Human Energy Budget Modeling in Urban Parks in Toronto and Applications to Emergency Heat Stress Preparedness

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(Manuscript received 29 November 2011, in final form 13 March 2012)

ABSTRACT

The current study tests applications of the Comfort Formula (COMFA) energy budget model by assessing the moderating effects of urban parks in contrast to streets, and it also looks at the influence of park types (“open” or “treed”). Exploration into energy budget modeling is based on empirical meteorological data collected in Toronto, Ontario, Canada, on fair-weather days plus the effects of a heat wave and climate change, at various metabolic activity levels. Park cooling temperature intensities ranged from 3.9 to 6.0°C, yet human energy budgets were more closely correlated to incoming solar radiation than to air temperature. A strong linear dependence was found, with absorbed radiation (correlation coefficient squared $r^2 = 0.858$) explaining the largest fraction of energy budget output. Hence, although the four parks that were examined are classified as urban green space, the distinctive treed areas showed a greater budget decrease than did open park areas ($-25.5$ W m$^{-2}$). The greatest difference in budget decrease was found when modeling the highest metabolic rate, giving $-32$ W m$^{-2}$ for “whole park,” $-3$ W m$^{-2}$ for treed sections, and $-3$ W m$^{-2}$ in open park areas. These results are intuitive within energy budget modeling and indicate that blocking radiant energy is a vital aspect in lowering high budgets under the conditions tested. Strong empirical support was provided through successful prediction of emergency-response calls during a heat wave in Toronto (5–7 July 2010) and surrounding days. Calls were found to be significantly dependent on the energy budget estimations ($r^2 = 0.860$). There is great potential for outdoor energy budget modeling as a meaningful guide to heat stress forecasting, future research, and application in bioclimatic urban design for improving thermal comfort.

1. Introduction

Evidence of the benefits of a comfortable microclimate within parks is extensive and has been correlated with increased use of outdoor space (Mayer et al. 2008). Lower heat stress, coupled with increased frequency and duration of exercise in parks, also results from improved thermal comfort (TC) (Watkins et al. 2007; Gaitani et al. 2007). Such benefits are transferable into higher quality of life and functionality (Eliasson 2000; Watkins et al. 2007), fewer heat-related casualties, and a decrease in rates of obesity and cardiovascular disease as a result of exercise (Galea and Vlahov 2005; Brotherhood 2008). Many human health indicators are more strongly related to the amount of green space than to the degree of urbanity (deVries et al. 2003), with vegetation found to be significantly correlated with TC in urban areas such as Phoenix, Arizona (Harlan et al. 2006).

Vital changes such as increases in vegetative shading, albedos of ground and building surfaces, presence of water, and alternating building heights can reduce the air temperature $T_a$ in an urban climate (Eliasson et al. 2007; Watkins et al. 2007). According to Lin et al. (2010), shading is an important component of long- and short-term outdoor TC, specifically within urban canyons...
Thermal balance is influenced by metabolic activity and field settings using physiological heat balance models. Very few studies in human biometeorology have been completed on exercising individuals in realistic field settings using physiological heat balance models. Thermal balance is influenced by metabolic activity $M_{act}$, micrometeorological conditions, clothing properties, and psychological perceptions. Overall thermal sensation (TS), often expressed as TC, is influenced by personal differences in mood, culture, social factors (Djongyang et al. 2010), expectations, perceived control, time of exposure, fitness, aesthetics, season, weather, perception, and readiness to exercise (Thorsson et al. 2004; Vanos et al. 2012a).

Hence, studies have been completed to note overall adaptive processes: behavioral, physiological, and psychological (de Dear and Brager 1998; Fanger and Toftum 2002; Yao et al. 2009). Human adaptive strategies to climate change—in particular, in urban areas—is a principal focus in current research (Smoyer et al. 2000; Nikolopoulou and Lykoudis 2006; Golden et al. 2008; Matzarakis and Endler 2010), with an expected increase in magnitude and frequency of heat waves as climate change advances (Gosling et al. 2007; O’Neill and Ebi 2009).

Heat is suggested to remain the most important extreme-weather-related killer in the United States (Sheridan et al. 2009). During intense heat waves, individuals may not be able to escape the heat, with urban heat islands (UHI) diminishing nighttime cooling and thus heat relief. Particular importance should be placed on protecting vulnerable individuals—the elderly (>65 yr; Luber and McGeehin 2008), young, sick, unacclimatized, and unconditioned—who may have compromised thermoregulation (Smoyer et al. 2000). This vulnerability is increased in poor populations that do not have adequate resources (Curriero et al. 2002; Harlan et al. 2006), such as air conditioning (Luber and McGeehin 2008). Havenith (1997) gives evidence that cardiovascular fitness is a more important determinant of heat mortality than age, however.

The purpose of the current study is to test the application of the Comfort Formula (COMFA) model to practical urban design issues using an existing dataset from Slater (2010). This study will spatially assess the moderating effect of urban parks on outdoor TC and under various human physiological states. Various tangible empirical applications are presented and proposed through the use of energy budget modeling. This is completed through accomplishment of the following: 1) assessment of the TC-moderating effects in urban parks using an energy budget approach while evaluating the impacts of gender, activity intensity, and conditioning level on TS; 2) provision of an example of heat stress modeling that displays the impacts of current and future extreme-heat events on those performing physical activity in an urban park; and 3) empirical evaluation of energy budget modeling to extreme-heat occurrences, demonstrating the use of energy budget modeling as a tool for predicting heat-related emergency-response calls.

