: PMV, Burt model, COMFA, MENEX, PET, PT and (OUT-)SET*.

In 2011, the International Society of Biometeorology (ISB; http://www.biometeorology.org) announced a new thermal index for outdoor thermal environments called the Universal Thermal Climate Index (UTCI; http://www.utci.org). The index was developed under ISB Commission 6 by COST (European Cooperation in Science and Technology) Action 730 under the umbrella of the WMO Commission on Climatology (Jendritzky, de Dear, & Havenith, 2012). The index has pros and cons. The cons are it employs only one simple equation and we cannot change people's activity levels and clothing types. The clothing insulation (clo) value is automatically driven by air temperature over a wide range to meet the behavior of the general population. Moreover, we cannot modify the index even if we find a better method than those used previously. The pros are it includes the most recent results of human body models (Fiala, Lomas, & Stohrer, 2001; Fiala, Havenith, Bröde, Kampmann, & Jendritzky, 2012) and clothing effects (Havenith et al., 2012). Therefore, the index can be called a state-of-the-art work in human thermal sensation and comfort studies (Bröde et al., 2012).

This study examines outdoor thermal environments of two urban locations in the summer of 2009 to illustrate the applicability of the UTCI for landscape planning and design.

2. Methods

2.1. Study locations

Two study locations were chosen: downtown Nanaimo, BC, Canada (49°10′ N, 123°56′ W; altitude, 12 m; study area size, 248 m × 332 m) (Fig. 1a) and downtown Changwon, Republic of Korea (35°13′ N, 128°41′ E; altitude, 17 m; study area size, 190 m × 210 m) (Fig. 1d).

Three sites (Nanaimo_1 to _3) on a pedestrian passage along NE-SW tending streets surrounded by buildings from 9 to 23 m high in downtown Nanaimo were chosen for radiation and wind speed comparison (Fig. 1a–c). A small park surrounded by 13–50 m high buildings was chosen for the Changwon observations (Fig. 1d–f). Data obtained from the NW and SE edges and the center of the park were used for wind speed comparison. The park's small size and openness allowed radiation to be measured at its center and spatial variation determined by modeling.

2.2. Materials

Three-dimensional (3D) computer aided design (CAD) computer files of the downtown area previously created by the Nanaimo Department of Engineering and geographic information system (GIS) files by the ECOGIS lab at Changwon National University were used in the simulation after changing vector-based data to raster-based [pixel size, 2 m (x) × 2 m (y) × 1 m (z)]. These included 3D building shapes, road and pedestrian passages and digital elevation model files. Vegetation sizes and locations were collected in situ with a tape and clinometer and input manually. For further information, see Park (2011).

Radiation data were collected on June 11, 2009 (11:30–17:00) at the Changwon site as single, point source measurements and on July 26, 2009 (morning, noon and afternoon) at the Nanaimo_1–3 sites using a transect method. Total net all-wave radiation [incoming solar radiation (K) and longwave radiation (L) minus outgoing K and L] was collected using a net radiometer (NR Lite made by Kipp & Zonen, Delft, the Netherlands). Solar radiation from the sky hemisphere ($K\downarrow$) and from the ground hemisphere ($K\uparrow$) were obtained from two pyranometers (CMP 11 made by Kipp & Zonen, Delft, the Netherlands and Middleton EP08 made by Carter-Scott Design, Melbourne, Australia) that were installed opposite one another, each one covered half a sphere (sky or ground hemisphere). Longwave radiation from the ground hemisphere ($L\uparrow$) was calculated with the surface temperatures measured using an infrared thermometer (Raytek PM Plus made by Raytek, Santa Cruz, CA, USA; accuracy, ±0.5 °C). The other radiation component, longwave radiation from the sky hemisphere ($L\downarrow$), was calculated using the three directional radiation data {=total net all-wave radiation − [$K\downarrow - (K\uparrow + L\uparrow)$]}. Air temperatures, relative humidities and wind speeds were also collected at the same time. Observation height was 1.2 m above the ground surface. The sky condition was clear and cloudless on all the data collection days. Information on equipment used in the data collection is listed in Table 1.

Radiation simulation was conducted using the human-urban radiation exchange simulation (HURES) model (Park, 2011). Wind speed was simulated at the height of 1 m with ENVI-met 3.1 (http://www.envi-met.com) because ENVI-met accepted only integer height, then was modified with the collected data. UTCI requires wind speed at the height of 10 m because it was originally developed for weather forecasting, so the modified data were converted to 10 m height using UTCI's wind speed converting formula. Bröde et al. (2012) give more detail on UTCI's wind speed conversion.

The required input data for UTCI calculation are air temperature, relative humidity, wind speed at 10 m height and mean radiant temperature. In this study, observed air temperatures and relative humidities were used. Wind speeds were from the converted ENVI-met data. Mean radiant temperatures (T_{mrt}) were obtained from the HURES model (Park, 2011). UTCI value for each pixel was calculated using a formula obtained from the UTCI website (http://www.utci.org/utci_doku.php). UTCI patterns at the study locations were mapped using a program written in Microsoft Visual

Fig. 1. Study locations: (a) Nanaimo location from Google map (http://maps.google.com), (b) street photographs of the Nanaimo sites (left, Nanaimo_1; right, Nanaimo_2 and 3), (c) fisheye lens photographs of the Nanaimo sites (left, Nanaimo_1, sky view factor (SVF) = 0.427; center, Nanaimo_2, SVF = 0.408; right, Nanaimo_3, SVF = 0.349) (Park, 2011, 2012), (d) Changwon location from Google map. Dots are site locations, (e) street photograph of the Changwon site, and (f) fisheye lens photograph of the Changwon site (SVF = 0.785) (Park, 2011, 2012). Fisheye lens photographs were taken using a Nikon Coolpix 8800 camera with Nikon FC-E9 fisheye converter lens and Nikon UR-E18 converter adapter. The collected ψ_{sky} values were determined using the BMSky-view computer program (Gál, Rzepa, Gromek, & Unger, 2007).

Table 1
Data collection equipment list.

Climate element	Equipment	
	Nanaimo	Changwon
Radiation	CMP 11 and NR Lite (Kipp & Zonen), Middleton EP08 (Carter-Scott Design), CR23X micrologger (Campbell Scientific Inc.)	
Air temperature and Relative humidity	Sling psychrometer (Sato Keiryoki MFO Co.)	Davis Pro. (Davis Instruments)
Wind speed	Kestrel 2000 Pocket Weather Meter (Nielsen-Kellerman)	Davis Pro.
Surface temperature	Raytek PM Plus infrared thermometer (Raytek)	

Basic 2008 (human bioclimatic maps) for various times of the day (Park, 2012).

3. Results

3.1. Climatic data

Air temperatures and relative humidities were 22.9–28.7 °C and 62–78% at the Nanaimo sites and 27.8–29.3 °C and 33–44% at the Changwon site (Table 2). Differences between the collected radiation data and the HURES model results were small. The collected data/model results coefficients of determination (r^2) were very high for solar radiation ($K\downarrow$, $r^2 = 0.995$; $K\uparrow$, $r^2 = 0.876$), but very low or moderate for longwave radiation ($L\downarrow$, $r^2 = 0.118$; $L\uparrow$, $r^2 = 0.600$) (Fig. 2). However, the range of longwave radiation was within 100 W m^{-2}, and the mean differences between the collected data

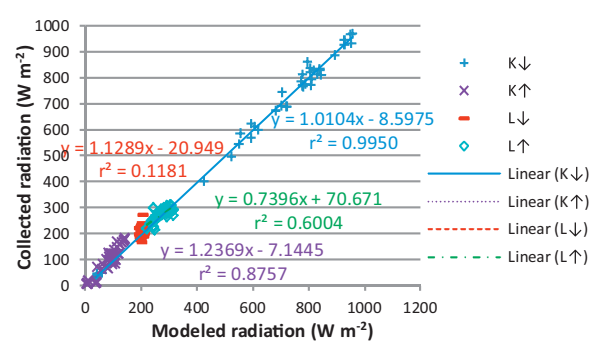

Fig. 2. Comparison of radiation components between the collected data and the HURES model results. K and L are solar and longwave radiation. ↓ and ↑ indicate radiation directions coming from the sky and ground hemispheres, respectively.

