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Assessment of measured and perceived microclimates within a tropical urban forest

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ABSTRACT

Urban greenery is a favoured approach applied towards reducing urban warmth and climate discomfort, but ascertaining its measured and perceived effectiveness in tropical climates is relatively understudied. To this end, we investigated microclimate differences within an urban park (the Singapore Botanic Gardens) to assess if variations in plot-scale land cover affect both objective (measured) and subjective (surveyed) microclimate data. Over two monsoonal seasons, we obtained data from four distinct sites—a tropical rainforest stand, a palm tree valley, a water-body feature, and the park visitors' centre. Measured climate data (e.g. air temperature, vapour pressure, wind velocity and globe temperatures) were used to derive mean radiant temperature T_{mrt} and three thermal comfort indices (e.g. temperature-humidity index *THI*, physiological equivalent temperature *PET*, and wet-bulb globe temperature *WBGT*). Concurrent to these measurements, we also surveyed park users ($n = 1573$) for perceived microclimate sensations and preferences in thermal, humidity, wind and sun exposure, as well as their overall assessment of climate comfort/discomfort. The results indicate significant differences in both measured and perceived microclimates over different sites and seasons, with (i) selected heat stress thresholds based on thermal comfort indices exceeded at several sites, and (ii) visitors perceived generally hot, humid and low-wind conditions throughout. Variations in respondent acclimatisation to tropical climates are observed between correlations of *WBGT* and some sensation votes, with apparently stronger correlations with more acclimated respondents. While humidity was voted as the most uncomfortable climate variable across all sites, a large majority of respondents felt comfortable climate conditions throughout. Present results confirm that vegetation canopy characteristics affecting wind and sun exposure appear to be important factors in outdoor thermal comfort. Lastly, we suggest that future tropical outdoor thermal comfort studies consider the critical aspects of site humidity and wind to discern comfort/discomfort levels.

Introduction

Land use and land cover change arising from the urbanisation process include the simultaneous reduction of vegetation cover and introduction of artificial surfaces. These processes radically alter the aerodynamic, hydrological and radiative aspects of the physical environment (e.g. Oke, 1988). Consequently, properties of near-surface climates are altered within urban areas relative to their non-urban surroundings; these changes include the urban heat island (UHI) effect, which is ubiquitous to every city (Arnfield, 2003). The development and morphology of the UHI directly affects outdoor thermal and climatic comfort, and also indirectly, and mostly unfavourably, affects human health and urban energy use over numerous spatio-temporal scales (Mills et al., 2010; Georgescu et al., 2015).

Given these multi-layered implications, several approaches aimed at reducing the potentially detrimental impacts of increased urban warmth have been investigated in numerous contexts. The morphology of buildings, vegetation density (i.e. the combined horizontal and vertical extent of vegetation canopies and surface cover), and location of water bodies in cities constitute important design elements in improving urban microclimate and subsequent outdoor thermal comfort in urban spaces (Emmanuel, 2003; Mayer et al., 2009). One frequently utilised management approach, especially at micro- and local-spatial scales (i.e. 10^0–10^4 m^2) is to

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increase urban vegetation density (Zhang et al., 2013). This can be applied through implementing rooftop gardens, or managing urban parks, forests and/or vegetated streetscapes (Chen and Ng, 2012). Overall increases in urban vegetation density lead to unequivocal reductions of intra-urban temperatures through (i) additional surface shading from insolation through plant canopies, and (ii) from increased surface and vegetation evapotranspiration, which reduces the Bowen ratio between sensible and latent heat fluxes (Spronken-Smith et al., 2000). The average cooling effect from increased urban vegetation is potentially substantial; Bowler et al. (2010) reviewed that the mean reduction in air temperatures from urban parks is ∼1 °C across a variety of climates.

Apart from air and surface temperatures in cities, other meteorological variables are critical in determining outdoor thermal comfort, especially that of site microclimates. In subtropical Hong Kong, Ng and Cheng (2012) note that increased wind velocities are important in mitigating urban heat stress. While greater wind speeds do not extend upper thresholds of comfortable ambient temperatures, it does increase upper boundaries of acceptable humidity levels (Ahmed, 2003). Variations in received insolation/incoming solar radiation at the surface also significantly influence thermal sensation, especially during summer (Cheng et al., 2012). Additionally, exposure to temperatures of urban surfaces adjacent to the individual is also a key factor in their perceived thermal sensation, with higher surface temperatures and corresponding larger radiative fluxes correlating with increasing thermal discomfort (Givoni et al., 2003).

While much work on intra-urban variations of air and surface temperatures has been done with respect to the UHI, investigations of outdoor thermal comfort – particularly in cities located within tropical climates – is a relatively new area of inquiry (Roth, 2007; Emmanuel, 2012). Consequently, knowledge of tropical outdoor thermal comfort lags behind that in the cooler, less humid and more seasonal temperate cities (Johansson and Emmanuel, 2006). Furthermore, a majority of these studies focus mainly on the measured thermal comfort and often neglect that subjective opinions and preferential responses of urban residents do not always correspond with derived thermal comfort measurements (e.g. Nikolopoulou et al., 2001; Hwang and Lin, 2007; Lin, 2009; Makaremi et al., 2012). While ambient microclimate conditions greatly affect an individual's thermal sensation, other psychological factors – including prior personal experience, time of exposure and acclimatisation – are also important in explaining the variance between measured and perceived thermal comfort (e.g. Nikolopoulou and Steemers, 2003).

Existing research within the tropical city-state of Singapore (1.3°N, 103.8°E) indicate that land cover variations of urban vs. non-urban surfaces significantly affect both microclimate (e.g. Roth and Chow, 2012), and subsequent thermal comfort conditions derived from meteorological observations of temperatures, wind, humidity and solar radiation (e.g. de Dear, 1990; Wong and Jusuf, 2010; Tan et al., 2013a,b; Yang et al., 2013). There is, however, limited investigation into how these land surface cover differences affect subjective thermal perceptions of individuals. Yang and Wong (2013) did combine objective data and subjective surveys ($n = 770$) of microclimate conditions between six urban parks in Singapore and found that perceptions of wind speed were critical in determining the thermal comfort of visitors; however, this study did not investigate land cover variations – such as vegetation type and density – within these parks, and thus assumed homogeneity of micro-scale thermal comfort therein. Further, the measured data were not investigated for seasonal variations in synoptic climate, which given strong differences between temperatures and precipitation in monsoonal seasons, may potentially influence thermal comfort *a priori*.

Consideration of these factors is therefore important in the context of utilising the effective design and management of urban green spaces as an approach towards ameliorating high urban temperatures and thermal discomfort. This is especially so within Singapore, where local authorities actively utilise urban forestry through gazetted nature reserves of secondary dipterocarp rainforest, widespread roadside greenery and an integrated island-wide park connector network, to cultivate an image of a "city in a garden" (e.g. Tan et al., 2013a,b). Despite its high population density and limited land area, approximately 50% of Singapore's total land area is covered by a combination of managed vegetation and young secondary forest (e.g. Yee et al., 2011).

In this study, we thus examine the outdoor thermal comfort conditions over different land covers within a tropical urban park space. These will be achieved through a combination of objective and subjective methods; namely, through the use of quantitative data obtained from sensor-loggers that record ambient microclimate conditions, and from structured questionnaire survey responses from park visitors that document their perceptions of current and ideal microclimate conditions. We attempt to answer the following research questions: For a large urban park sited within a tropical urban environment, (i) what is the impact of land cover variations on micro-scale outdoor thermal comfort, and (ii) what is the difference between measured and experienced outdoor thermal comfort, and how can it be explained? The answers should provide an understanding of the influence of land cover on both objective and subjective thermal comfort, and are critical for holistic urban planning of managed urban forestry that reduces UHI intensities across various spatial scales. Lastly, inferences from these results would also be important for urban park managers aiming for thermally comfortable conditions for park users' satisfaction (Nasir et al., 2012).

Methodology

Study site

The study was conducted in the Singapore Botanic Gardens (SBG), a 74-ha urban park located close to the centre of the main Singapore island, and which is adjacent to the city's commercial and financial core at the island's southern tip (Fig. 1). The SBG was founded in 1859, and it has been a key focus of biodiversity conservation, education, research and recreation within Singapore. The SBG is an immensely popular attraction with about 4.4 million visitors per year (Feng, 2013), and its importance towards Singapore's local identity is underlined by UNESCO inscribing it as a World Heritage Site in 2015.

We selected four zones within the SBG to examine microclimatic conditions associated with distinct land covers in urban greenery (Table 1 and Fig. 2). The first was a zone of high density vegetation located at a small, 6-ha stand of primary coastal dipterocarp rainforest (RF). The second is a zone of lower density urban forest located on a gently sloping valley ("Palm Valley"—PV) with tropical carpet grass (*Axonopus compressus*) and several palm tree species such as *Washingtonia robusta* and *Pritchardia pacifica*. The third is a cluster of low-rise buildings (mean height ∼8 m) surrounding a concrete-surfaced courtyard located at one of the major entry points of the park, the SBG Visitor's Centre (VC). The last zone is the Eco-Lake (EL), a small, titular artificial water body feature (∼3.5-ha) that is the centrepiece of a shrub and herb garden located along the SBG's northern section.