This paper is not intended to study the UHI or park cool intensity (PCI) effects in detail, as the spatial scope and temporal scope of the data are limited. It is intended to show that human comfort at any point in a built or park environment can be quantified for urban design and management using the COMFA energy budget model.

2. Methods
a. Site selection and characteristics

Toronto, Ontario, Canada has a population of approximately 4.28 million people in dense occupation, with a heterogeneous mix of modern core built-up areas and compact housing in residential and suburban areas (Stewart and Oke 2009). The city experiences a humid continental climate (Peel et al. 2007), having warm, humid summers with cold winters. Centered in the warmest climatic zone in Canada, Toronto has experienced above-average temperatures in six of the seven summers between 2004 and 2011 (Environment Canada 2010), is subjected to UHI effects (Mohsin and Gough 2010), and is predicted to have doubled heat-related mortality by 2050 (Cheng et al. 2005). Lemmen et al. (2008) anticipate growing public-health risk to heat, reporting a high likelihood that Toronto will face extreme-heat events of heightened intensity, duration, and frequency.

Table 1 lists the four urban-park study sites, as well as the nearest corresponding weather station to each park that is used for wind speed vectors. The four parks are found within 1.5–2.8 km of the urban core, as displayed in the GIS map of Toronto in Fig. 1. The parks did not contain ponds and were surrounded by similar urban form of high-density housing in older neighborhoods with narrow streets (7–7.25 m), and 2–3-story detached/semidetached houses set back 6–9 m (Slater 2010). Daily population densities (people per square
kilometer) range from 12,000 to 47,000 for all parks excluding Trinity Bellwoods, which has a density of 86,000 to 228,000 (Glazier et al. 2007, 119–129). These ranges are relatively wide because of daily migration of people to and from activities such as work, school, business, and recreation. All four parks have been preserved and thus contain mainly deciduous and coniferous tree species that are typical to the area, which include various mature species of ash (Fraxinus), oak (Quercus), maple (Acer), elm (Ulmus), and pine trees (Pinus).

b. Microclimate data collection and modeling

Four urban parks within Toronto, Ontario, were chosen on the basis of the ability to complete a relatively straight transect line through the park from the streets and hence not to alter the wind direction effects on the instruments significantly. Figure 2 displays an aerial view of Dovercourt Park as an example transect taken through each park.

Instruments monitoring microclimatic parameters were securely fastened at a height of 1.5 m to the front of

<table>
<thead>
<tr>
<th>Park (area) coordinates</th>
<th>Bordering height/width ratio*</th>
<th>Transect length* (m)</th>
<th>Park length (m)</th>
<th>Corresponding weather station**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Withrow (8.5 ha) 43°40'30&quot;, 79°20'49&quot;</td>
<td>0.32</td>
<td>1310</td>
<td>192</td>
<td>Leslieville</td>
</tr>
<tr>
<td>Trinity Bellwoods (15.1 ha) 43°38'352&quot;, 79°24'51&quot;</td>
<td>0.38</td>
<td>922</td>
<td>646</td>
<td>Toronto Island</td>
</tr>
<tr>
<td>Dovercourt (2.4 ha) 43°39'55&quot;, 79°26'01&quot;</td>
<td>0.35</td>
<td>961</td>
<td>126</td>
<td>Davis</td>
</tr>
<tr>
<td>Dufferin Grove (5.8 ha) 43°39'22&quot;, 79°20'56&quot;</td>
<td>0.35</td>
<td>928</td>
<td>230</td>
<td>Davis</td>
</tr>
</tbody>
</table>

* Mean values.
** Nearest weather station at similar altitude to corresponding outdoor park.
a bicycle, which moved with a speed of \( \sim 9 \text{ km h}^{-1} \) along a street–park–street transect. Microclimate data were collected along the transects in September of 2009 at times between 1300 and 1630 LT on sunny days (see Table 2). These data define the meteorological environment in which the human activity takes place, which is required for input to the model.

Air temperature \( T_a \) was measured using a fine-diameter (0.02 mm) copper–constantan (Type “T”) thermocouple (Omega Engineering, Inc.). Relative humidity RH was measured using an HC-S3 temperature and RH sensor probe (Rotronic Instrument Corp.), with the metal mesh cap removed for improved response time. Total incoming shortwave radiation \( K_{in} \) from the atmosphere, buildings, and trees was measured using a lightweight portable LI-200 pyranometer (Li-Cor, Inc.). Data were collected at 0.8-s intervals using a 21X datalogger (Campbell Scientific, Inc.), with all instruments mounted on a bicycle (Manoeuvre model from Diamondback Bicycles Co.), at 1.5-m height. A quick-release apparatus was used for consistent and timely mounting setup and for easy portability. Speed (m s\(^{-1}\)) and distance (m) were measured using two wired computer sensors (dZ4L model from Filzer Co.). Transects consisted of two or four passes each, in which one pass of each pair was reversed for averaging of all data at an observation point.