Table 2
Air temperature (T_a) and relative humidity (RH) data.

Nanaimo, BC, Canada					Changwon, Republic of Korea				
July 26, 2009					June 11, 2009				
Site	Time	Sunny/Shady	T_a (°C)	RH (%)	Site	Time	Sunny/Shady	T_a (°C)	RH (%)
2	9:37	Sunny	25.1	69		11:30	Sunny	28.1	36
3	9:45	Shady	25.0	69		12:00	Sunny	28.3	34
3	10:12	Shady	25.5	68		12:30	Sunny	28.7	33
2	10:20	Sunny	24.7	69		13:00	Sunny	27.8	41
1	10:44	Sunny	25.0	69		13:30	Sunny	27.9	41
1	12:08	Sunny	22.9	78	Central site of	14:00	Sunny	28.6	38
2	12:34	Sunny	26.0	70	the small park	14:30	Sunny	29.3	40
3	13:17	Shady	26.0	67		15:00	Sunny	29.2	40
2	13:23	Sunny	28.1	63		15:30	Sunny	28.8	41
1	13:43	Sunny	26.2	68		16:00	Sunny	28.8	44
1	14:54	Shady	25.0	72		16:30	Sunny	28.9	42
2	15:18	Shady	27.2	66		17:00	Sunny	29.1	42
3	15:28	Sunny	27.2	66					
3	15:46	Sunny	28.7	62					
2	15:53	Shady	28.7	62					
1	16:11	Shady	25.3	68					

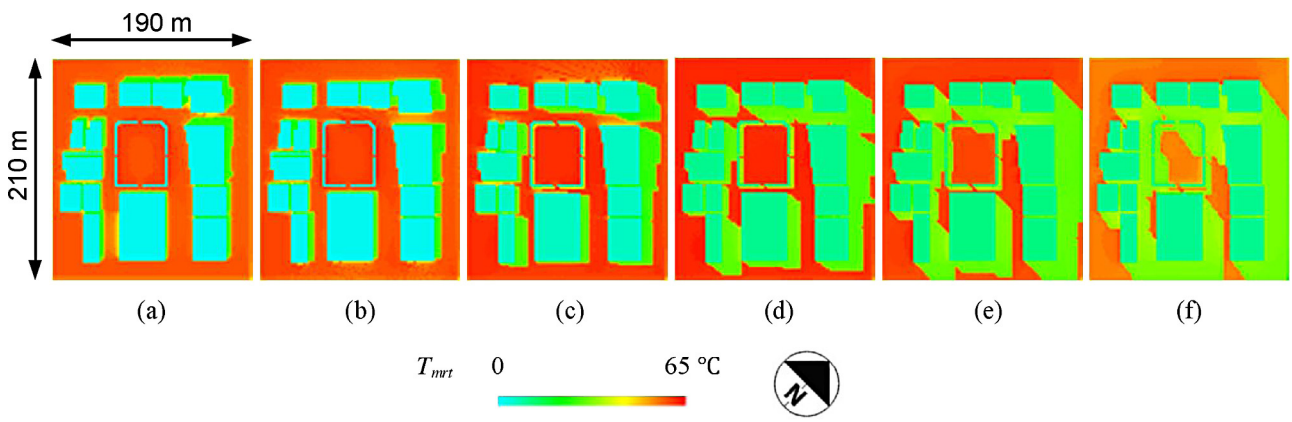

Fig. 3. Mean radiant temperature (T_{mrt}) maps of the Changwon location at (a) 12:00, (b) 13:00, (c) 14:00, (d) 15:00, (e) 16:00 and (f) 17:00.

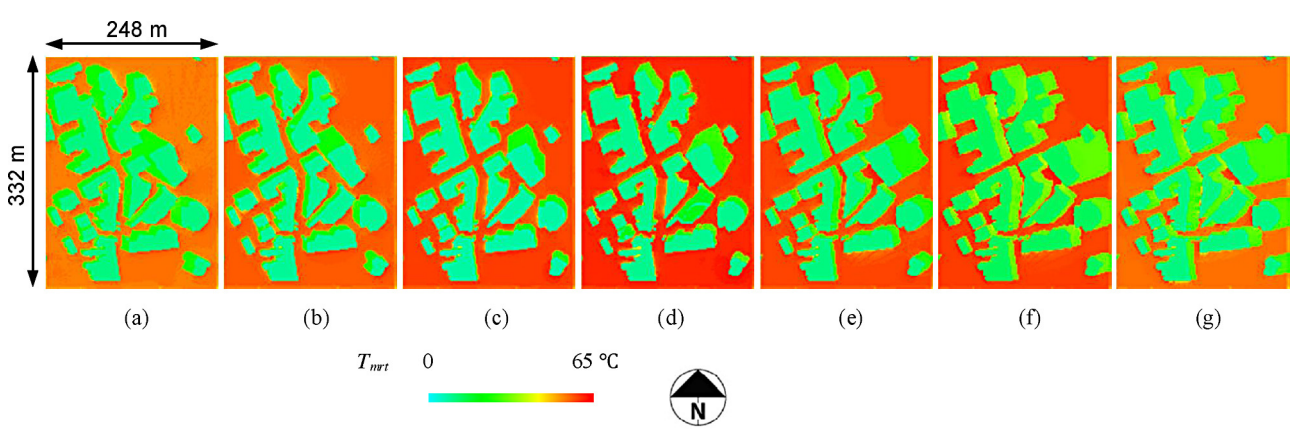

Fig. 4. Mean radiant temperature (T_{mrt}) maps of the Nanaimo location at (a) 9:45, (b) 10:44, (c) 12:34, (d) 13:23, (e) 14:54, (f) 15:46 and (g) 16:11.

Table 3
Radiation mean differences between the collected data and the HURES model results (collected data minus the HURES model results).