While there are clear land cover variations between the VC (predominantly "urban") and EL (predominantly "water") sites, explicit distinctions in vegetation density need to be made between the PV and RF sites through estimating its surface greenery. The

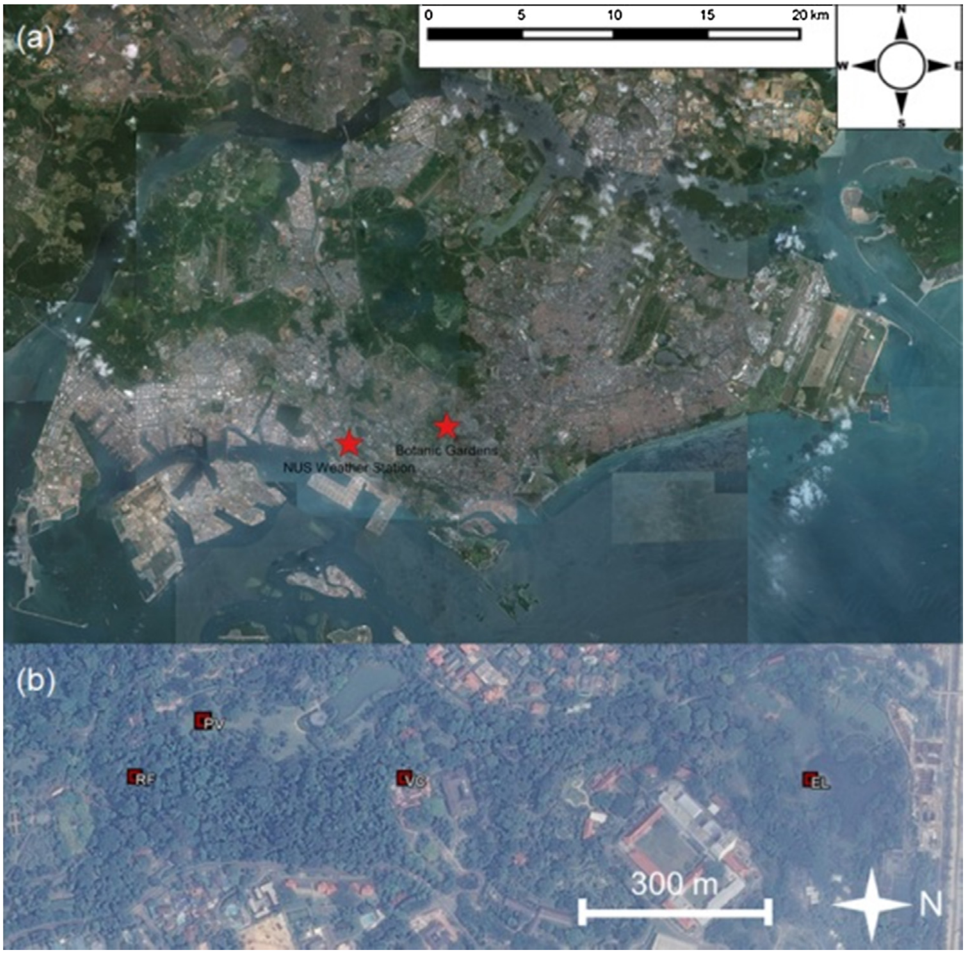

Fig. 1. (a) Location of the study site (Singapore Botanic Gardens) and reference NUS Geography weather station within the main island of Singapore; both locations are marked with red stars, and (b) location of the four study sites within the Botanic Gardens. RF—Rainforest, VC—Visitors' Centre, EL—Eco-Lake, and PV—Palm Valley [*Source:* Google Earth^{TM}]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 2. The four sites selected for microclimate observations; clockwise from top left: RF—Rainforest, VC—Visitors' Centre, EL—Eco-Lake, and PV—Palm Valley. The location of the red "x" and the insets indicate the precise location of each sensor tripod within each site [*Source:* Authors' own]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Selected sites within SBG and their respective land cover characteristics.

Site/classification	Site characteristics
Rainforest (RF)/high density vegetation	Primary, multi-layered lowland evergreen dipterocarp rainforest with >314 species including emergents (e.g. *Dyera costulata*), Lianas and Tree Ferns. A boardwalk trail is installed within the understorey layer
Palm Valley (PV)/low density urban forest	Valley lined with palms of various sub-families (Arecoideae, Coryphoideae, Calamoideae, Ceroxyloideae, Phytelephantoideae and Nypoideae) with lawn base of tropical carpet grass *Axonopus compressus*
Visitors' Centre (VC)/"Urban" built-up area	Small 1-ha concrete courtyard lined with fan palms and ringed by low-rise (~8 m) buildings, a small fountain pond feature, and a single-lane asphalt road
Eco-Lake (EL)/water feature	A small 3.5-ha lake sited within a garden with bamboo, fruit trees and common herbs/spices with small pavilions/gazebos scattered around the lake

percentage of different vegetation cover between both sites was done through a combination of methods. First, we assessed surface cover around a circular area of 100 m radius at both sites via the i-Tree Canopy tool (Nowak et al., 2008). The distance of 100 m was selected as it is appropriate for micro-scale climate observations (Oke, 2006). This tool employs a simple random sampling of points to produce an estimate of land cover types using Google Map^{TM} images. We augmented this analysis through ground-truthing visits at PV and RF to assess the analysis accuracy, with a total of 600 survey points within a100 m radius of both PV and RF sites. This amount is within the recommended range (500–1000 points) suggested by the tool's developers to increase the estimate's precision.

We also measured on-site (i) mean vegetation height, (ii) the typical species distribution found within the buffer area, and (iii) mean crown thickness and diameter. Subsequently, PV and RF were classified using the main surface cover present in both sites; these were grouped into six different categories: (i) Concrete or other impervious surfaces, (ii) Water features, (iii) Grasses, (iv) Shrubs and Bushes (e.g. Plants of less than 5 m in height, shrubs, ferns and other herbaceous plants), (v) Single-layer (e.g. tree and grass layers), and (vi) Multi-layer (e.g. trees, shrubs, and grass layers) plant communities (Table 2).

Our land cover analysis arising from the i-Tree tool confirms distinct differences in vegetation density between RF and PV, with the former site possessing a higher density – ~61% of total plot area – of multi-layer plant communities typical of a closed forest canopy, whereas PV has a larger proportion of single-layer plants, grass and shrubs – ~48% of total plot area – indicative of more open vegetation cover. Similarly, on-site vegetation measurements show that RF has a higher mean vegetation height, higher mean crown thickness and width relative to PV.

Instrumentation for objective microclimate measurements

To obtain in-situ, objective microclimate data from each site, we used the Kestrel 4400 Heat Stress integrated sensor-logger (Nielsen-Kellerman; Pennsylvania, U.S.A). To ensure consistency in measurement accuracy, each instrument was calibrated and tested both prior to and post-field data collection. The sensor-loggers were programmed to sample and log ambient air temperature (T_a), relative humidity (RH), horizontal wind velocity (u), and globe temperatures (T_g) every 60 s. Vapour pressure (e) based on T_a and RH was derived through the Clausius–Clapeyron equation. At the culmination of each day's observation, these data were downloaded to a field notebook computer through the associated Kestrel data transfer cradle and software prior to analysis.

We mounted each instrument onto a tripod at 1.3 m a.g.l. (above ground level), which approximates the average centre-of-gravity height for adults often used in bio-meteorological research (1.1 m a.g.l.; e.g. Mayer and Höppe, 1987). The sensor-loggers at EL and VC were installed at open areas adjacent to the lake and buildings, respectively, while the Kestrel at RF was sited under the vegetation canopy but next to a pedestrian pathway; at PV, the sensor-logger was sited at the approximate centre of the valley (Fig. 2).

Subsequently, these microclimate data were utilised to derive common indices utilised in prior research directly pertaining to outdoor thermal comfort. First, respective site mean radiant temperatures (T_{mrt}), defined as the 'uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure' (ASHRAE, 2001), were calculated. T_{mrt}, which is also the sum of all short-wave and long-wave radiation fluxes that the human body absorbs, directly affects the human body's heat balance and influences outdoor thermal comfort especially during clear and calm summer days (Emmanuel, 2012). T_{mrt} is a variable that has been used in several previous urban microclimate studies investigating outdoor thermal comfort (e.g. Ali-Toudert et al., 2005; Chow and Brazel, 2012). In this study, we utilise an equation proposed by Thorsson et al. (2007) to estimate ambient T_{mrt} from direct measurements:

$$T_{\mathrm{mrt}} = \left[\left(T_g + 273.14\right)^4 + \frac{\left(1.10 \times 10^8 V_a^{0.6}\right)}{\varepsilon D^{0.4}} * \left(T_g - T_a\right) \right]^{1/4} - 273.15\,[^\circ\mathrm{C}] \tag{1}$$

Table 2
Results of i-Tree Canopy analysis for Rainforest (RF) and Palm Valley (PV) sites, and summary of vegetation characteristics from site surveys.