**TABLE 2. Summary of meteorological conditions recorded on-site and from corresponding weather stations expressed as a mean over each sampling period (LT) in September 2009: \( T_a \) (°C), \( e \) (kPa), \( v_w \) (m s\(^{-1}\); compass-point wind direction is in parentheses), and \( \tau \) (sky transmissivity; Kenny et al. 2008). Sampling periods consisted of two or four transect passes. [Averaged wind data for all transect passes were obtained from the nearby weather station (10-m height)].**

<table>
<thead>
<tr>
<th>Park</th>
<th>Date</th>
<th>Sampling period</th>
<th>No. of transect passes</th>
<th>( T_a )</th>
<th>( e )</th>
<th>( v_w )</th>
<th>( \tau ) (dir)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Withrow</td>
<td>6 Sep</td>
<td>1535–1615</td>
<td>2</td>
<td>22.0</td>
<td>1.5</td>
<td>4.0 (E)</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>7 Sep</td>
<td>1435–1636</td>
<td>4</td>
<td>23.1</td>
<td>1.7</td>
<td>5.8 (E)</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>8 Sep</td>
<td>1330–1450</td>
<td>4</td>
<td>23.9</td>
<td>2.0</td>
<td>4.4 (E)</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>9 Sep</td>
<td>1440–1600</td>
<td>4</td>
<td>22.9</td>
<td>1.9</td>
<td>4.0 (E)</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>20 Sep</td>
<td>1540–1600</td>
<td>2</td>
<td>19.7</td>
<td>1.7</td>
<td>8.8 (E)</td>
<td>0.87</td>
</tr>
<tr>
<td>Dovercourt</td>
<td>4 Sep</td>
<td>1500–1520</td>
<td>2</td>
<td>23.4</td>
<td>1.3</td>
<td>9.3 (S)</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>15 Sep</td>
<td>1525–1615</td>
<td>2</td>
<td>24.0</td>
<td>1.0</td>
<td>6.7 (N)</td>
<td>0.78</td>
</tr>
<tr>
<td>Trinity Bellwoods</td>
<td>4 Sep</td>
<td>1545–1615</td>
<td>2</td>
<td>23.4</td>
<td>1.4</td>
<td>6.9 (S)</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>15 Sep</td>
<td>1430–1500</td>
<td>2</td>
<td>24.5</td>
<td>1.0</td>
<td>6.7 (N)</td>
<td>0.78</td>
</tr>
<tr>
<td>Dufferin Grove</td>
<td>15 Sep</td>
<td>1555–1610</td>
<td>2</td>
<td>23.8</td>
<td>1.0</td>
<td>6.7 (N)</td>
<td>0.78</td>
</tr>
</tbody>
</table>
Moving averages of budget values were plotted, but point-averaged meteorological data and budget components were used for analysis. Averaging-distance windows increased with activity speed, yielding walking, running, and cycling windows of 6, 25, and 140 m, respectively. Intensities of air temperatures, budget outputs, and radiation levels between street and park were determined using nonaveraged data of the maximum on the urban street (street$_{max}$) minus the minimum within the park (park$_{min}$).

Kenny et al. (2008) provide a method for reliable absorbed radiation $R_{abs}$ estimates for a human on the basis of outdoor horizontal radiation fluxes that has been successfully applied in subsequent studies (Vanos et al. 2012a,b). For estimation of outgoing shortwave radiation, $K_{sw}$ was multiplied by ground albedo $\alpha_{gr}$. Albedo $\alpha_{gr}$ was estimated with respect to the surfaces over which the transect passed. Wide concrete/asphalt surfaces and paths on streets and within parks were given an albedo of 0.12, grass surfaces were estimated as 0.25, and locations at which both surfaces would influence shortwave radiation reflected toward a human were estimated as a midrange value of 0.18.

Wind velocity measurements and directions were obtained from the weather station that was nearest to the corresponding outdoor park. Wind speed at the representative human environment height of 1.5 m (Souch and Souch 1993) was found by using a ratio of the logarithmic wind profile as follows:

$$\frac{v_2}{v_1} = \ln \left( \frac{z_2}{z_1} \right) \div \ln \left( \frac{z_{20}}{z_{10}} \right), \quad (1)$$

where $v_2$ and $v_1$ are the wind speeds $w_w$ and $z_2$ and $z_1$ are the heights $z$ at 10 and 1.5 m, respectively. Also, $z_{20}$ and $z_{10}$ are the roughness lengths of the given areas, estimated as 0.8 m for built-up street areas and 0.4 m when inside parks (Wieringa et al. 2001).

c. COMFA model

To test an application of the COMFA model revision (Vanos et al. 2012b) to practical urban design issues, an existing dataset from Slater (2010) was employed. The COMFA energy budget model requires meteorological inputs ($u_w$, $T_a$, vapor pressure $e$, and radiant temperature $R_{RT}$) and physiological inputs ($M_{act}$ and clothing insulation $I_{cl}$) to produce a human energy budget output in watts per meter squared. It has been extensively tested and revised under various dynamic outdoor conditions for agreement with tested subjects (Brown and Gillespie 1986; Kenny et al. 2009a,b; Vanos et al. 2012a). Most-recent improvements involve more accurate and efficient predictions of human physiological effects and behavior (Vanos et al. 2012b). These improvements are adaptation of $I_{cl}$ with respect to $M_{act}$ and $T_a$, incorporation of individual conditioning level (discussed below), and corrections for wind angle to body movement (Vanos et al. 2012b).