Location	K difference (W m^{-2})			L difference (W m^{-2})			Total (W m^{-2})
	$K\downarrow$	$K\uparrow$	Total	$L\downarrow$	$L\uparrow$	Total	
Nanaimo	−7.2 ± 20.2	−4.1 ± 14.5	−11.2 ± 26.3	−15.9 ± 15.3	−6.7 ± 16.8	−22.6 ± 29.4	−33.8 ± 39.9
Changwon	5.4 ± 15.0	−33.8 ± 5.6	−28.4 ± 19.3	7.3 ± 10.6	16.2 ± 12.9	23.5 ± 17.3	−4.9 ± 25.6
All	−1.8 ± 18.4	−16.8 ± 18.8	−18.6 ± 24.0	−5.9 ± 17.8	3.1 ± 18.9	−2.8 ± 34.2	−21.4 ± 36.4

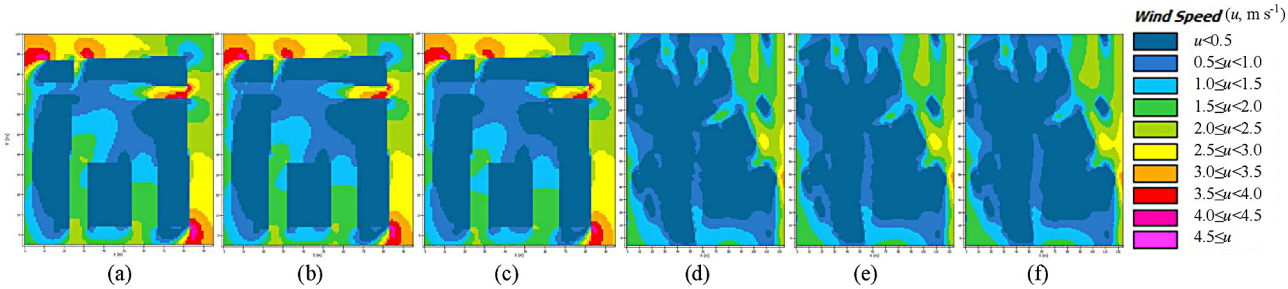

Fig. 5. ENVI-met wind speeds at (a) 11:30, (b) 14:00 and (c) 16:30 of Changwon and (d) 9:30, (e) 13:00 and (f) 16:30 of Nanaimo.

Table 4
Wind speed data at the Nanaimo sites.

July 26, 2009	Sites	Time	Measured wind speed ($m\,s^{-1}$)	ENVI-met wind speed ($m\,s^{-1}$)	Difference ($m\,s^{-1}$)
Morning	2	9:37	0.40	0.01	−0.39
	3	9:45	0.70	0.04	−0.66
	3	10:12	0.60	0.04	−0.56
	2	10:20	0.70	0.01	−0.69
	1	10:44	1.00	0.48	−0.52
	Mean				−0.56 ± 0.12
Noon	1	12:08	1.00	0.46	−0.54
	2	12:34	0.50	0.00	−0.50
	3	13:17	0.30	0.03	−0.27
	2	13:23	0.60	0.00	−0.60
	1	13:43	1.00	0.41	−0.59
	Mean				−0.50 ± 0.13
Afternoon	1	14:54	1.00	0.40	−0.60
	2	15:18	0.30	0.00	−0.30
	3	15:28	0.40	0.03	−0.37
	3	15:46	0.70	0.03	−0.67
	2	15:53	0.80	0.00	−0.80
	1	16:11	0.60	0.38	−0.22
	Mean				−0.49 ± 0.23
All day	Mean				−0.52 ± 0.17

and the HURES model results were small: $L\downarrow = -5.9 \pm 17.8\,W\,m^{-2}$ and $L\uparrow = 3.1 \pm 18.9\,W\,m^{-2}$. The largest mean difference was in $K\uparrow$, $-16.8 \pm 18.8\,W\,m^{-2}$ (Table 3). For further information, please see (Park, 2011).

T_{mrt} in sunny areas were around 50–60 °C in open spaces and 40–50 °C in narrow streets (Figs. 3 and 4). T_{mrt} was between 15 and 40 °C in shady areas. Direct beam solar radiation was the dominant control. T_{mrt} differences between open spaces and narrow streets were also affected by diffuse and reflected solar radiation and longwave radiation emitted by urban surfaces.

3.2. Wind speed modification

Wind speeds computed using ENVI-met did not change much during the day (Fig. 5). These wind speeds were adjusted to better represent those actually observed. Collected wind speeds at both study locations were up to $2.2\,m\,s^{-1}$ (Tables 4 and 5). In the square-shaped Changwon location, there was a very good relationship between sky view factor (SVF) and the differences between the collected data and the ENVI-met results ($u_{\text{-envi}}$) at the three sites, $r^2 = 0.996$ (Fig. 6). The absolute wind speed difference was generally greater at more open sites with higher wind speed indicating a possible systematic bias in ENVI-met wind speeds in this limited sample. However, exposure of different sites varies with wind direction which can be quite variable and the pattern is not consistent among individual values. The new data for Changwon ($u_{\text{-new}}$) were modified with the formula:

$$u_{\text{-new}} = u_{\text{-envi}} + (1.4871 \times \text{SVF} - 0.6423) \quad m\ s^{-1} \tag{1}$$

However, the three Nanaimo sites were composed of many narrow streets and the ENVI-met results were continuously lower than observed wind speeds. Individual values ranged from $-0.22\,m\,s^{-1}$ to $-0.80\,m\,s^{-1}$ with a mean of $-0.52\,m\,s^{-1}$ (Table 4). To compensate, $0.52\,m\,s^{-1}$ was added to the ENVI-met results at the Nanaimo sites. To convert $u_{\text{-new}}$ from the height of 1 m to 10 m ($u_{\text{-new10}}$) which is required as input data for the UTCI, UTCI's wind speed converting formula was used:

$$u_{\text{-new10}} = u_{\text{-new}} \times \frac{\log(10/0.01)}{\log(1/0.01)} \quad m\ s^{-1} \tag{2}$$

(Bröde et al., 2012)

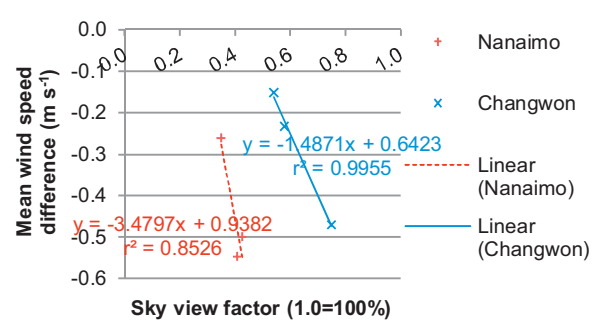

Fig. 6. Comparison between sky view factor and ENVI-met minus measured mean wind speeds.