Site	% Cover (±standard error)					
	Concrete (impervious surfaces)	Water features	Grasses	Shrubs/bushes (<5 m)	Single layer	Multi-layer
RF	14.3 ± 1.43	1.17 ± 0.44	5.33 ± 0.92	2.33 ± 0.62	16.2 ± 1.50	60.7 ± 1.99
PV	11.5 ± 1.30	0.17 ± 0.17	19.5 ± 1.62	7.17 ± 1.05	20.7 ± 1.65	41.0 ± 2.01
Vegetation characteristics	RF			PV		
Canopy	Closed			Open		
Leaf type & phenology	Broadleaved; Evergreen					
Canopy stratification	Tree layer + tree layer/shrub layer + grass			Tree layer + Shrub layer + Grass		
Typical species	*Tree ferns* (Shrub—Undergrowth) *Pinanga coronate* (Shrub—Undergrowth) *Callerya atropurpurea* (Tree layer—Canopy) *Palaquium obovatum* (Tree layer—Canopy) *Koompassia malaccensis* (Tree layer—Emergent)			*Iguanura wallichiana* (Shrub) *Normanbya normanbyi* (Tree layer) *Dypsis cabadae* (Tree layer)		
Mean tree height (m)	19.28			17.86		
Mean crown thickness (m)	8.67			4.41		
Mean crown diameter (m)	12.32			8.63		

where T_g is globe temperature (°C), T_a is air temperature (°C), V_a is air velocity (m s^{-1}), D is globe diameter (m) (0.01542 for the Kestrel 4400), ε is emissivity (0.95 for the black-coloured copper globe on the Kestrel 4400).

Second, we derived Thom's (1959) Temperature-Humidity discomfort index (*THI*), which is based on measured T_a and *RH* data:

$$THI = (0.8 * T_a) + \left(\frac{T_a * RH}{500}\right) \quad [^{\circ}\mathrm{C}] \tag{2}$$

THI and several variants based on Eq. (2) have been utilised in several thermal comfort studies e.g. Nieuwolt (1977), Deosthali (1999), Emmanuel (2005), and Kakon et al. (2010). Nieuwolt (1977) suggested that comfort thresholds exist based on empirical analysis of *THI* in mid-latitude cities. For instance, 50% of a given population would feel comfortable when *THI* ranges between 24 and 26 °C, but 100% of subjects would feel uncomfortably hot when *THI* exceeds 26 °C. Notably, this discomfort index does not account for variations in u, which is a dominant cooling mode in hot humid environments, and is thus often criticised as inadequate. Further, the suggested *THI* ranges for mid-latitude comfort are likely inapplicable to low-latitude cities as tropical residents are likely to tolerate higher levels of *THI*, due to adaptation through acclimatization and variations in behavioural factors like clothing choice (Emmanuel, 2003). To this end, Mohd Din et al. (2014) proposed that the *THI* range in the tropics be increased – with the "uncomfortable" range being >30.1 °C – based on research in equatorial Malaysia.

Third, we derived the wet-bulb globe temperature (*WBGT*), which is a thermo-physiological index that measures heat stress of an individual under direct sunlight. The Kestrel 4400 directly calculates *WBGT* based on the following equation:

$$WBGT = 0.7 * T_{\mathrm{wb}} + 0.2 * T_g + 0.1 * T_a \quad [^{\circ}\mathrm{C}] \tag{3}$$

where T_{wb} is the meteorological wet-bulb temperature, which is also logged by the sensor and is derived from *RH* and dew-point temperatures. *WBGT* accounts for several meteorological variables such as air and globe temperatures, humidity, wind speed, sun angle and insolation. It is also widely used by the United States National Weather Service and several branches of the United States military, as well as in several thermal comfort studies as an outdoor heat stress index in hot environments (Lin et al., 2013). There are suggested thresholds for *WBGT* used by these agencies—such as moderate (high) levels of risk of heat stress if physical exertion continues at 26 (28) °C (Willett and Sherwood, 2012). Notably, when *WBGT* exceeds 32 °C, suspension of play at major sporting events, such as the Australian Open, is considered (Leighton and Baldwin, 2008). A notable caveat of using these *WBGT* thresholds is that it applies towards fit and healthy adults used to physical exertion – as opposed to normal members of the general public – and thus these limits may potentially overstate thermal stress for most segments of the population who are less physically active.

Last, we utilised T_a, *RH*, u and T_{mrt} derived from Eq. (1) to calculate physiological equivalent temperatures (*PET*). An index that is based on the balance between two human body nodes (core and skin), *PET* can be defined as the air temperature in which the heat balance of the human body, when both clothed and under typical indoor conditions, is maintained with node temperatures equal to the outdoor conditions being assessed (Höppe, 1999). When compared with thermal perception surveys, Matzarakis et al. (1999) have suggested that "comfortable" conditions occur when *PET* falls 18–23 °C; "warm" conditions are perceived at *PET* = 29–35 °C; and hot conditions occur when *PET* = 35–41 °C. Site *PET* were estimated through RayMan Pro (v2.1) model simulations (Matzarakis et al., 2007, 2010), which were based on the observed Kestrel data.

Subjective thermal comfort surveys

As thermal comfort is based on personal situations where the mind expresses satisfaction with the thermal micro-environment, its comprehensive analysis requires subjective assessments at an individual basis (Hwang and Lin, 2007). Thus, the use of on-site questionnaire surveys was necessary within this study in order to elicit information from SBG visitors vis-à-vis outdoor thermal comfort at each site. Ideally, the sampling of SBG visitors would be unbiased and representative of the outdoor general public in Singapore, enabling potential transferability of results to a larger population; this assumption is however unrealistic given that typical outdoor thermal comfort surveys are unable to target specific segments of the at-large population (Ng and Cheng, 2012). That said, we followed established protocols utilised in previous studies (e.g. Cheng and Ng, 2006) to minimise potential age or gender biases in our sampling; for instance, surveyors were briefed to avoid an imbalance of having more males (or female) respondents being questioned. Respondents were asked to complete a questionnaire on perceived thermal comfort by surveyors based at each Kestrel. Park users passing by within 3–5 m of the sensor-loggers were invited to complete the survey; this distance was selected as it is reasonable to assume a consistent microclimate within concurrent station measurements (Spagnolo and de Dear, 2003).

The format of the questionnaire employed was adapted from previous studies also surveying thermal comfort perceptions (e.g. Spagnolo and de Dear, 2003). It consisted of two separate components. First, the surveyor indicated the time of survey to ensure correspondence with the sensor-logger measurement, whilst also indicating approximate age, gender, clothing type and current position of the respondent. Second, the respondent completes two sub-sections pertaining to level of activity (to gauge baseline metabolic levels), time of residence in Singapore (to ascertain acclimatisation to its tropical climate) and finally, questions were posed related to site microclimate thermal comfort perception i.e. through sensations and preferences of climate conditions. Closed questions were mainly used to limit the number of responses to facilitate quantitative analysis.

To assess outdoor thermal comfort, we used the ASHRAE seven-point scale to gauge the thermal sensation vote (*TSV*): The ordinal scale of responses ranged from cold (−3), cool (−2), slightly cool (−1), neutral (0), slightly warm (+1), warm (+2), and hot (+3). The *TSV* assumes equal intervals between each point, and is symmetrical about the neutral/zero point. While the ASHRAE Standard 55 assumes that 'neutral' reflects the user's preferred ideal condition (Brager et al., 1993), terms such as 'cold' and 'warm' are subjective and may have different interpretations (Nicol, 2008). Thus, we also included questions based on the three-point McIntyre preference scale to reflect the user's ideal comfort levels for the site (i.e., the question asked is 'would you prefer conditions to be warmer (+1), no change (0), or cooler? (−1)?').

Apart from *TSV*, other microclimate parameters – wind, humidity and sunlight – were also measured in the survey through clearly-indicated questions that gauged the respondent's wind sensation vote (*WSV*), humidity sensation vote (*HSV*) and sun sensation vote (*SSV*) through a five-point scale (−2, −1, 0, +1, and +2), with negative responses indicating low wind, low humidity, and low sunlight conditions (and vice versa for positive responses). These sensation data were also supplemented by three-point scales for the user's "ideal" wind, humidity and sun preferences conditions that are also ranked. Finally, we asked park users for their votes on each site's thermal acceptability (i.e. a binary "acceptable/unacceptable" vote), as well as their perception of which of the four variables surveyed was deemed to be the "most unpleasant" (NB: users were also given the option of indicating "none"),

Table 3
Fieldwork dates and descriptive weather observations based on the NUS Geography weather station data (NUS, 2015).

Fieldwork date/day	24-h mean (and standard deviation)			
	Air temperature (°C)	Relative humidity (%)	Wind speed ($m\,s^{-1}$)	Incoming [maximum] shortwave radiation ($W\,m^{-2}$)[a]
Winter (northeast) monsoon[*]				
08.12.2013[b] (Sunday)	24.99 (1.40)	85.30 (10.37)	2.37 (0.98)	142.23 [409.2] (159.60)
21.12.2013 (Saturday)	25.76 (2.09)	80.80 (10.98)	3.00 (1.33)	233.44 [501.7] (178.57)
24.01.2014 (Friday)	25.02 (1.43)	69.28 (6.73)	4.81 (0.56)	217.33 [475.1] (164.39)
26.01.2014 (Sunday)	24.99 (1.93)	69.75 (6.91)	4.71 (0.91)	262.79 [477.2] (172.76)
Summer (southwest) monsoon[*]				
25.05.2014 (Sunday)	29.02 (1.24)	72.95 (6.71)	1.49 (1.03)	314.44 [771.0] (273.05)
07.06.2014[c] (Saturday)	28.38 (1.34)	81.33 (8.82)	1.89 (1.13)	260.02 [476.5.2] (166.39)
08.06.2014 (Sunday)	29.21 (1.46)	75.92 (10.02)	2.18 (0.72)	366.71 [698.7] (230.79)
15.06.2014 (Sunday)	28.74 (1.12)	77.24 (9.79)	2.54 (0.89)	248.90 [590.4] (221.99)

[*] Student's *t*-test (unequal variance of samples) for hourly weather observations between winter (NE) and summer (SW) monsoons showed significant differences for air temperature, wind speed and incoming shortwave radiation at $p < 0.05$ levels.
[a] Data are for daytime periods (07:00–190:0 h LT) only; daytime maximums are reported in block parentheses.
[b] 21.4 mm of rain was measured at the station from 16:00 to 21:00 h LT.
[c] 0.25 mm of rain was measured at the station from 15:00 to 16:00 h LT.

and finally they were asked to rank their overall comfort at the site on a four-point, non-neutral scale.