The intrinsic $I_{cl}$ (in clo units, defined below), referring to the whole body, was estimated from ambient $T_a$ using Eq. (2), shown below (Havenith et al. 2011). Bare and clothed body fractions were accounted for as in Tikuisis et al. (2001) and Vanos et al. (2012a,b), as were accurate $I_{cl}$ values for each body segment, obtained from ISO (2007). Equation (2) was originally designed for use with metabolic rates of 175 W m$^{-2}$. To account for clothing adjustments when a user experiences a higher $M_{act}$ (greater endogenous heat load), the reference $I_{cl}$ value from Eq. (2) was shifted according to the change in metabolic rate (Vanos et al. 2012b). This was done by computing on the basis of $M_{act}$ an “equivalent $T_a$” value for use in Eq. (2). This equivalent temperature is higher than the actual $T_a$ and therefore lowers the $I_{cl}$ value with increasing $M_{act}$ at any actual $T_a$. Equation (2) is given by

$$I_{cl} = 1.372 - 0.01866T_a - 0.0004849T_a^2$$
$$- 0.000009333T_a^3,$$                                 \hspace{1cm} (2)

where $T_a$ is in degrees Celsius and $I_{cl}$ is in clo, which is an arbitrary unit ($1 \text{ clo} = 186.6 \text{ s m}^{-1} = 0.1555 \text{ m}^2 \text{ °C}^{-1} \text{ W}^{-1}$).

Average $M_{act}$ was quantified using a detailed energy expenditure estimation method by Strath et al. (2000) and is discussed further in Vanos et al. (2012b) as well as within the current paper. The $M_{act}$ levels for energy budget input are based on maximum volume of oxygen intake levels VO$_{2max}$ for individuals who are unconditioned (lower VO$_{2max}$) and conditioned (higher VO$_{2max}$). The overall activity VO$_2$ (VO$_{2max}$), and hence $M_{act}$, can be determined through knowledge of the level at which a person is working (we assume a level that yields cardiorespiratory benefits from exercise; Whaley et al. 2006), their VO$_{2max}$, and their energy expenditure at rest (which is 1 metabolic equivalent, being 58.15 W m$^{-2}$). The metabolic modeling was based on an estimate of the average age of a person who would be using the park for the chosen activities; hence an age of 25 was chosen.

Three activities (walking, running, and cycling) at three conditioning levels (unconditioned, conditioned, and elite) were employed in the current study. Values for $M_{act}$ and corresponding activity speeds $u_a$ are listed in Table 3. The main controllers of $M_{act}$ are gender and
TABLE 3. List of activities and corresponding $M_{act}$ and $v_a$ that were used for energy budget prediction. Values for males are listed, with values for equivalently aged females in parentheses.

<table>
<thead>
<tr>
<th>Activity</th>
<th>$M_{act}$ (W m$^{-2}$)</th>
<th>$v_a$ (m s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unconditioned</td>
<td>320 (262)</td>
<td>1.5 (1.4)</td>
</tr>
<tr>
<td>Conditioned</td>
<td>436 (326)</td>
<td>2.1 (1.7)</td>
</tr>
<tr>
<td>Elite</td>
<td>756 (582)</td>
<td>3.5 (3.0)</td>
</tr>
<tr>
<td>Cycling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unconditioned</td>
<td>320 (262)</td>
<td>4.5 (4.0)</td>
</tr>
<tr>
<td>Conditioned</td>
<td>436 (326)</td>
<td>5.1 (4.5)</td>
</tr>
<tr>
<td>Brisk walking</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avg</td>
<td>221 (221)</td>
<td>1.3 (1.3)</td>
</tr>
</tbody>
</table>

For scenarios 2 and 3, 2° and 3°C were added, respectively, to the scenario-1 $T_a$ transect pattern.

The RH and $v_a$ for the latter two scenarios were assumed to stay constant with average 5 July values, which were 63% and 1.2 m s$^{-1}$, respectively. It was assumed that enhanced evaporation would increase both moisture content and temperature of the air, and therefore the RH remained unchanged from values in July 2010. We altered only $T_a$ for the future climate scenarios because other accompanying changes are more uncertain and this approach isolates the impact of increased temperature by holding other variables equal.

d. Heat stress emergency calls during heat wave

The final objective of the current study involved evaluating the application of the COMFA energy budget model as a tool for prediction of heat stress emergency response. Therefore, we employ the use of meteorological data from the 5–7 July 2010 Toronto heat wave, as well as heat-related morbidity. Morbidity was quantified using daily dispatch-call data obtained from Toronto Emergency Medical Services (J. Kilch 2011, personal communication) for the dates of 28 June–15 July, which allowed heat stress analysis before, during, and after the heat wave. Emergency medical services (EMS) ambulance calls are categorized as a complaint of symptoms of heat, such as “light-headed” or “poor breathing,” rather than as environmental heat stress (J. Kilch 2011, personal communication). Therefore, analysis was completed using the following heat-related illness categories related to heat stress: breathing problems, headache, heat/cold exposure, stroke/heat stroke (cerebrovascular accident), unconscious/faint, cardiac/respiratory arrest, and chest pain (Luber and McGeehin 2008).

Energy budget modeling was completed for the duration of the heat wave, as well on surrounding days. This was accomplished using an $M_{act}$ of 221 W m$^{-2}$ for sedentary–slow walking and clothing insulations that are based on $T_a$, as described in section 2c. Using the Davis weather station, $T_a$, RH, and $v_a$ were collected. These data, along with theoretically estimated radiation data from 1100 to 1800 eastern standard time, were averaged into 5-min aggregates and then into a single daytime energy budget average. The empirical temperature–humidity index [“humidex” (HX)] was also assessed for heat stress prediction [HX (°C) = $T_a + 5/9(ε - 10)$, where $ε$ is in hectopascals]. Daytime HX and energy budget, as well as daily (24 h) maximum, minimum, and average air temperatures ($T_{max}$, $T_{min}$, and $T_{avg}$), were tested as predictive tools for heat-related EMS calls during the heat wave using linear regression analysis.
Then, the prediction of total EMS calls was calculated using a multiple linear equation [Eq. (3), shown below], developed specifically for the city of Toronto by Dolney and Sheridan (2006) on the basis of total EMS calls for a 4-yr period (1999–2002). Therefore, this study implements this equation during the heat wave to test the agreement and validity of this equation from the literature, using the total EMS calls, rather than only heat-related calls, as utilized in the rest of the current study.