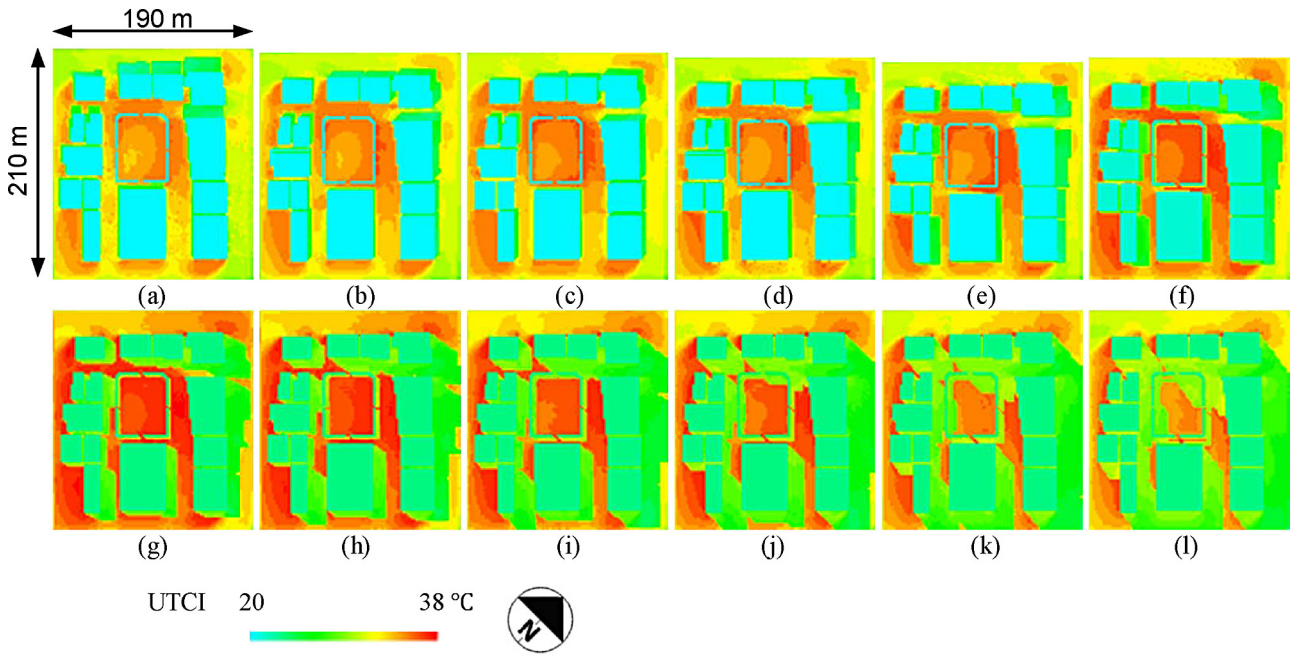

Fig. 7. Universal Thermal Climate Index (UTCI) maps of the Changwon location at (a) 11:30, (b) 12:00, (c) 12:30, (d) 13:00, (e) 13:30, (f) 14:00, (g) 14:30, (h) 15:00, (i) 15:30, (j) 16:00, (k) 16:30 and (l) 17:00.

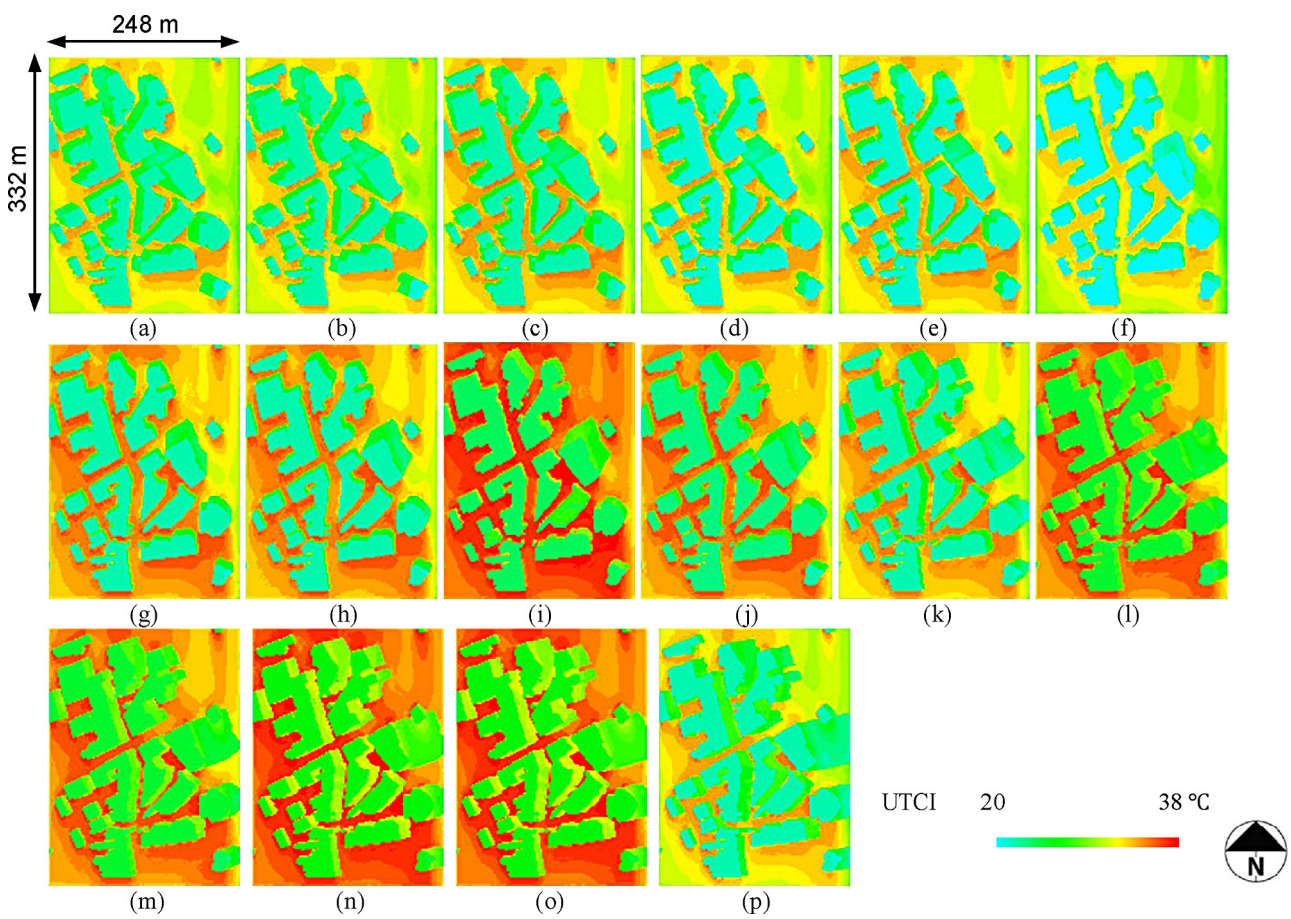

Fig. 8. Universal Thermal Climate Index (UTCI) maps of the Nanaimo location at (a) 9:37, (b) 9:45, (c) 10:12, (d) 10:20, (e) 10:44, (f) 12:08, (g) 12:34, (h) 13:17, (i) 13:23, (j) 13:43, (k) 14:54, (l) 15:18, (m) 15:28, (n) 15:46, (o) 15:53 and (p) 16:11.

Table 5
Wind speed data at the Changwon sites.

June 11, 2009	Sites									
	NW		Center		SE		NW	Center	SE
Time	Measured wind speed ($m\,s^{-1}$)	ENVI-met wind speed ($m\,s^{-1}$)	Measured wind speed ($m\,s^{-1}$)	ENVI-met wind speed ($m\,s^{-1}$)	Measured wind speed ($m\,s^{-1}$)	ENVI-met wind speed ($m\,s^{-1}$)	Differences ($m\,s^{-1}$)		
11:30	0.90	0.94	0.90	1.23		1.05	0.04	0.33	
12:00	0.90	0.93	1.30	1.20		1.03	0.03	−0.10	
12:30	0.40	0.92	1.30	1.17		1.00	0.52	−0.13	
13:00	1.30	0.90	1.80	1.13	1.49	0.98	−0.40	−0.67	−0.51
13:30	1.30	0.89	2.20	1.10	1.43	0.96	−0.41	−1.10	−0.47
14:00	1.30	0.88	1.30	1.06	0.85	0.93	−0.42	−0.24	0.08
14:30	0.90	0.87	1.30	1.02	0.86	0.91	−0.03	−0.28	0.05
15:00	1.30	0.85	1.80	0.98	0.88	0.89	−0.45	−0.82	0.01
15:30	1.30	0.84	1.80	0.95	1.37	0.87	−0.46	−0.85	−0.50
16:00	0.90	0.83	1.80	0.91	1.34	0.85	−0.07	−0.89	−0.49
16:30	0.90	0.82	1.30	0.87	0.96	0.82	−0.08	−0.43	−0.14
17:00	0.90	0.80	1.30	0.83	0.93	0.80	−0.10	−0.47	−0.13
Mean							−0.15 ± 0.29	−0.47 ± 0.41	−0.23 ± 0.26
All day Mean								−0.29 ± 0.35	

Table 6
Universal Thermal Climate Index (UTCI) assessment scale: UTCI categorized in terms of thermal stress (International Union of Physiological Sciences-Thermal Commission, 2003; UTCI Assessment Scale.doc, http://www.utci.org/utci_doku.php).