SBG fieldwork period

We conducted fieldwork on a total of eight days over two distinct seasons; four days during the year-end Winter Monsoon when wind direction is predominantly from the NE, and four days during the mid-year Summer Monsoon where winds are generally from the SW. Weather conditions during the winter (summer) monsoon in Singapore are associated with windy and rainy (calm and cloud-free) conditions, and there is a notable seasonal influence of the monsoons on Singapore's UHI intensity with SW monsoon periods generally corresponding with higher UHI magnitudes (Roth and Chow, 2012). Observations from a weather station located ~5 km away from the SBG indicated that there were significant differences (at $p < 0.05$ levels) in hourly (i) air temperature, (ii) wind speed and (iii) incoming shortwave radiation between these seasons (Table 3). Subsequent analysis examines potential seasonal variations in outdoor thermal comfort data accordingly. While we note that this station did not fully accord to World Meteorological Organisation (WMO) specifications (Oke, 2006), its close proximity relative to the SBG enables us to record data that likely are more representative of larger-scale weather conditions affecting the study area, such as precipitation and insolation. Substantial variations of precipitation between the WMO station of record in Singapore, which is located at the far eastern end of the island, with other parts of the island have been noted in previous studies (e.g. Chow and Roth, 2006).

To maximise the response rate for the survey questionnaires, data were collected during weekend days during which most visits to the SBG occur. During these days, fieldwork at all four sites commenced from 09:00 h local time (LT), which is ~2 h after sunrise, and concluded at 20:00 h LT (~1 h after sunset); after the latter time, few visitors to all sites were observed except for at VC, which made survey sampling unnecessary. Measurement and survey data were also excluded in afternoon and evening of 08/12/13, and also from 15:00–16:00 h on 07/06/14 due to precipitation that occurred during these periods. A total of 1573 surveys from all sites were compiled with the mean survey response rate being ~80% for all sites, suggesting that the respondent sample is not biased towards people who are more favourable towards survey participation (Wheater and Cook, 2000). The profile of the typical respondent is a male or female aged 20–40 years, clad in a short-sleeved, light-coloured T-shirt with shorts, who has resided in Singapore for more than 6 months and visits the SBG once or twice a year (Table 4).

Results

Measured micro-climate data

Ensemble mean hourly plots of observed climate variables indicated that distinct intra-site variations were measured throughout the entire fieldwork period (Fig. 3). While the most "urban" site (VC) had highest average T_a in the morning and early afternoon (peaking at ~31 °C), T_a at the more exposed EL site were warmer, on average, until the early evening. While the site with the greatest vegetation density (RF) consistently had the lowest T_a for most of the day, mean T_a at the relatively less dense PV cooled at considerably faster rate by sunset. As expected for the equatorial synoptic climate, humidity at all sites was consistently high (*e* varied from 3.5–4.8 kPa), with slightly less humid daytime conditions. More vegetated sites (RF and PV) generally had higher observed humidity, even when compared to conditions around the EL water body; however, one-way ANOVA of mean hourly *e* did not indicate significant differences (at the $p < 0.05$ level) between sites (Table 5). Conversely, significant intra-site differences existed for both mean hourly *u* and T_g

Table 4
Selected survey results of the profile description of SBG survey respondents (in percent).

Survey question	EL (%)	PV (%)	VC (%)	RF (%)
Age				
18–20 years	15	5	9	13
20–40 years	67	74	53	50
41–60 years	16	18	30	28
>60 years	2	2	7	9
Gender				
Male/female	51/49	52/48	48/52	48/52
Clothes				
Upper body				
T-shirt	73	73	73	76
Vest or tank-top	16	16	14	11
Other	11	11	13	13
Lower body				
Pants	38	35	45	35
Shorts or Skirt	62	65	55	65
Frequency of visits to SBG				
>2 times/week	7	3	7	12
1–2 times/week	13	10	16	23
1–2 times/month	20	23	22	24
1–2 times/year	37	37	35	21
First time	23	27	20	22
Residence duration in Singapore >6 months				
Yes/no	79/21	75/25	79/21	82/18

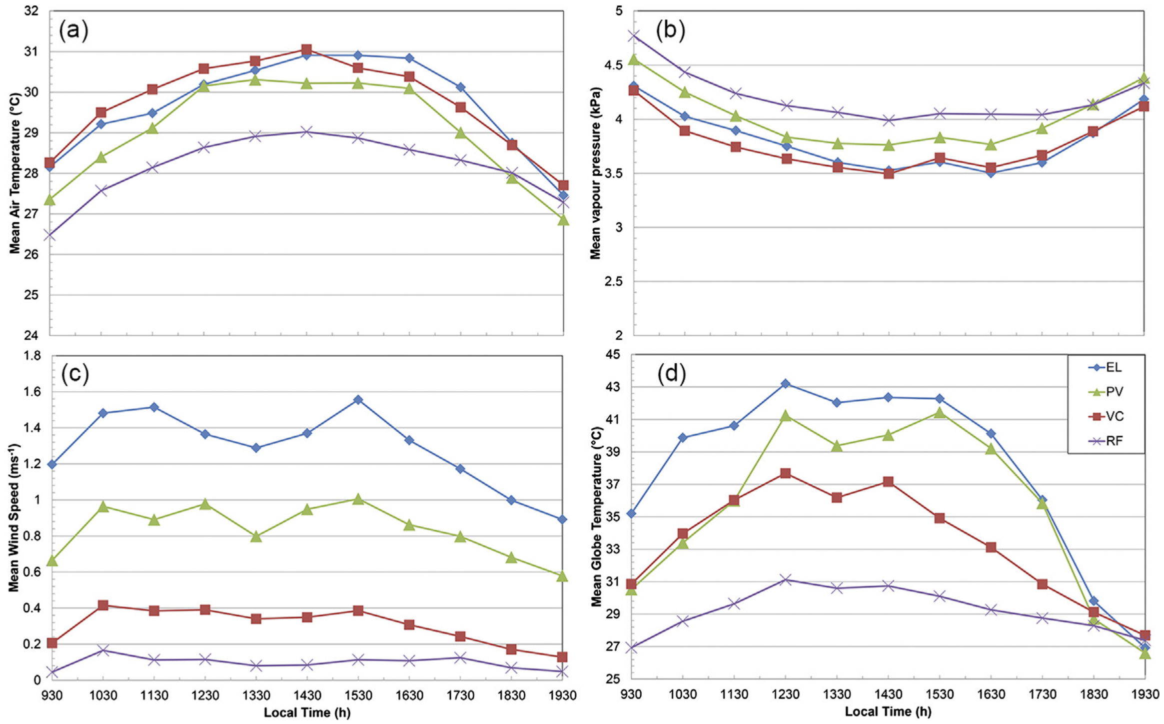

Fig. 3. Observed (a) hourly mean air temperature, (b) mean vapour pressure, (c) mean wind-speed, and (d) mean globe temperature at all four sites over all eight fieldwork days in which data were collected. RF—Rainforest, VC—Visitors' Centre, EL—Eco-Lake, and PV—Palm Valley.

when post-hoc one-way ANOVA was applied for the entire study duration. In general, the more exposed the site was, the higher the average u or T_g measured; it is also notable that the "urban" site at VC had observed considerably lower afternoon T_g compared to the EL and PV sites.

Seasonal averages of T_a, u and T_g reveal significant variations exist between both SW (summer) monsoon and NE (winter) observations (Fig. 4; Table 5). Mid-year conditions were generally warmer by ~3 °C for each site's mean T_a, and more direct insolation was measured with SW monsoon T_g varying by ~4–10 °C at all sites. Considerably less turbulent (i.e. less windy) conditions were seen at PV and EL in the SW monsoon by ~1.2 m s^{-1}, but significantly more windy mid-year conditions were documented at the RF site while little seasonal variation in wind speed was measured at VC. As with the NUS weather station data, there appeared to be little seasonal difference in average humidity, with measured e for all sites indicating little variation between the consistently humid NE and SW monsoon conditions.

Table 5
Mean magnitudes (and reported 95% confidence intervals) of measured hourly microclimate variables and derived thermal comfort indices for all SBG sites.