\[
\text{Calls} = 444.9 - 11 \times \text{Day} + 3.1(\text{AT}_{1700}),
\]

where Day = 0 (weekday) or 1 (weekend) and AT$_{1700}$ is the apparent temperature (temperature–humidity index) at 1700 LT (°C) according to Steadman (1979). Because this algorithm utilizes the apparent temperature index, we use this index as opposed to HX for use in this equation only. The HX was used throughout the remainder of the current study, rather than the AT used in the United States, because this is Canada’s current heat stress warning index and is thus more meaningful in the current study than AT would be.

3. Analysis and results

a. Application of COMFA energy budget model in urban-park transects

All averages are reported as means ± standard deviation (SD). Bivariate correlation analysis was reported as a Pearson correlation coefficient r assessing the linear dependence of one variable to another, using a level of statistical significance p of 0.05, unless otherwise stated. Energy budget analyses under various physiological and meteorological conditions were completed graphically and statistically for each urban park as listed below (these were chosen randomly to display all possible combinations of varying microclimates, exercise, clothing, gender, and vegetative cover on thermal energy budgets within separate parks):

1) Trinity Bellwoods Park—4 and 15 September 2009, with an $M_{\text{act}}$ of brisk walking, conditioned running, and conditioned cycling,
2) Withrow Park—6–9 and 20 September 2009, with an $M_{\text{act}}$ of conditioned running,
3) Dufferin Grove Park—15 September 2009, with an $M_{\text{act}}$ of unconditioned, conditioned, and elite running males and females, and
4) Dovercourt Park—4 and 15 September 2009 and 5–7 July 2010, with climate change scenarios and an $M_{\text{act}}$ of conditioned running.

The budget results found in the current study fell within the ranges of “neutral” (from −20 to +150 W m$^{-2}$), “warm” (from +151 to +200 W m$^{-2}$), and “hot” (> +201 W m$^{-2}$). The listed ranges are based on an “activity skewing effect,” in which there is a widening of the comfort zone toward the warm end during exercise (Kenny et al. 2009b), as compared with sedentary ranges (Brown and Gillespie 1986). At a high $M_{\text{act}}$, humans will be more accepting of slight thermal discomfort (Vanos et al. 2012b) and motivational effects during exercise (Roberts 2007; Brotherhood 2008). Metabolically active humans have been found to report lower TS than that predicted by an energy budget model, even when in heat stress; thus, it is more important to follow guidelines predicted by the model than those reported by a human to stay in a “thermally safe” budget range. Descriptive results of human energy budgets for each study site, as well as correlation analysis and select intensities, are listed in Tables 4 and 5, respectively.

1) URBAN-PARK TRANSECTS

Figure 3 displays the spatial budget and $R_{\text{abs}}$ of a human for three activities (walking, running, and cycling) within Trinity Park. Open areas lacking tree cover—such as that indicated by the “B” boxed portions—resulted in increased $R_{\text{abs}}$ when compared with tree-covered portions within the park (average = +14 W m$^{-2}$; maximum = +34 W m$^{-2}$), directly causing the energy budget to increase ($r^2 = 0.947$). The $R_{\text{abs}}$ intensity (streetmax − park$_{\text{min}}$) was 53 W m$^{-2}$. Increased $u_a$ aided strong increases in the convective heat loss C, giving $C = 72 \pm 3$, 90 ± 4, and 168 ± 6 W m$^{-2}$ for walking, running, and cycling, respectively. Within-park wind speeds averaged 0.70 m s$^{-1}$ as a consequence of fair weather and high surface roughness; hence, the $u_a$ of cycling (4.5 m s$^{-1}$)
gave a greater reduction in energy budget than when running at 2.1 m s\(^{-1}\). Thus, cycling budgets fell below that of running even though \(M_{\text{act}}\) was equal.

Figure 4 demonstrates the variations in \(T_a\) with \(R_{\text{abs}}\) and energy budget variations along a transect in Withrow Park. A total of 16 transects on days with easterly winds (6–9 and 20 September) were averaged for the three variables. The path chosen through Withrow Park had very little tree cover, shown by slight \(R_{\text{abs}}\) variations and reductions and hence decreased reductions in budget output. The budget follows a pattern strongly related to the plotted \(R_{\text{abs}}\) (\(r^2 = 0.784\)) because of relatively constant \(M_{\text{act}}\), convection, evaporation, and emitted longwave radiation. The PCI effect of \(T_a\) (\(\text{street}_{\text{max}} - \text{park}_{\text{min}}\)) (Spronken-Smith and Oke 1998; Slater 2010) was 3.9°C and is dramatically displayed in this figure. This was found to have a weak relationship with budget (\(r = 0.504\), with \(p < 0.01\)), as compared with budget being strongly related to \(K_{\text{in}}\) (\(r = 0.951\), with \(p < 0.01\)). Hence, the human energy budget is controlled more so by receiving and absorbing radiative fluxes, which overrides the effect of \(T_a\).