UTCI (°C) range	Stress category
Above +46	Extreme heat stress
+38 to +46	Very strong heat stress
+32 to +38	Strong heat stress
+26 to +32	Moderate heat stress
+9 to +26	No thermal stress
+9 to 0	Slight cold stress
0 to −13	Moderate cold stress
−13 to −27	Strong cold stress
−27 to −40	Very strong cold stress
Below −40	Extreme cold stress

3.3. UTCI

The UTCI is divided into 10 different stress levels: no thermal stress, 4 heat stress levels and 5 cold stress levels (Table 6). Greatest heat stress at the study locations occurred in the mid-afternoon (Figs. 7 and 8). Thermal stress levels varied greatly between sunny and shaded areas. This means that direct beam solar radiation was the dominant control.

The Changwon location had strong heat stress, 34 °C UTCI, at the sunny area and no thermal stress, 24 °C, at the shaded area at 11:30 (Fig. 7). The sunny areas had 1–2 °C more in the afternoon than at 11:30, but the shaded areas had 4–5 °C more and changed to moderate heat stress. Within the shaded areas, areas close to buildings had 1 °C lower UTCI's than areas farther away. At 14:00 and 16:00, the sunny areas in front of buildings located in the NE portion of the study location had the highest UTCI's. The buildings here are much higher, 40–50 m, than others, 13–32 m, so more reflected solar radiation and longwave radiation from the building wall surfaces create the strong heat stress environment. Moreover, the wind speed result from ENVI-met was lower than those of other areas (Fig. 5b and c).

The Nanaimo location had moderate to strong heat stress at 9:37, around 32 °C UTCI, at the sunny areas and no thermal stress, 24 °C, at the shaded areas (Fig. 8). During the morning, there was only a 1 °C increase in UTCI. At 12:08, the air temperature was low, 22.9 °C, so the sunny areas had only 29 °C UTCI and the shaded areas had 19 °C. The highest UTCI values were at 15:46 and 15:53, 38 °C at the sunny areas and 29–30 °C at the shaded areas. The sunny areas close to building walls had 1–2 °C higher values than sunny areas farther away.

4. Discussion

4.1. Comparison between UTCI and three other human thermal indices

The UTCI results were compared with three other human thermal indices: PMV, SET* and PET. PMV was calculated using Fountain and Huizenga's (1995) computer codes, and SET* and PET were done with RayMan Pro (Matzarakis, Rutz, & Mayer, 2000; Matzarakis, Rutz, & Mayer, 2007; Matzarakis, Rutz, & Mayer, 2010). The metabolic energy was set to 135 $W\,m^{-2}$ (2.3 MET; 243 W when a human body surface area is 1.8 m^2) which is walking at 4 $km\,h^{-1}$ (1.1 $m\,s^{-1}$) activity. The clothing insulation was set to 0.5 clo, a typical summer ensemble.

Blazejczyk, Epstein, Jendritzky, Staiger, and Tinz (2012) compared UTCI with selected thermal indices including SET*, PMV and PET. They found that the above three thermal indices based on human energy (or heat) balance had very high coefficients of determination (r^2) with UTCI, over 0.96 (96%), and that SET* had the

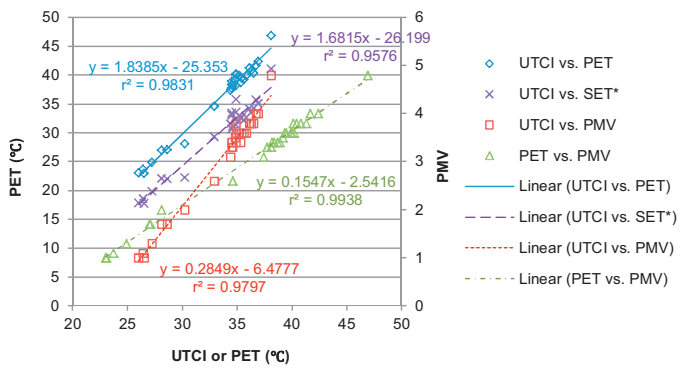

Fig. 9. Comparison of UTCI with SET*, PMV and PET.

closest results to UTCI in urban areas. This study showed similar results (Fig. 9): the r^2s between the three thermal indices and UTCI were over 0.95 (95%). Also, r^2 between PET and PMV was the highest among all thermal indices, 0.99 (99%). PMV, SET* and PET have already been used in various urban and landscape studies. However, UTCI is a recently developed state-of-the-art index that can be a very useful tool for outdoor thermal environment analysis in urban and landscape planning and design.

4.2. The use of human bioclimatic maps

Human bioclimatic maps are images which contain the results from human thermal sensation or comfort models (e.g., PMV, PET, UTCI), mapped at a spatial resolution appropriate for the scale of a design or the problem being investigated. Examples of these maps can be found in a website (e.g., http://www.staedtebauliche-klimafibel.de/Climate_Booklet/kap_2/kap_2-6.htm) and in previous studies (e.g., Chen & Ng, 2011; Matzarakis et al., 2005; Matzarakis, 2007a, 2007b; Ng, 2012). They have been used for various purposes such as tourism strategy (e.g., Matzarakis et al., 2005; Matzarakis, 2007a, 2007b), urban heat island modification (e.g., http://www.kankyo.metro.tokyo.jp/en/other_issues/heat_island.html), a guideline for urban development planning (e.g., Chen & Ng, 2011; Ng, 2012) and climate change impact analysis (e.g., Jendritzky & Tinz, 2009).

For urban and landscape planning and design, the maps can be produced in two different spatial resolutions: local/meso scale and micro scale. Local/meso scale spatial resolution which is from about 100 m to several 10s of kilometers (Oke, 1987) is good for quickly evaluating thermally uncomfortable portions of a large area such as an entire city (Ng, 2012) but cannot be used as an implementing tool for modifying those areas at the design level. The examples in the current study are at the micro scale spatial resolution which is normally less than several meters in computer simulations (Lindberg & Grimmond, 2011; Lindberg, Holmer, & Thorsson, 2008; Park, 2011). This scale can be easily adapted to the design level but requires long computing time for a large area. However, computer systems are advancing rapidly and computer simulation time will be reduced so that the micro scale approach can be applied over large areas in the near future.

5. Conclusions

Outdoor thermal environments at the Nanaimo and Changwon locations were investigated with the UTCI using two computer simulation programs: HURES and ENVI-met 3.1. The purpose of the paper was to illustrate how UTCI and human bioclimate maps might provide information useful in urban and landscape planning and design. Our illustration uses data from only one day at each location. Therefore, the results should be considered as preliminary and representative of conditions at each location at the particular times.

Both study locations had strong afternoon heat stresses in sunny areas. Especially, mid-afternoon, 14:00–16:00, had the strongest heat stress level. The shaded areas had no thermal stress in the morning and early afternoon, but had moderate heat stress after 15:00. Areas close to building walls had 1 °C lower (at the shaded areas) and 1–2 °C higher (at the sunny areas) UTCI values than areas farther from buildings.