Variable/index (season)[a]	EL	PV	VC	RF
Microclimate				
T_a (both) (°C)	29.68 ± 0.54	29.06 ± 0.48	29.75 ± 0.44	28.15 ± 0.41
T_a (SW monsoon) (°C)	31.37 ± 0.59	30.45 ± 0.56	30.92 ± 0.53	29.43 ± 0.42
T_a (NE monsoon) (°C)	27.71 ± 0.38	27.45 ± 0.39	28.40 ± 0.43	26.68 ± 0.36
e (both) (*kPa*)	3.813 ± 0.10	4.027 ± 0.10	3.772 ± 0.11	4.210 ± 0.10
e (SW monsoon) (*kPa*)	3.808 ± 0.15	4.147 ± 0.15	3.876 ± 0.16	4.221 ± 0.15
e (NE monsoon) (*kPa*)	3.819 ± 0.13	3.889 ± 0.13	3.651 ± 0.14	4.197 ± 0.13
u (both) (m s^{-1})	1.293 ± 0.17	0.835 ± 0.13	0.304 ± 0.04	0.097 ± 0.03
u (SW monsoon) (m s^{-1})	0.706 ± 0.12	0.371 ± 0.08	0.343 ± 0.06	0.167 ± 0.05
u (NE monsoon) (m s^{-1})	1.972 ± 0.18	1.373 ± 0.11	0.260 ± 0.04	0.016 ± 0.01
T_g (both) (°C)	38.17 ± 2.35	35.70 ± 2.19	33.51 ± 1.20	29.22 ± 0.63
T_g (SW monsoon) (°C)	42.44 ± 3.83	39.77 ± 3.62	35.37 ± 1.93	30.85 ± 0.86
T_g (NE monsoon) (°C)	33.22 ± 1.43	30.98 ± 1.04	31.35 ± 1.02	27.34 ± 0.48
Thermal Comfort Indices (all units are in °C)				
T_{mrt} (both)	46.73 ± 2.82	39.99 ± 2.09	34.90 ± 1.20	29.21 ± 0.59
T_{mrt} (SW monsoon)	45.72 ± 3.82	40.63 ± 3.16	36.09 ± 1.75	30.78 ± 0.76
T_{mrt} (NE monsoon)	47.90 ± 4.33	39.25 ± 2.76	33.53 ± 1.58	27.40 ± 0.50
THI (both)	28.19 ± 0.48	27.83 ± 0.45	28.22 ± 0.39	27.13 ± 0.36
THI (SW monsoon)	29.83 ± 0.42	29.34 ± 0.42	29.47 ± 0.36	28.41 ± 0.26
THI (NE monsoon)	26.28 ± 0.34	26.09 ± 0.34	26.76 ± 0.37	25.64 ± 0.29
WBGT (both)	28.61 ± 0.86	28.09 ± 0.86	27.46 ± 0.63	26.31 ± 0.47
WBGT (SW monsoon)	31.50 ± 0.85	30.95 ± 0.91	29.63 ± 0.55	28.07 ± 0.27
WBGT (NE monsoon)	25.26 ± 0.56	24.78 ± 0.47	24.94 ± 0.50	24.27 ± 0.33
PET (both)	34.98 ± 0.21	32.74 ± 0.16	31.26 ± 0.09	29.08 ± 0.05
PET (SW monsoon)	36.38 ± 0.29	34.54 ± 0.22	31.39 ± 0.12	29.77 ± 0.07
PET (NE monsoon)	33.24 ± 0.28	30.45 ± 0.19	31.09 ± 0.14	28.22 ± 0.05

[a] Sample size for both seasons = 82; SW monsoon = 44; NE monsoon = 38.

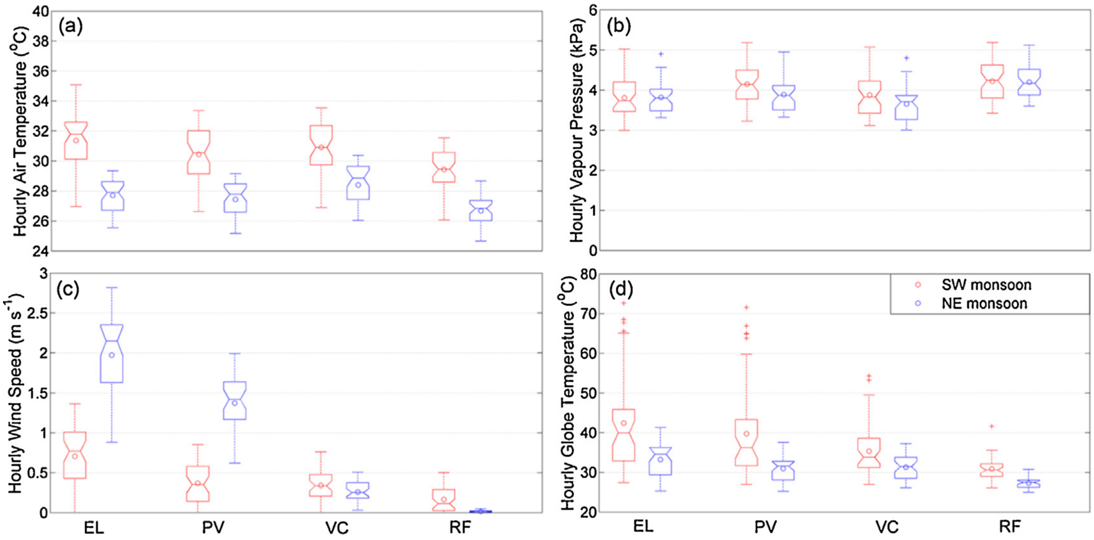

Fig. 4. Notched boxplots of climate variables displayed in Fig. 3 that are observed during the SW monsoon (red) and NE monsoon (blue) seasons. These are (a) hourly mean air temperature, (b) mean vapour pressure, (c) mean wind-speed, and (d) mean globe temperature. Respective seasonal means for each variable are represented by the circular dot within each boxplot, while seasonal extremes are indicated by respective coloured "+" markers. Medians are the horizontal lines within each boxplot. Medians between categories are different at $p < 0.05$ significance levels if respective notched intervals do not overlap. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Thermal comfort measures/indices

All measures/indices of thermal comfort derived in this study – T_{mrt}, *THI*, *WBGT* and *PET* – revealed several intra-site differences for both hourly (Fig. 5) and seasonal (Fig. 6) time periods, but notable variations existed within trends of site rankings. While all indices indicated that RF had relatively "comfortable" conditions for the majority of hourly periods in both seasons, distinct differences in site rankings are apparent depending on the index used (Fig. 5). Throughout the day, EL conditions were consistently the most uncomfortable compared to other sites when using T_{mrt}, *WBGT* or *PET*, with peak thermal discomfort occurring around solar noon (~13:00 h). There is substantial intra-site variance in the distribution of T_{mrt} compared to other indices. Between sites, magnitudes of the index difference between EL and PV (~10–15 °C) was consistently larger for T_{mrt} compared to *WBGT* or *PET* during most of the day; we also noted little difference in *WBGT* and *PET* magnitudes between EL and PV after 12:30 h. Despite having less vegetation density compared to EL and PV, the urban VC site was consistently more comfortable when compared with EL and PV via T_{mrt}, *PET* and *WBGT*. This trend does not apply, however, to hourly *THI*, which indicated that VC was the most uncomfortable site prior to 14:30 h.

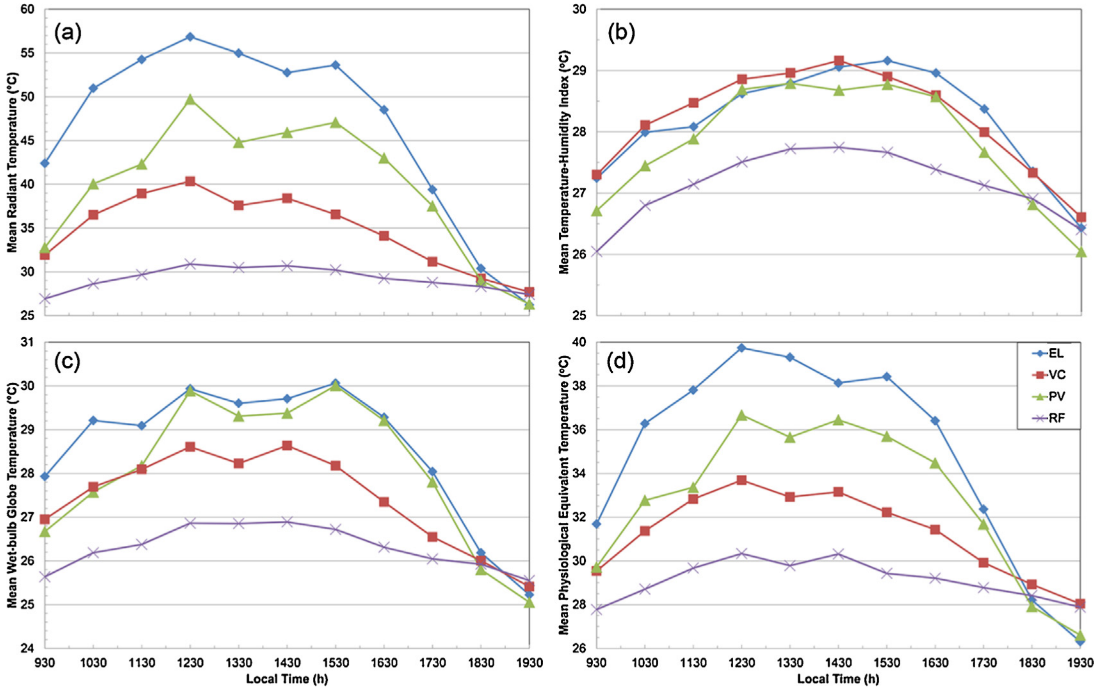

Fig. 5. Derived (a) hourly Mean Radiant Temperature (T_{mrt}), (b) mean Temperature-Humidity Index (*THI*), (c) mean Wet-Bulb Globe Temperature (*WBGT*), and (d) mean Physiological Equivalent Temperatures (*PET*) for each site. RF—Rainforest, VC—Visitors' Centre, EL—Eco-Lake, and PV—Palm Valley.