Figure 5 displays the effect of gender and individual conditioning levels on energy budgets in Dufferin Grove Park. Weather conditions present on 15 September produced neutral budgets in and outside the park (65 and 81 W m\(^{-2}\), respectively) for unconditioned individuals exercising at levels that would elicit a cardiovascular improvement. Elite athletes enter or become close to the warm budget zone both in and outside the park (male = 207 and 227 W m\(^{-2}\); female = 140 and 160 W m\(^{-2}\), respectively), however, even in moderate weather conditions. The overall energy budget correlations with \(K_{\text{in}}\) and \(T_a\) were found to be statistically significant, giving \(r = 0.966\) and 0.574, respectively. Street-to-park budget intensity increased with \(M_{\text{act}}\), with elite athletes experiencing a 69 W m\(^{-2}\) difference, as compared with unconditioned athletes experiencing 61 W m\(^{-2}\). The greatest difference in street-to-park budget decrease was found in elite athletes (highest \(M_{\text{act}}\)), giving \(-20\) W m\(^{-2}\) for “whole park,” \(-32\) W m\(^{-2}\) for treed sections, and a minimal \(-3\) W m\(^{-2}\) in open-park areas. The average surface wind speed of 0.6 m s\(^{-1}\).

![Figure 3](image-url)  
**FIG. 3.** For Trinity Bellwoods Park, the modeled energy budget and \(R_{\text{abs}}\) (W m\(^{-2}\)) for brisk walking, conditioned running, and conditioned cycling on 4 Sep (south wind) and 15 Sep (north wind) 2009. Each panel consists of 6-, 25-, and 70-m moving averages for the three respective activities. Boxes labeled A and B indicate examples of visible tree cover and uncovered path areas within the park, respectively.
from the north extended urban air temperatures southward into the park for approximately 65 m and extended park cool air temperatures approximately 50–80 m beyond the park.

2) Heat-wave and climate scenarios

Figure 6 displays original data from Dovercourt Park from three sources: 1) September 2009 data; 2) 5 July 2010 heat-wave weather data; and 3) two climate change scenarios applied to the 2010 heat wave. A decrease was found in the budget values within the park relative to those on the streets for all scenarios, with similar mean budget difference and maximum budget intensity found in the latter three scenarios (Label “Orig” = 12 and 40 W m$^{-2}$, respectively, and 12 and 41 W m$^{-2}$ for all three scenarios). Although these difference values are equal for the heat-wave and climate change scenarios, the absolute budget averages are significantly different when paired together and compared with the original 2009 data (See Table 4).

b. Emergency-response prediction using the COMFA energy budget model during a heat wave

During the July 2010 heat wave in Toronto, heat-related dispatch calls within the city of Toronto increased by an average of 29% from the prior 3-day average. During the heat wave, mean 24-h $T_{\text{max}}$ and $T_{\text{min}}$ were 32.4°C and 24.1°C, which were 7.1°C and 8.1°C higher than the surrounding six days, respectively. The commonly used humidex in Canada was also assessed with an average daytime HX during the heat wave of 39.5°C (+10.1°C greater than surrounding six days). Even with low metabolic rate modeling ($M_{\text{act}} = 221$ W m$^{-2}$), the budgets were consistently in a “heat stress zone” (>121 W m$^{-2}$) (Brown and Gillespie 1986; Harlan et al. 2006), and commonly fell above warm and hot levels of TS.

Figure 7 displays temporal changes of EMS calls, $T_{\text{max}}$, $T_{\text{avg}}$, and energy budget. Dispatch calls follow a close pattern with both budget and $T_{\text{max}}$, showing significant linear dependence ($r^2 = 0.860$ and 0.603, respectively). Weak dependence of EMS calls was found with daily $T_{\text{min}}$ ($r^2 = 0.116$). Peak values for all curves occurred on 5 July when discomfort was at its greatest. The average HX was also found to be a significant predictor of EMS calls ($r^2$ of 0.86); the HX lacks the vital energy budget component of spatial variations in radiation, however, and hence $R_{\text{abs}}$. The current study did not apply a spatial comparison with EMS calls and energy budget modeling and hence did not exhibit the benefit of this. Such spatial analysis is possible given accurate microclimate measurements using a denser network of simple weather stations throughout a city, further addressed in the discussion section.

4. Discussion

a. Urban-park transects

Overall results from testing the COMA energy budget model displayed the ability to adequately predict the
moderating effect of microclimate variations within urban parks on outdoor TC. In all four parks under the tested climatic and metabolic conditions, decreases in $T_a$ occurred, yet this did not cause the human energy budget to decrease to the same extent as a reduced incoming solar radiation. Solar radiation had the largest effect on energy budgets in all cases; therefore, blocking this radiation is the most effective way to lower high human heat budgets. These results show that the model performs in a realistic fashion and therefore can aid users such as researchers, planners, and urban designers in creating usable and effective urban green space by highlighting the sensitive variables when modeling human energy budgets.

The relatively lower heat capacities and evaporative cooling of existing moist vegetation and soil in green space—in comparison with surrounding concrete and asphalt—aided in the decrease of overall sensible heating and $T_a$ in the park yet was overcome by incoming shortwave and longwave radiation when a human was not modeled beneath a tree canopy. This was revealed by the differences found when beneath a canopy versus in open space or on the street, as well as strong budget correlations with $K_{in}$ and moderate to weak correlations with $T_a$. Hence, a park-induced decrease in $T_a$ is not enough to aid in heat stress reduction and to keep recreational athletes out of dangerous budget zones (as compared with low $M_{act}$ and/or sedentary individuals).