In this study, direct beam solar radiation variations changed UTCI by three heat stress levels, diffuse beam and reflected solar radiation and longwave radiation by 1.5 levels and wind speed (u) by half a level. u varied by up to 3.3 m s^{-1} at 10 m height in this study.

This study analyzed UTCI using wind speed data at the height of 10 m which is the same measuring height at weather stations. How to obtain precise and adequate wind speed data will be of great concern for the use of UTCI because urban areas are composed of complex building and tree settings. However, UTCI has great potential to be a useful tool for analyzing outdoor thermal environments in various studies of landscape and urban planning and design.

Modern computer hardware and software allow the computation and mapping of human thermal exchange/comfort index values, i.e. human bioclimatic maps. This allows planners to investigate and easily visualize potential effects of urban and landscape designs on human thermal comfort and stress. The maps can be used to both illustrate and assess the overall distribution of human thermal exchange over an area and to identify specific spots prone to heat or cold stress that might require specific attention. Designs can then incorporate focused corrective measures to reduce or alleviate any problems. Areas of spatial and temporal favorable conditions can also be identified. The relative effects of different climate elements can be determined and used as a guide for which elements to address. Attention to effects on outdoor human thermal comfort/stress maximizes the overall benefits of a design and helps alleviate one possible area of criticism.

This study illustrated the application of the new UTCI to urban areas using reliable measured and modeled input data. The results were reasonable and spatial variations are what would be expected in urban settings showing this up-to-date index should be useful in planning and design. At the same time the use of UTCI quantified spatial variations of a synthesis of a number of climatic elements allowing the mapping of the composite climate as opposed to that of single elements. We recommend further tests and applications of the new UTCI and use of bioclimatic maps whenever the effects of design of outdoor spaces on human thermal comfort is of interest.

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References

Alcoforado, M., Andrade, H., Lopes, A., & Vasconcelos, J. (2009). Application of climatic guideline to urban planning. The example of Lisbon (Portugal). *Landscape and Urban Planning*, *90*, 56–65.

Alexandri, E., & Jones, P. (2008). Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Building and Environment*, *43*, 480–493.

Ali-Toudert, F., & Mayer, H. (2007). Effects of asymmetry, galleries, overhanging facades and vegetation on thermal comfort in urban street canyons. *Solar Energy*, *81*, 742–754.

Antics, A., Pascal, M., Laaidi, K., Wagner, V., Corso, M., Declercq, C., et al. (2013). A simple indicator to rapidly assess the short-term impact of heat waves on mortality within the French heat warning system. *International Journal of Biometeorology*, *57*(1), 75–81. http://dx.doi.org/10.1007/s00484-012-0535-9

Arnfield, J. (2003). Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology*, *23*, 1–26.

Auliciems, A., & Kalma, J. D. (1979). A climatic classification of human thermal stress in Australia. *Journal of Applied Meteorology*, *18*, 616–626.

Benedict, F. G., & Carpenter, T. M. (1910). *The metabolism and energy transformations of healthy man during rest*. Carnegie Institution of Washington, Publication No. 126.

Blazejczyk, K. (1994). New climatological-and-physiological model of the human heat balance outdoor (MENEX) and its applications in bioclimatological studies in different scales. In K. Blazejczyk, & B. Krawczyk (Eds.), *Bioclimatic research of the human heat balance* (pp. 27–58). Warsaw: Polish Academy of Sciences, Institute of Geography and Spatial Organization.

Blazejczyk, K. (2004). Assessment of radiation balance in man in various meteorological and geographical conditions. *Geographia Polonica*, *77*, 63–76.

Blazejczyk, K. (2005). *MENEX_2005-the updated version of man-environment heat exchange model*. http://www.igipz.pan.pl/tl_files/igipz/ZGiK/opracowania/indywidualne/blazejczyk/MENEX_2005.pdf (22.02.13)

Blazejczyk, K., Epstein, Y., Jendritzky, G., Staiger, H., & Tinz, B. (2012). Comparison of UTCI to selected thermal indices. *International Journal of Biometeorology*, *56*(3), 515–535. http://dx.doi.org/10.1007/s00484-011-0453-2

Bonan, G. B. (2000). The microclimate of a suburban Colorado (USA) landscape and implications for planning and design. *Landscape and Urban Planning*, *49*, 97–114.

Bowler, D. E., Buyung-Ali, L., Knight, T. M., & Pullin, A. S. (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape and Urban Planning*, *97*, 147–155.

Bröde, P., Fiala, D., Blazejczyk, K., Holmér, I., Jendritzky, G., Kampmann, B., et al. (2012). Deriving the operational procedure for the Universal Thermal Climate Index (UTCI). *International Journal of Biometeorology*, *56*(3), 481–494. http://dx.doi.org/10.1007/s00484-011-0454-1

Brown, R. D. (2011). Ameliorating the effects of climate change: Modifying microclimates through design. *Landscape and Urban Planning*, *100*(4), 372–374. http://dx.doi.org/10.1016/j.landurbplan.2011.01.010

Brown, R. D., & Gillespie, T. J. (1986). Estimating outdoor thermal comfort using a cylindrical radiation thermometer and an energy budget model. *International Journal of Biometeorology*, *30*, 43–52.

Brown, R. D., & Gillespie, T. J. (1995). *Microclimatic landscape design: Creating thermal comfort and energy efficiency*. New York: Wiley.

Burt, J. E. (1979). *A model of human thermal comfort and associated comfort patterns for the United States*. Centerton, NJ: C.W. Thornthwaite Associates.

Ca, V. T., Asaeda, T., & Abu, E. M. (1998). Reductions in air conditioning energy caused by a nearby park. *Energy and Buildings*, *29*, 83–92.

Chen, H., Ooka, R., & Kato, S. (2008). Study on optimum design method for pleasant outdoor thermal environment using genetic algorithms (GA) and coupled simulation of convection radiation and conduction. *Building and Environment*, *43*, 18–30.

Chen, L., & Ng, E. (2011). Quantitative urban climate mapping based on a geographical database: A simulation approach using Hong Kong as a case study. *International Journal of Applied Earth Observation and Geoinformation*, *13*, 586–594.

Chow, W. T. L., Pope, R. L., Martin, C. A., & Brazel, A. J. (2011). Observing and modeling the nocturnal park cool island of an arid city: Horizontal and vertical impacts. *Theoretical and Applied Climatology*, *103*(1/2), 197–211. http://dx.doi.org/10.1007/s00704-010-0293-8

Corbella, O. D., & Magalhães, M. A. A. A. (2008). Conceptual differences between the bioclimatic urbanism for Europe and for the tropical humid climate. *Renewable Energy*, *33*, 1019–1023.

Davis, R. E., Knappenberger, P. C., Novicoff, W. M., & Michaels, P. J. (2003). Decadal changes in summer mortality in U.S. cities. *International Journal of Biometeorology*, *47*(3), 166–175.

de Freitas, C. R. (1985). Assessment of human bioclimate based on thermal response. *International Journal of Biometeorology*, *29*(2), 97–119.

de Freitas, C. R. (2003). Tourism climatology: Evaluating environmental information for decision making and business planning in the recreation and tourism sector. *International Journal of Biometeorology*, *48*, 45–54.

de Freitas, C. R., Scott, D., & McBoyle, G. (2008). A second generation climate index for tourism (CIT): Specification and verification. *International Journal of Biometeorology*, *52*, 399–407.