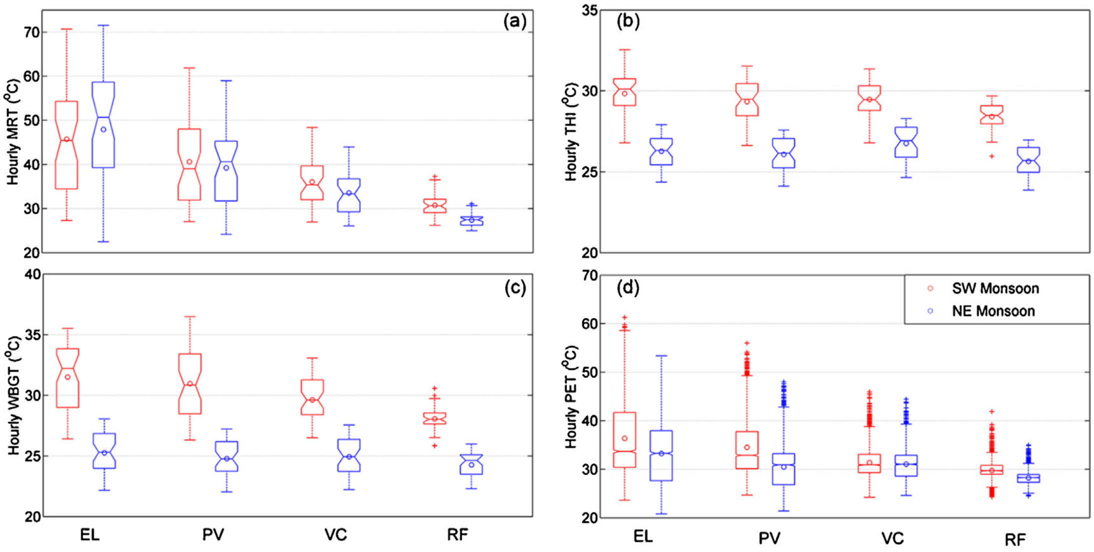

Fig. 6. Similar notched boxplots as per Fig. 4, but of (a) T_{mrt}, (b) *THI*, (c) *WBGT*, and (d) *PET* observed during the SW monsoon (red) and NE monsoon (blue) seasons. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Although *THI* at EL was marginally higher in the late afternoon periods, conditions at VC were more uncomfortable during in the brief period sampled after sunset.

We can also examine Fig. 5b–d to determine how hourly microsite thermal conditions relate to indices with explicit stated thresholds (i.e. *THI*, *WBGT* and *PET*). Based on Nieuwolt's (1977), the "uncomfortably hot" 26 °C threshold based on a population of a mid-latitude city is clearly exceeded at all times for all SBG sites, but falls within the "partially uncomfortable" range (20–30 °C) when the adjusted Mohd Din et al. (2014) *THI* limits are applied. In contrast, there is some stratification of intra-site rankings when *WBGT* and *PET* threshold ranges are surpassed. While *moderate* levels of *WBGT* heat stress risk (when > 26 °C) are experienced at RF after 10:30 h until sunset, the other SBG sites exceed *high* levels of heat stress risk (when >28 °C) by 11:30 h. This limit is exceeded until 16:30 h at VC, and at 18:30 h for both PV and EL sites. *Moderate* heat stress (>28 °C) as per *PET* is felt at all sites after 10:30 h, but *strong* heat stress (>35 °C) is measured at EL from 10:30 to 16:30 h, and from 12:30 to 16:30 at PV. *Slight* heat stress (*PET* < 29 °C) occurs at all sites after 18:30 h.

Finally, there are significant variations for all sites that can be observed for summer and winter monsoon periods for both *THI* and *WBGT* (both at $p < 0.05$ levels), although minimal seasonal differences are seen for T_{mrt} and *PET* for all sites except for RF (Fig. 6; Table 5). On average, thermally uncomfortable conditions exceeding 30 °C for *THI*, *WBGT* and *PET* are consistently observed during the SW monsoon at EL, PV and VC vs. the cooler NE monsoon. In contrast, thermal comfort conditions measured at RF for these three indices are significantly cooler when compared to EL, PV and RF with post-hoc ANOVA at $p < 0.05$ levels during both monsoon seasons (Table 5).

Survey questionnaire data

Sensation vote data for each microclimate variable – thermal, humidity, wind, and sun exposure – were analysed for each site for summer (SW monsoon), winter (NE monsoon), and both seasons (Fig. 7). A significant majority of respondents perceived that thermal conditions all sites were "Slightly warm" to "Hot", with a marked increase of thermal sensation during the SW monsoon. Of particular interest was that respondents at RF and PV had the largest number of "Hot" and "Warm" votes despite these sites having the lowest average measured summer T_a. The *HSV* data indicated that the majority surveyed felt either "Humid" or "Too humid" throughout both periods at all sites, although most respondents at EL surprisingly felt either neutral or "Dry/Too dry", especially during the NE monsoon, despite the site being next to a water feature. The *WSV* data analysis indicated that a majority (>50%) of people surveyed consistently perceived "Little/No wind" conditions, except for the more exposed sites at PV and EL during the windier winter monsoon. Analysis of *SSV* data revealed that most respondents consistently felt neutral sun exposure conditions (>50%) at all sites – especially at RF – with the exception of visitors at the exposed EL site where strong sun conditions were felt during the summer monsoon.

For each perceived climate variable, we applied post-hoc Kruskal–Wallis tests to ascertain if seasonal differences in variances for these non-parametric survey data were present within the four sites (Table 6). While there were insignificant differences for *TSV* and *SSV* variations during the summer and winter monsoons, respectively, clear intra-site variations existed between seasonal *HSV* and *WSV*, suggesting that apparent differences in wind and humidity are more clearly perceived by respondents. In summary, the majority of survey respondents indicated that warm, humid, non-windy and neutral-sun conditions were distinctly felt at all sites during both seasons, although seasonal, intra-site variations of sensation votes depended on the climate variable being sampled.

The corollary preferential vote data to each climate sensation clearly indicated that while respondents prefer cooler, drier and windier conditions at all sites, they are mostly neutral towards changes to sun sensations (Fig. 8). These preferences are unambiguous for both seasons, although a slightly larger percentage of respondents preferred a greater change for thermal, wind, and humidity votes during the summer monsoon. Results from the final set of survey questions on site temperature acceptability, most uncomfortable climate variable and overall comfort suggested that

Table 6
Reported Kruskal–Wallis test *p* values for variance of site sensation votes between seasons. Bold values indicate significance when $p < 0.05$.

Season	TSV	HSV	WSV	SSV
SW monsoon	0.2319	**0.0034**	**0.0001**	**0.0001**
NE monsoon	**0.0422**	**0.0001**	**0.0001**	0.0572

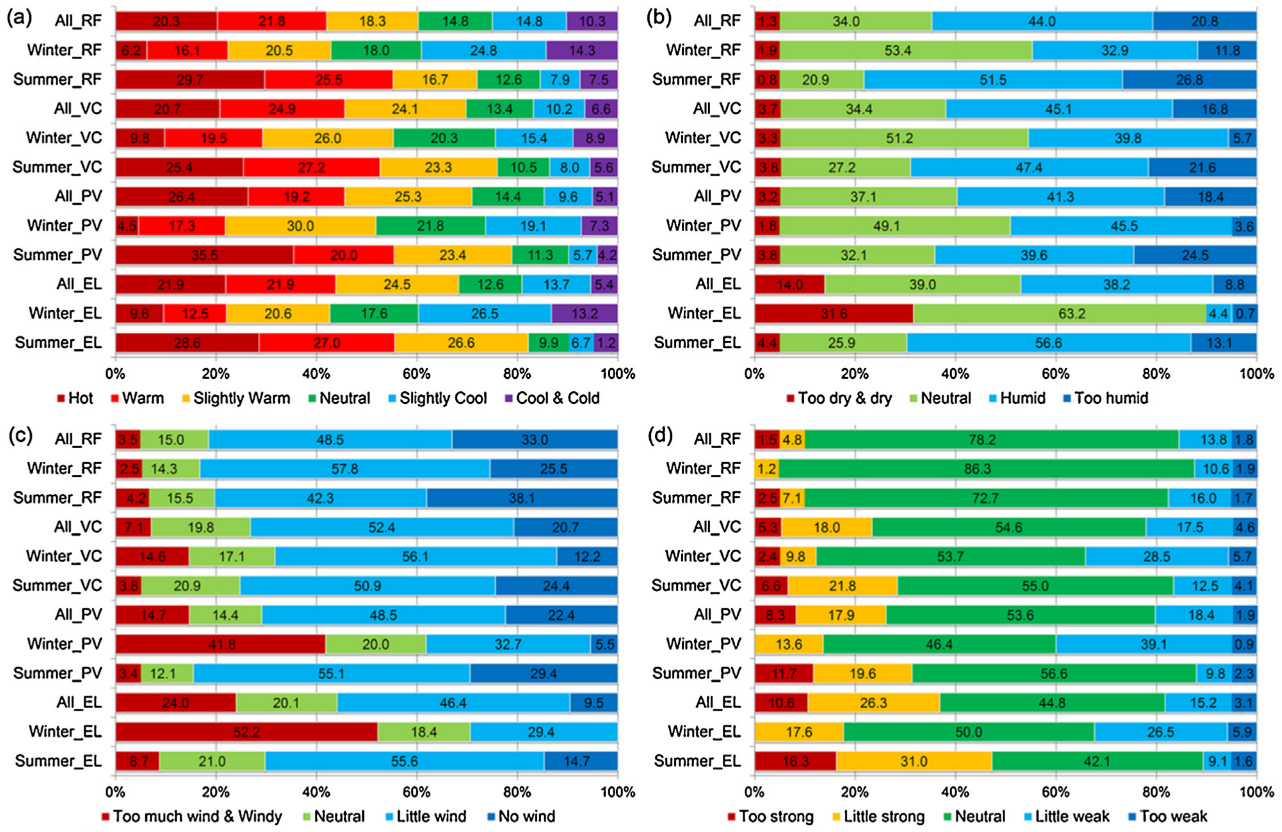

Fig. 7. Mean proportions of votes for (a) Thermal, (b) Humidity, (c) Wind, and (d) Sun sensations perceived at each of the four SBG sites for all, winter (NE) monsoon and summer (SW) monsoon conditions.