These results clearly demonstrate that addition of deciduous trees with minimal summertime transmittance will reduce the radiant heat loads on humans (Koppe and Jendritzky 2005). According to Matzarakis and Endler (2010), under shady conditions (low-transmitting trees), the mean radiant temperature $T_{mrt}$ is assumed to be equal to $T_a$ yet is much greater in open areas, as supported by our results. Conveying more information of $T_{mrt}$ and/or other TC measures gives a more realistic measure for human health impacts of future climate scenarios (Thorsson et al. 2011).

Differing levels of conditioning (fitness) and gender displayed in Fig. 5 demonstrate how diverse the energy budget can be as a result of an extra endogenous metabolic heat load. When a person has the fitness ability and motivation to reach a higher $M_{act}$, their risk of heat
stress is much greater (Vanos et al. 2012b). Heat casualties in athletes have been reported in ambient temperatures of less than 20°C (Hughson et al. 1980); hence, awareness of heat injury possibilities is essential. Metabolic levels, commonly greater by a factor of 10–20 during physical exertion, are a greater contributor than $T_a$ to heat stress.

Trinity Bellwoods tested all three activities, where the effective body areas $A_{eff}$ modeled were 0.70 for cycling and 0.78 for running/walking (Nielsen et al. 1988; Nielsen 1990; Campbell and Norman 1998). This accounts for the differences in $R_{abs}$ displayed between upright and sitting activities. The comparisons of walking, running, and biking in Trinity Bellwoods Park and of running at various speeds based on conditioning in Dufferin Grove Park display the impacts of $v_a$ on budget balance. With the higher $v_a$, the energy budget is significantly lowered, even with a constant $M_{act}$, because of...
increased convective and evaporative heat losses. Although a greater wind results in convective cooling within the park, the greater wind also results in more turbulent mixing and the diminishment of park-cooling extension into the surrounding streets. Cooler air from the park canopies extends outside the park in the direction of prevailing winds, with greater effect and extent on calm days, yet busy roadways can mix and diminish the cool air (Slater 2010). Lower average \( v_w \) for test days within Dufferin Grove and Withrow Parks gave cool air extensions of \( \sim 50 \) and \( 20 \) m, yet warm air from the street was also brought into each park \( \sim 80 \) and \( 20 \) m, respectively, by the prevailing wind.

b. Heat-wave and future climate scenarios

Under extreme heat, the main interest is the length of time in which a person is under heat stress and their ability to achieve heat balance given the environmental constraints. The low cooling effect of Dovercourt Park during the extreme-heat scenarios is problematic considering that this is when people are most susceptible to heat illness. This susceptibility, however, is dependent on the combination of sensitivity to TS, along with the intensity, length, and seasonal time (Koppe and Jendritzky 2005). Although preservation of “open” green space has been cited as a great benefit for cooling cities by Harlan et al. (2006) and Luber and McGeehin (2008), abundant tall greenery and trees is a much greater microclimatic controlling factor during the day and is essential during heat waves (Harlan et al. 2006). This agrees with the current study, finding that budget cooling of the body corresponds more with vegetatively dense and covered areas, largely because of the presence of trees for PCI development (Spronken-Smith and Oke 1998).

Figure 6 shows that the model is able to identify important differences that are representative of reality now and forecasts of the future. Although these results display humans entering into dangerous energy budget zones within scenarios 1–3, the heat stress remains lower within urban parks than in the streets. According to Harlan et al. (2006), “extreme caution” and “danger” levels of heat stress occur at budgets \( >121 \text{ W m}^{-2} \) and \( >200 \text{ W m}^{-2} \), respectively. The current modeling was completed on humans running at moderate levels (\( M_{\text{act}} = 436 \text{ W m}^{-2} \)) who will report a lower TS than that actually predicted because of the activity-skewing effect. This effect is displayed when an exercising subject responds as neutral with a budget level up to \( 150 \text{ W m}^{-2} \). Yet a sedentary individual would be warm at this level (Kenny et al. 2009a). This offsetting of thermal stress with psychological adjustments (broader sensation/comfort ranges during exercise; Havenith et al. 2002; Kenny et al. 2009b) and acceptances can draw people into zones of thermal heat stress (Vanos et al. 2012a). Hence, the activity level must be considered when assessing a person’s actual TC versus their subjective responses. Understanding the underlying microclimatic mechanisms surrounding energy budget output values allows researchers to meaningfully quantify the human impact of urban design decisions during heat waves, which may become more frequent with climate change.

c. EMS prediction during heat wave

Energy budget assessments are shown to be a strong predictive tool for emergency response to heat morbidity. Although elevated \( T_{\text{min}} \) has also been associated with high mortality (Greene and Kalkstein 1996; Sheridan and Kalkstein 2004), the current study did not find a predictive relationship with EMS calls and \( T_{\text{min}} \) with temperatures that fell to an average of 24.1°C each night. The heightened number of EMS calls continued after the heat subsided (9–11 July). This lag effect can be due to a greater ability to withstand excessive heat in the short term (Luber and McGeehin 2008) from delayed physiological response and/or the perception of heat threat declining with time.

In addition, the accuracy of the predictive equation [Eq. (3)] shows that investing in accurate and advanced heat health warning systems (HHWS) for Toronto (Sheridan and Kalkstein 2004) is an essential step for emergency preparedness and protection of heat-vulnerable populations and areas. To do so, however, further important variables must be considered, because heat stress situations are affected by time and space from such factors as local microclimates and population dynamics (deVries et al. 2003; Harlan et al. 2006). There is need in the literature for such a study, with further research applying accurate energy budget models. Accounting for both energy budget and population density on an hourly time scale gives a finer temporal assessment. Although the HX was also a significant predictor of EMS calls, it lacks the vital energy budget component of variations in radiation and wind speed, which vary the greatest spatially. Given the sensitivity of the energy budget output to variations in radiation, investing in a higher spatial density of urban weather stations will improve spatial modeling of heat stress-prone zones, hence guiding the deployment of EMS and coping resources. From this, urban planners and designers can be aware of areas of high heat stress, and the most oppressive hours of the day within that area, thereby knowing the most vital areas in which to implement corrective bioclimatic design.