Dessai, S. (2002). Heat stress and mortality in Lisbon. Part 1. Model construction and validation. *International Journal of Biometeorology*, *47*(1), 6–12.

Díaz, J., García, R., López, C., Linares, C., Tobías, A., & Prieto, L. (2005). Mortality impact of extreme winter temperatures. *International Journal of Biometeorology*, *49*(3), 179–183.

Dimoudi, A., & Nikolopoulou, M. (2003). Vegetation in the urban environment: Microclimatic analysis and benefits. *Energy and Buildings*, *35*, 69–76.

Eliasson, I. (2000). The use of climate knowledge in urban planning. *Landscape and Urban Planning*, *48*, 31–44.

Eliasson, I., Knez, I., Westerberg, U., Thorsson, S., & Lindberg, F. (2007). Climate and behaviour in a Nordic city. *Landscape and Urban Planning*, *82*, 72–84.

Fahmy, M., & Sharples, S. (2009). On the development of an urban passive thermal comfort system in Cairo, Egypt. *Building and Environment*, *44*, 1907–1916.

Fanger, P. O. (1972). *Thermal comfort: Analysis and applications in environmental engineering*. New York: McGraw-Hill.

Fiala, D., Lomas, K. J., & Stohrer, M. (2001). Computer prediction of human thermoregulatory and temperature responses to a wide range of environmental conditions. *International Journal of Biometeorology*, *45*, 143–159.

Fiala, D., Havenith, G., Bröde, P., Kampmann, B., & Jendritzky, G. (2012). UTCI-Fiala multi-node model of human heat transfer and temperature regulation. *International Journal of Biometeorology*, *56*, 429–441.

Fountain, M., & Huizenga, C. (1995). *A thermal sensation model for use by the engineering profession*. Piedmont: Environmental Analytics.

Gagge, A. P., Stolwijk, J., & Nishi, Y. (1971). An effective temperature scale based on a simple model of human physiological regulatory response. *ASHRAE Transactions*, *77*(1), 247–262.

Gagge, A. P., Fobelets, A. P., & Berglund, P. E. (1986). A standard predictive index of human response to the thermal environment. *ASHRAE Transactions*, *92*, 709–731.

Gál, T., Rzepa, M., Gromek, B., & Unger, J. (2007). Comparison between sky view factor values computed by two different methods in an urban environment. ACTA Climatologica et Chorologica, Universitatis Szegediensis. *Tomus*, *40/41*, 17–26.

Golden, J. S., Hartz, D., Brazel, A., Luber, G., & Phelan, P. (2008). A biometeorology study of climate and heat-related morbidity in Phoenix from 2001 to 2006. *International Journal of Biometeorology*, *52*, 471–480.

Georgi, J. N., & Dimitriou, D. (2010). The contribution of urban green spaces to the improvement of environment in cities: Case study of Chania, Greece. *Building and Environment*, *45*, 1401–1414.

Gosling, S. N., McGregor, G. R., & Páldy, A. (2007). Climate change and heat-related mortality in six cities. Part 1: Model construction and validation. *International Journal of Biometeorology*, *51*, 525–540.

Gulyás, Á., Unger, J., & Matzarakis, A. (2006). Assessment of the microclimatic and human comfort conditions in a complex urban environment: Modelling and measurements. *Building and Environment*, *41*, 1713–1722.

Harlan, S. L., Brazel, A. J., Prashad, L., Stefanov, W. L., & Larsen, L. (2006). Neighborhood microclimates and vulnerability to heat stress. *Social Science & Medicine*, *63*, 2847–2863.

Havenith, G., Fiala, D., Błażejczyk, K., Richards, M., Bröde, P., Holmér, I., et al. (2012). The UTCI-clothing model. *International Journal of Biometeorology*, *56*(3), 461–470. http://dx.doi.org/10.1007/s00484-011-0451-4

Höppe, P. R. (1993). Heat balance modeling. *Experientia*, *49*, 741–746.

Höppe, P. R. (1999). The physiological equivalent temperature – A universal index for the biometeorological assessment of the thermal environment. *International Journal of Biometeorology*, *43*, 71–75.

International Union of Physiological Sciences-Thermal Commission. (2003). Glossary of terms for thermal physiology. *Journal of Thermal Biology*, *28*, 75–106.

Jendritzky, G., Schirmer, H., Menz, H., & Schmidt-Kessen, W. (1990). *(Method for spatial evaluation of the thermal component in the bioclimate of man (updated Klima-Michel-Model)) Methode zur raumbezogenen Bewertung der thermischen Komponente im Bioklima des Menschen (Fortgeschriebenes Klima-Michel-Modell)*. Akad. f. Raumforschung u. Landesplanung, Hannover, Beiträge, No. 114.

Jendritzky, G., & Tinz, B. (2009). The thermal environment of the human being on the global scale. *Global Health Action*, *200*, 9. http://dx.doi.org/10.3402/gha.v2i0.2005

Jendritzky, G., de Dear, R., & Havenith, G. (2012). UTCI – Why another thermal index? *International Journal of Biometeorology*, *56*, 421–428.

Kalkstein, A. J., & Sheridan, S. C. (2007). The social impacts of the heat-health watch/warning system in Phoenix, Arizona: Assessing the perceived risk and response of the public. *International Journal of Biometeorology*, *52*, 43–55.

Kántor, N., & Unger, J. (2010). Benefits and opportunities of adopting GIS in thermal comfort studies in resting places: An urban park as an example. *Landscape and Urban Planning*, *98*, 36–46.

Landsberg, H. E. (1981). *The urban climate*. New York: Academic Press.

Lin, T., & Matzarakis, A. (2008). Tourism climate and thermal comfort in Sun Moon Lake, Taiwan. *International Journal of Biometeorology*, *52*, 281–290.

Lin, T. (2009). Thermal perception adaptation and attendance in a public square in hot and humid regions. *Building and Environment*, *44*, 2017–2026.

Lindberg, F., Holmer, B., & Thorsson, S. (2008). SOLWEIG 1.0 – Modelling spatial variations of 3D radiant fluxes and mean radiant temperature in complex urban settings. *International Journal of Biometeorology*, *52*(7), 697–713.

Lindberg, F., & Grimmond, C. S. B. (2011). The influence of vegetation and building morphology on shadow patterns and mean radiant temperatures in urban areas: Model development and evaluation. *Theoretical and Applied Climatology*, *105*(3/4), 311–323. http://dx.doi.org/10.1007/s00704-010-0382-8

Mahmoud, A. H. A. (2011). An analysis of bioclimatic zones and implications for design of outdoor built environments in Egypt. *Building and Environment*, *46*(3), 605–620. http://dx.doi.org/10.1016/j.buildenv.2010.09.007

Matzarakis, A. (2007a). Climate and bioclimate information for tourism – The example of Evros Prefecture. In A. Matzarakis, C. R. de Freitas, & D. Scott (Eds.), *Developments in tourism climatology* , ISBN 978-3-00-024110-9 (pp. 12–17).

Matzarakis, A. (2007b). Climate, human comfort and tourism. In B. Amelung, K. Blazejczyk, & A. Matzarakis (Eds.), *Climate change and tourism: Assessment and coping strategies* (pp. 139–154), 978-00-023716-4.

Matzarakis, A., Rutz, F., & Mayer, H. (2000). Estimation and calculation of the mean radiant temperature within urban structures. In R. J. de Dear, J. D. Kalma, T. R. Oke, & A. Auliciems (Eds.), *Biometeorology and urban climatology at the turn of the millennium* (pp. 273–278). ICB-ICUC'99, Sydney, WCASP-50, WMO/TD No. 1026.