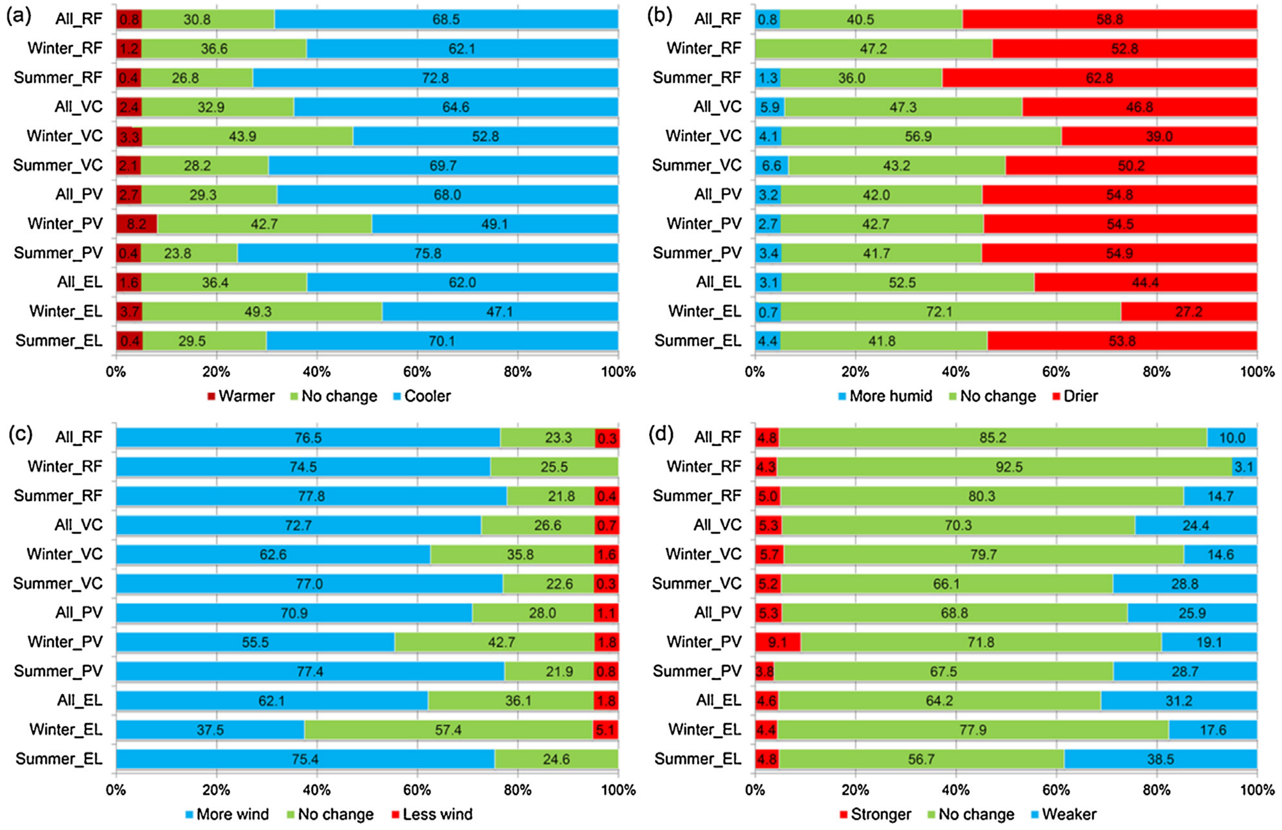

Fig. 8. Same as Fig. 7, but for site preference votes.

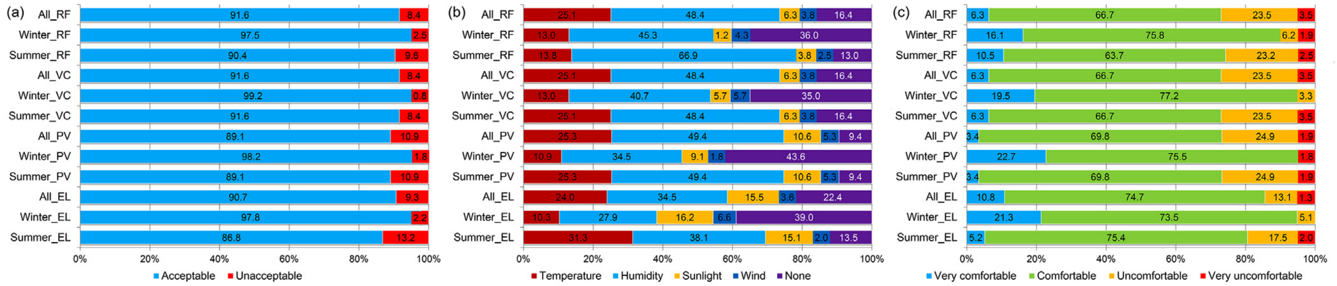

Fig. 9. Mean proportions of votes for (a) acceptability of site temperatures; (b) for the climate variable that is the most uncomfortable, and; (c) for overall perception of climatic comfort at each of the four SBG sites for all, winter (NE) monsoon and summer (SW) monsoon conditions.

(i) the micro-scale temperatures at each site were acceptable for the vast majority of the park users surveyed; (ii) in general, ambient humidity conditions were perceived to be the variable causing the most discomfort, although most respondents at PV and EL during the winter monsoon did not select any variable as causing discomfort and; (iii) overall, most park users consistently felt comfortable at all sites within the park (Fig. 9).

Comparison of objective vs. subjective climate comfort data

We examined both objective and subjective datasets for potential correlations of microclimate comfort both for within sites, and over different seasons. Given (i) the relatively large variance of T_{mrt}, especially between seasons at each site that may result in spurious correlations (Fig. 6a), (ii) the dependence of utilising T_{mrt} in deriving site *PET*, and (iii) the omission of wind and sun exposure inputs in *THI*, we thus selected *WBGT* as the objective metric examined with respect to each sensation vote through Spearman's rank correlation (ρ). Prior to this analysis, we examined individual factors of survey respondents summarised in Table 4 (i.e. age, gender, clothing, frequency of visit and residence duration in Singapore) with respect to T_{mrt}, *THI*, *WBGT*, and *PET* through either Mann–Whitney or Kruskal–Wallis tests; no significant differences at $p < 0.05$ levels were discerned for all but one factor (residence duration). This factor can be viewed as a representative proxy measure for acclimatisation towards local climate, and is also similar to analysis undertaken by Makaremi et al. (2012), who found local respondents exhibiting higher tolerance compared to non-local respondents due to acclimatization. Thus, we examined correlations between *WBGT* and the various sensation votes depending on whether the respondents were acclimatised (i.e. >6 months in Singapore, $n = 1242$ for all sites) or non-acclimatised (<6 months in Singapore, $n = 331$ for all sites) (Table 7).

In general, there were strong positive (negative) correlations of *WBGT* with *TSV* and *SSV* (*HSV* and *WSV*) apparent at all sites for both seasons, but considerable intra-site and inter-seasonal differences in ρ exist. For example, despite being the most "urban" site, the relationship between *TSV* and *WBGT* at VC was not as strong relative to other sites. Compared to the humid RF site, the relatively drier EL, PV and VC sites also had stronger negative relationships over both seasons (i.e. perceived humid conditions at these sites are inversely related to *WBGT*). The relationship between *WSV* and *WBGT* switched in direction between seasons, which was unsurprising given the significant seasonal differences in u, but the effect on the relationships between objective and subjective climate measures appears to be best discerned at the most (EL) and least (RF) open/exposed sites. The level of exposure of each site also is important in examining the correlation between *SSV* and *WBGT* over both seasons, with stronger and direct relationships seen at EL, PV and VC.

While the correlation results of acclimatised and non-acclimatised respondents have, in general, similar reported ρ for *TSV* and *HSV* over both seasons and for all sites, there are some notable variations reported for the other sensation votes. Significant variations are also seen for the response to *WSV*; in general, the more acclimatised the person is, the stronger the correlation to *WBGT* for all seasons at all sites. Subtle differences in reported *SSV* are also notable. For instance, ρ of *SSV* vs. *WBGT* during the SW monsoon which is substantially larger for the non-acclimatised sample at all sites but RF. The nature of correlation differs at several sites during the NE monsoon, however, where opposing ρ are documented (e.g. at RF, EL and VC).

Table 7
Spearman Correlation matrix of micro-climate sensation votes with *WBGT* for acclimatised and non-acclimatised (in parentheses) respondents. Correlations (ρ) between sensation votes and *WBGT* that are significant at the $p < 0.05$ level are marked in bold.