This can be demonstrated with GIS mapping, as in Dolney and Sheridan (2006), to visually recognize the location and frequency of heat stress situations and other potential confounders of heat stress, such as...
socioeconomics. Hence, we can identify areas in need of improved or corrective bioclimatic design, the most important one being incorporating trees to induce the effects of PCIs, as displayed throughout this study. Furthermore, populations within predefined at-risk areas can benefit from the removal of structural constraints for improving environmental conditions, added green space, and additional coping resources—such as shade, water, and air conditioning (Harlan et al. 2006). Positioning an emergency vehicle in areas found to experience higher heat stress during heat waves and ensuring proper staffing for a number of vehicles are both strong applications for lowering serious heat-illness cases (Dolney and Sheridan 2006).

The International Panel on Climate Change (Conflalonieri et al. 2007) confidently classifies heat waves as extreme events that even high-income countries are not well prepared to cope with, with adaptive capacity improvements needed everywhere. Public-health officials and researchers cannot assume that all individuals will be adapted to heat during the summer months—in particular, in conditions of heat plus exercise—given increasingly sedentary and indoor lifestyles. Further quantification of seasonal and long-term adaptation is needed, as done by Matzarakis et al. (2011) for a 30-yr period in Vienna, Austria. They suggest implementation of HHWS as a tool to reduce the impact of heat waves.

In a highly populated and growing midlatitude city such as Toronto, the implementation of a location-specific HHWS is vital now and in the future. The 30-yr trends of the extreme-heat air masses of moist tropical and dry tropical (MT and DT) in Toronto show a weak increase on the basis of synoptic weather-type classification (Kalkstein et al. 1996; Sheridan 2002). Heat waves are linked to specific atmospheric conditions (Meehl and Tebaldì 2004), with MT and DT stagnant and oppressive hot air masses associated with 9.8% and 9.4% increase in daily deaths in Toronto, respectively (Sheridan and Kalkstein 2004). This is a broader implication of heat-wave and UHI problems; it does, however, highlight the need for decision makers to focus on both climate change and UHI mitigation (through bioclimatic design) to lessen the likelihood of such air masses reaching “offensive” levels (i.e., resulting in heat death; Sheridan and Kalkstein 2004).

5. Conclusions

The current study demonstrated finescale modeling of human thermal energy budgets while under various metabolic activity rates, fitness levels, clothing, and vegetative covers on heterogeneous street–park–street transects. Through using an existing dataset from Slater (2010) for quantitative analysis, the capabilities of the COMFA model, as well as numerous application methods, were displayed. On the basis of this analysis, the following findings were presented: 1) there is a lack of energy budget decrease without tree cover, 2) there is a small extension of cool park air into nearby streets and warm air into parks, 3) activity level, gender, and conditioning are important influences on heat stress, and 4) there was successful prediction of EMS calls for heat stress using the COMFA energy budget model, showing independent correlation with empirical data.

Significant budget decreases were not found with a lack of tree cover. The presence and high density of tall trees (>5 m) that have the ability to block solar radiation is of greater importance than just vegetation density alone, because this may only refer to low-lying vegetation. To have a strong “sensible” effect on TC and TS, with extension into surrounding neighborhoods/streets, parks must be larger, but, more important, they must contain adequate amounts of canopy cover from trees to block out penetrating solar radiation and provide evaporative cooling. In doing so, human energy budgets can be decreased and individuals can be kept within the “neutral” safe zone so that heat stress and morbidity do not occur.

Implementing the use of energy budget models using a small number of readily available variables can allow for easy determination of TC, cooling potential, and UHI mitigation of designs by urban designers and landscape architects (Slater 2010). This study has discussed the threats of amplified urban growth and air temperatures causing UHI effects related to poor human health and morbidity. This becomes increasingly important with future predictions of climate change causing intensified, more frequent, and lengthier heat waves. Development and ongoing sprawl call for further consideration of spatial and temporal variations in population density and heat stress levels.

Future TC studies for climate adaptation should incorporate the change in temperature distribution separately from variability (Gosling et al. 2009) for quantifying spatially diverse adaptive processes (Lin 2009; Yao et al. 2009) and comparative analysis of varied geographies (Golden et al. 2008). Such studies can be coupled to sport-specific heat stress to identify areas and individuals most at risk of heat stress, along with remote sensing or GIS methods for effective public-health response (Luber and McGeehin 2008). In addition, the relatively small size of the studied parks in the current study warrants further research to assess the geographical extent of budget cooling potentials with respect to size and tree cover. Additional applications of this model include quantifying crucial weather parameters for heat events, estimating...
and mapping green space present and/or needed in built-up areas, analyzing health trends of various urban regions, and linking TS with ground-level air pollution. There is a breadth of knowledge and information required to address current and future TC situations, yet preventative measures are available for creation of comfortable places for people to use.

Acknowledgments. Funding for this project was generously provided by the Natural Sciences and Engineering Research Council of Canada (NSERC). The authors thank Toronto Emergency Medical Services for providing emergency-dispatch data. The use of the data was allowed through a confidentiality agreement that was reached between Toronto Emergency Medical Services and the current study’s lead author.

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