Matzarakis, A., Rudel, E., Zygmuntowski, M., & Koch, E. (2005). Thermal human bioclimatic conditions for Austria and the Alps. *Croatian Meteorological Journal*, *40*, 190–193.

Matzarakis, A., Rutz, F., & Mayer, H. (2007). Modelling radiation fluxes in simple and complex environments-application of the RayMan model. *International Journal of Biometeorology*, *51*, 323–334.

Matzarakis, A., Rutz, F., & Mayer, H. (2010). Modelling radiation fluxes in simple and complex environments: Basics of the RayMan model. *International Journal of Biometeorology*, *54*, 131–139.

Mayer, H., & Höppe, P. (1987). Thermal comfort of man in different urban environments. *Theoretical and Applied Climatology*, *38*, 43–49.

Nakai, S., Itoh, T., & Morimoto, T. (1999). Deaths from heat-stroke in Japan: 1968–1994. *International Journal of Biometeorology*, *43*(3), 124–127.

Ng, E. (2012). Towards planning and practical understanding of the need for meteorological and climatic information in the design of high-density cities: A case-based study of Hong Kong. *International Journal of Climatology*, *32*(4), 582–598. http://dx.doi.org/10.1002/joc.2292

Nicholls, N., Skinner, C., Loughnan, M., & Tapper, N. (2008). A simple heat alert system for Melbourne, Australia. *International Journal of Biometeorology*, *52*(5), 375–384. http://dx.doi.org/10.1007/s00484-007-0132-5

Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*, *108*, 1–24.

Oke, T. R. (1987). *Boundary layer climates* (2nd edition). London: Methuen.

Oke, T. R. (1989). The micrometeorology of the urban forest. *Philosophical Transactions of the Royal Society of London, Series B*, *324*, 335–349.

Park, S. (2011). *Human-urban radiation exchange simulation model (Ph.D. dissertation)*. Victoria, BC, Canada: University of Victoria.

Park, S. (2012). Landscape planning and design methods with human thermal sensation. *Journal of the Korean Institute of Landscape Architecture*, *40*(1), 1–11 (in Korean).

Pascal, M., Laaidi, K., Ledrans, M., Baffert, E., Caserio-Schönemann, C., Tertre, A. L., et al. (2006). France's heat health watch warning system. *International Journal of Biometeorology*, *50*, 144–153.

Pascal, M., Wagner, V., Tertre, A. L., Laaidi, K., Honoré, C., Bénichou, F., et al. (2013). Definition of temperature thresholds: The example of the French heat wave warning system. *International Journal of Biometeorology*, *57*(1), 21–29. http://dx.doi.org/10.1007/s00484-012-0530-1

Pickup, J., & de Dear, R. (2000). An outdoor thermal comfort index (OUT-SET*) – Part I – The model and its assumptions. In R. J. de Dear, J. D. Kalma, T. R. Oke, & A. Auliciems (Eds.), *Biometeorology and urban climatology at the turn of the millennium* (pp. 279–283). ICB-ICUC'99, Sydney, WCASP-50, WMO/TD No. 1026.

Picot, X. (2004). Thermal comfort in urban spaces: Impact of vegetation growth Case study: Piazza della Scienza, Milan, Italy. *Energy and Buildings*, *36*, 329–334.

Raatikka, V., Rytkönen, M., Näyhä, S., & Hassi, J. (2007). Prevalence of cold-related complaints, symptoms and injuries in the general population: The FINRISK 2002 cold substudy. *International Journal of Biometeorology*, *51*(5), 441–448.

Rosenfeld, A. H., Akbari, H., Romm, J. J., & Pomerantz, M. (1998). Cool communities: Strategies for heat island mitigation and smog reduction. *Energy and Buildings*, *28*, 51–62.

Roth, M. (2007). Review of urban climate research in (sub)tropical regions. *International Journal of Climatology*, *27*, 1859–1873.

Shashua-Bar, L., & Hoffman, M. E. (2000). Vegetation as a climatic component in the design of an urban street. An empirical model for predicting the cooling effect of urban green areas with trees. *Energy and Buildings*, *31*, 221–235.

Shashua-Bar, L., Pearlmutter, D., & Erell, E. (2009). The cooling efficiency of urban landscape strategies in a hot dry climate. *Landscape and Urban Planning*, *92*, 179–186.

Shashua-Bar, L., Pearlmutter, D., & Erell, E. (2011). The influence of trees and grass on outdoor thermal comfort in a hot-arid environment. *International Journal of Climatology*, *31*(10), 1498–1506. http://dx.doi.org/10.1002/joc.2177

Shiue, I., & Matzarakis, A. (2011). Estimation of the tourism climate in the Hunter Region, Australia, in the early twenty-first century. *International Journal of Biometeorology*, *55*(4), 565–574.

Smoyer, K. E., Rainham, D. G. C., & Hewko, J. N. (2000). Heat-stress-related mortality in five cities in Southern Ontario: 1980–1996. *International Journal of Biometeorology*, *44*(4), 190–197.

Söderström, G. F., & DuBois, E. F. (1917). The water elimination through skin and respiratory passages in health and disease. *Archives of Internal Medicine*, *19*, 931.

Staiger, H., Bucher, K., & Jendritzky, G. (1997). Gefühlte Temperatur. Die physiologisch gerechte Bewertung von Wärmebelastung und Kältestress eim Aufenthalt im Freien in der Maßzahl Grad Celsius. *Ann Meteorol Deutscher Wetterdienst, Offenbach*, *33*, 100–107.

Staiger, H., Laschewski, G., & Grätz, A. (2012). The perceived temperature – A versatile index for the assessment of the human thermal environment. Part A: Scientific basics. *International Journal of Biometeorology*, *56*, 165–176.

Steadman, R. G. (1979). The assessment of Sultriness. Part II: Effects of wind extra radiation and barometric pressure on apparent temperature. *Journal of Applied Meteorology*, *18*, 874–885.

Steadman, R. G. (1984). A universal scale of apparent temperature. *Journal of Climate and Applied Meteorology*, *23*, 1674–1687.

Stewart, I. D. (2011). A systematic review and scientific critique of methodology in modern urban heat island literature. *International Journal of Climatology*, *31*, 200–217.

Tan, J., Kalkstein, L. S., Huang, J., Lin, S., Yin, H., & Shao, D. (2004). An operational heat/health warning system in Shanghai. *International Journal of Biometeorology*, *48*, 157–162.

Tan, J., Zheng, Y., Song, G., Kalkstein, L. S., Kalkstein, A. J., & Tang, X. (2007). Heat wave impacts on mortality in Shanghai, 1998 and 2003. *International Journal of Biometeorology*, *51*(3), 193–200.

Tuller, S. E. (1990). Standard seasons. *International Journal of Biometeorology*, *34*, 181–188.

Winslow, C. E. A., Herrington, L. P., & Gagge, A. P. (1937). Physiological reactions of the human body to varying environmental temperatures. *The American Journal of Physiology*, *120*(1), 1–22.

Wong, N. H., Jusuf, S. K., & Tan, C. L. (2011). Integrated urban microclimate assessment method as a sustainable urban development and urban design tool. *Landscape and Urban Planning*, *100*(4), 386–389. http://dx.doi.org/10.1016/j.landurbplan.2011.02.012

Yaglou, C. P., & Miller, W. E. (1925). Effective temperature with clothing. *ASHRAE Transactions*, *31*, 89–99.