Season	EL	PV	VC	RF
Acclimatised $n = 1242$ (non-acclimatised $n = 331$)				
TSV vs. WBGT				
SW monsoon	**0.27 (0.24)**	**0.30 (0.49)**	0.11 (0.11)	**0.22** (−0.08)
NE monsoon	**0.54** (0.41)	**0.40** (−0.08)	**0.42 (0.59)**	0.09 (−0.10)
Both seasons	**0.52 (0.56)**	**0.36 (0.49)**	**0.29 (0.31)**	**0.34 (0.36)**
HSV vs. WBGT				
SW monsoon	−0.01 (−0.15)	−**0.13** (−0.19)	−**0.19** (−0.07)	0.02 (0.12)
NE monsoon	−**0.35 (−0.50)**	−**0.29** (0.02)	−0.04 **(−0.55)**	−0.09 (0.09)
Both seasons	−**0.23 (−0.34)**	−**0.24 (−0.28)**	−**0.25** (−0.11)	−0.08 (−0.10)
WSV vs. WBGT				
SW monsoon	**0.17** (−0.07)	0.09 (0.03)	0.10 (0.09)	**0.22** (0.08)
NE monsoon	−**0.41 (−0.44)**	−**0.25** (0.11)	−**0.31 (−0.35)**	−**0.18** (0.11)
Both seasons	−**0.16** (−0.11)	−**0.19** (−0.10)	−**0.13** (−0.12)	−0.03 (0.09)
SSV vs. WBGT				
SW monsoon	**0.44 (0.58)**	**0.31 (0.58)**	**0.20 (0.48)**	0.12 (0.10)
NE monsoon	**0.27** (−0.03)	0.08 **(0.42)**	**0.24 (−0.50)**	**0.14** (−0.03)
Both seasons	**0.54 (0.41)**	**0.29 (0.51)**	**0.22** (0.20)	0.11 (0.11)

Discussion

The notable variations in both measured and perceived data underline the importance of the physical site characteristics, such as its horizontal surface cover (i.e. "urban" vs. "water" vs. high/low density vegetation) and vertical structure (i.e. open/closed canopy, variations in stand architecture, and mean building height) towards influencing intra-site micro-scale climate variations. In particular, the degree of site exposure – either from the placement of artificial structures or tree canopy extent – has a strong influence towards (i) reduction of radiative fluxes arising from daytime shading and (ii) reduction of wind velocities (and possibly turbulence) that are critical towards tropical climatic comfort. These features of site exposure can be inferred by the low measured T_g and u at VC and RF, and the negative perceptions of *WSV* at these sites relative to the more exposed EL and PV locations. Differences in data are magnified substantially during the generally warmer SW monsoon period, where the PV and EL sites can be categorised having more climatically uncomfortable conditions either with the objective (i.e. *PET or WBGT*) or subjective (sensation and preference votes) comfort data.

The effect of exposure/shading in this outdoor tropical context appears to be more substantial compared to evaporative cooling either from greenery or from water sources. In cities located in other climates, e.g. in hot arid cities (Chow and Brazel, 2012), increase in urban greenspace evapotranspiration is important for micro-scale cooling and increasing climatic comfort via decreasing the Bowen ratio. A pre-requisite is that a large surface-atmosphere humidity gradient is present for this to be effective; further, the cooling effect may be accentuated by a large horizontal advective flux through higher synoptic-scale wind speeds in these mid- or higher-latitude cities. In this study, however, the high ambient humidity conditions, coupled with relatively low wind speeds at each site (and for the entire study area), suggest that evapotranspirative cooling may not be a significant influence—especially when humidity is consistently voted as the most uncomfortable climate variable across all sites. Moreover, the relatively higher levels of thermal discomfort measured and perceived at EL illustrate that the evaporative cooling from the titular lake may not be significant towards improving site microclimate comfort conditions. Even though the relatively high exposure at EL enables higher wind speed/advective flux conditions, it also increases direct sunlight/radiative fluxes that potentially overwhelm the evaporative cooling influence beneficial for thermal comfort at the site. We stress, however, that our results are in the context of a tropical urban park; with large heterogeneity present in urban land use and land cover types, there are limits to which our results are generalisable towards other urban surface types. Further, micro-scale humidity gradients in other urban/suburban land covers may favour evapotranspirative cooling from vegetation to improve thermal comfort. We suggest that direct measurement of surface evapotranspiration, such as through plot lysimeter or eddy covariance measurements, should be undertaken to quantify this effect especially in other commercial, residential or industrial locations with relatively less vegetation densities versus urban parks like the SBG.

The study also confirmed the finding of many outdoor thermal comfort studies that using T_a as the sole indicator of the ambient thermal environment is insufficient. The high morning VC T_a may suggest that ambient thermal conditions at the site are most unfavourable objective and subjective comfort, but its low *WBGT* relative to other non-urban sites reveal otherwise. The differences in intra-site rankings of mean T_a vs. other indices highlighted in Fig. 6 also clearly illustrate the importance of wind, humidity and sun exposure as factors of outdoor thermal comfort are consistent at other sites. Furthermore, the subjective perceptions of *TSV* at VC are not distinctly different – and in some cases average *TSV* is lower there especially during the summer monsoon period – compared to other sites. As such, we strongly suggest that future investigations into tropical urban thermal comfort should focus more on the critical aspects of humidity and wind to discern comfort/discomfort levels at each site sampled or modelled.

The implications of the aforementioned site characteristics, in particular the importance of wind and site exposure, towards applied urban greenery management of climatic comfort in a tropical context are thus worth considering. As the use of outdoor spaces is often predicated upon thermal comfort levels (Lin, 2009; Chen and Ng, 2012), determining what influences thermal discomfort can facilitate reconfiguration of city design through urban greenery in order to promote comfortable conditions, especially in the context of projected rapid global urbanisation. To maximise daytime urban climatic comfort at micro-scales, such as for streetscapes or small parks, a balance should be sought between the long-term shade effect of trees beneficial in warm weather conditions (e.g. Lin and Lin, 2010), against its "windbreak" effect of substantially reducing canopy wind speeds (e.g. Park et al., 2012). Identification of tree or shrub species with ideal vertical canopy and leaf area density profiles that reduce T_g (sun exposure) and increase u (wind sensations) should be performed prior to urban forestry management decisions that account for outdoor thermal comfort.

The relatively high thermal comfort indices that exceed thresholds for discomfort (*THI*) and heat stress (*WBGT*), combined with the sensation votes that unambiguously report generally hot, overly humid, and low wind-speed conditions across all four sites, are at odds with the consistent votes of acceptable thermal and overall comfort conditions reported by respondents at all sites in both seasons (Fig. 9). This contradiction is unsurprising, as complex interactions between objective and subjective measures are a distinctive feature of assessing outdoor thermal comfort (e.g. Nikolopoulou and Steemers, 2003; Lin, 2009; Cohen et al., 2013). While it is possible that this contrast can be explained by acclimatisation to tropical sun and wind conditions, as seen in the variance of ρ in Table 7 with respect to *SSV* and *WSV* between acclimated and non-acclimated respondents, other psychological and behavioural factors should be considered (Nikolopoulou et al., 2001). These factors include viewing the aesthetics of urban greenery being an individual adaptive strategy towards coping with climate discomfort (e.g. Klemm et al., 2015), or from respondents psychologically predisposed towards physical activity that are likely tolerant of thermal discomfort vs. individual commuters passing through the SBG who may be more intolerant of physical exertion. Investigating the influence of these factors cannot be ascertained by the methods applied herein, but should be attempted in future studies of perceived outdoor thermal comfort.

Summary and conclusion

Using several indices derived from measured in-situ climate data, we have found that there are significant differences in micro-scale outdoor thermal comfort across four distinct sites for an urban forest park in tropical Singapore. There are also seasonal differences in thermal comfort arising from variations in synoptic, large scale climate in the summer and winter monsoon periods. Depending on the index, several sites were subject to thermally uncomfortable or high heat stress conditions during parts of day. We also conducted surveys of thermal comfort sensation and preferences at each site concurrent to the measurements; the results generally showed that site respondents felt warm/hot, humid, calm with low wind, but with neutral sun exposure conditions; the corollary preference votes all indicated a strong inclination towards cooler, drier and windier conditions across all sites, with humidity especially being the most uncomfortable climate variable. Despite the discomfort sensations and preferences, a large majority of survey respondents felt comfortable/very comfortable at all sites in both monsoon periods.

The results have interesting implications towards the applied management of urban greenery in tropical cities at small spatial scales, especially towards the influence of vertical structure of canopies and their impacts towards site shading and turbulence reduction. The shading from trees with broad canopies at large heights and large leaf area densities could be considered more important as a factor towards increasing thermal comfort vs. evapotranspiration, with the latter process possibly being less effective due to low humidity gradients in the tropics. The contrasting and important difference between objective measurements and subjective perceptions of urban forest microclimates suggest that other aspects of urban forestry/greenery, such as perceptions of greenery aesthetics, should be investigated in the context of thermal adaptation.

While results from this study provide useful information on outdoor thermal comfort, which should be an inherently important consideration for urban planners and designers with respect to sustainable urban climates in tropical cities (Roth, 2007), there are aspects that should be expanded upon for future research. These include assessment and comparison of other heat indices, such as neutral temperatures (Mui and Wong, 2007) and the Universal Thermal Climate Index *UTCI* (Bröde et al., 2012), for measured data obtained within the SBG, as well as with comparisons in other urban spaces in which greenspace densities and extent are considerably lower. Future analyses could also include more detailed temporal examination, such as the comparison of pre-noon and post-noon measured and subjective thermal comfort, as well as post-sunset, nocturnal analyses within the urban forest that also could provide useful UHI mitigation information as the latter phenomenon is at its greatest extent at night.

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