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The role of one large greenspace in mitigating London's nocturnal urban heat island

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HIGHLIGHTS

- Trees help regulate urban air temperatures and combat the urban heat island effect.
- We describe cooling of London's heat island by one large greenspace over 5 months
- Cooling of up to 4 °C over 440 m distance from the park was observed on single nights.
- The park cooled London when cooling was most needed, on warm still nights.

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ABSTRACT

The term urban heat island (UHI) describes a phenomenon where cities are on average warmer than the surrounding rural area. Trees and greenspaces are recognised for their strong potential to regulate urban air temperatures and combat the UHI. Empirical data is required in the UK to inform predictions on cooling by urban greenspaces and guide planning to maximise cooling of urban populations. We describe a 5-month study to measure the temperature profile of one of central London's large greenspaces and also in an adjacent street to determine the extent to which the greenspace reduced night-time UHI intensity. Statistical modelling displayed an exponential decay in the extent of cooling with increased distance from the greenspace. The extent of cooling ranged from an estimated 20 m on some nights to 440 m on other nights. The mean temperature reduction over these distances was 1.1 °C in the summer months, with a maximum of 4 °C cooling observed on some nights. Results suggest that calculation of London's UHI using Met Stations close to urban greenspace can underestimate 'urban' heat island intensity due to the cooling effect of the greenspace and values could be in the region of 45% higher. Our results lend support to claims that urban greenspace is an important component of UHI mitigation strategies. Lack of certainty over the variables that govern the extent of the greenspace cooling influence indicates that the multifaceted roles of trees and greenspaces in the UK's urban environment merit further consideration.

1. Introduction

Cities frequently demonstrate higher mean average air temperatures than surrounding rural areas, a phenomenon termed the 'urban heat island' (UHI) (Oke, 1987). The UHI is a result of the process of urbanisation, which alters the energy balance of a city in comparison to that of the countryside. More energy from the sun is used for raising air temperature than in evapo-transpiration as vegetated surfaces are replaced by engineered surfaces (Greater London Authority, 2006). The intensity of the UHI, defined as the difference in air temperature between the city and the surrounding rural area, varies diurnally and seasonally (Watkins et al., 2002), and is reported to be up to 9 °C on some nights in London, England (Greater London Authority, 2006). Concentrated human activities in more built-up areas support the formation of a more intense UHI than in less densely grouped centres, although small urban centres do demonstrate the phenomenon (Watkins et al., 2002).

Global temperatures are set to rise during the foreseeable future as a consequence of anthropogenic activities (Stern, 2006). Current climate change projections are for south-eastern England to warm by 2.5–4 °C by the 2080s (Davies et al., 2008; Department for Environment Food and Rural Affairs, 2012). There is a direct impact of heat on human health and the Department of Health has identified threshold temperatures for each region within the UK that, when exceeded, give rise to heat-related stress and excess summer deaths (Department of Health, 2008). The frequency of days with temperatures above these regional thresholds and UHI induced heat stress are set to increase under the changing climate predicted for the UK, with major implications on the thermal comfort and health of city dwellers. Heat-related mortality already accounts for around 2000 premature deaths in the UK and is

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forecast to increase to around 3400 premature deaths in the 2020s and to around 10,800 premature deaths in the 2080s (Health Protection Agency, 2012). The risks are greatest in large metropolitan areas that suffer from the UHI, such as London, Manchester and Birmingham (Department for Environment Food and Rural Affairs, 2012).

Trees and greenspaces are recognised for their strong potential to regulate urban air temperatures and combat the UHI. Delivering several mechanisms of cooling simultaneously and in a complementary manner vegetation gives rise to air temperatures within a greenspace that are as much as 8 °C cooler than the surrounding urban area (Oke, 1987) and a cooling effect that extends out beyond the boundaries of the greenspace (Taha et al., 1988; Saito et al., 1990). The neighbourhood cooling effect of greenspaces has been demonstrated in highland subtropical (Jauregui, 1991), humid sub-tropical (Saito et al., 1990; Chang et al., 2007), moderate oceanic (Spronken-Smith and Oke, 2010), Mediterranean (Givoni, 1998; Spronken-Smith and Oke, 2010) and continental climates (Mayer, 1988). There are comparatively few published data for a temperate oceanic climate, as experienced in the UK (Chandler, 1965; Watkins, 2002; Smith et al., 2011).

Studies investigating the cooling effect of greenspace typically compare the air temperature within the greenspace with a reference point located just beyond the range of the greenspace influence (Chang et al., 2007); often assumed to be equivalent to the width of the greenspace (Honjo and Takakura, 1991; Jauregui, 1991; Spronken-Smith and Oke, 2010). The extent of cooling is reported to be affected by the size, structure and design of the greenspace, the design and structure of the surrounding urban environment, and the prevailing weather patterns (Yu and Hien, 2006). To what extent cooling changes with increased distance from a greenspace and if and how this varies with time is less clear, however. Following systematic review of urban cooling by greenspaces, Bowler et al. (2010) concluded that future research must explicitly investigate the distance effect to efficiently guide the planning of urban greenspace and to investigate the importance of the abundance and distribution of greenspaces in providing cooling benefit to urban dwellers. In addition to these specific research needs, UK empirical data is required to:

- Demonstrate the cooling potential of trees and greenspaces in the UK, and
- Support modelling of the role of trees and greenspaces in mitigating the UHI and its effects under a changing climate.

The aim of this research was to provide empirical evidence for the extent of cooling of London's UHI by one large greenspace. To achieve this aim, the following objectives were set:

- Measure and describe the temperature profile of one of central London's large greenspaces and in an adjacent street
- Determine UHI intensity across the study area
- Determine reduction in UHI intensity with increasing distance from the greenspace
- Assess the impact of weather on UHI reduction by greenspaces.

2. Methodology

2.1. Study area

The study area was centred on Kensington Gardens in London, England. A Royal Park, Kensington Gardens covers an area of 111 ha. It lays immediately to the west of Hyde Park (142 ha) and abuts Green Park (19 ha) and St. James' Park (23 ha). Kensington Gardens contain two large stretches of water: the Long Water (4.9 ha) and the Round Pond (2.8 ha), mixed grass land and treed landscapes, and formal avenues and gardens including the sunken Dutch garden and the Italian Garden (containing four water fountains).

2.2. Survey methods

Air temperature was monitored using Temperature Data Loggers (model: EL-USB-1) purchased from Lascar Electronics (Whiteparish, UK). The sensors have a stated accuracy of ±1 °C over the operating range of −35 to 80 °C. Sensors were set to monitor continuously (50 Hz) and average over 5 min. Surface and globe temperature measurements where not taken during the study. While surface temperature measurements are useful in understanding the regional effects of particular surfaces (e.g. within the street canyon) on air temperatures and globe temperature is a better measure of thermal comfort than air temperature, the case study location and the transect design were not conducive to their continuous in-situ measurement. The methodology is considered appropriate to the study's focus: the impact of greenspace on air temperature and UHI intensity.

Radiative warming of sensors is a known issue with these types of monitoring campaigns (Holden et al., 2013). Thus, following the method of Yu and Hien (2006), data loggers were housed in plastic boxes. Each sensor housing unit had 14 ventilation holes and was coated in self-adhesive reflective foil (Scotch™ Pressure Sensitive Tape by 3M) for protection from the effects of direct solar radiation. The accuracy of the sensors mounted in their housing units was tested at the Met Office's synoptic weather station at Alice Holt, Surrey prior to the field monitoring campaign in London. Five sensors in their housing units were used to monitor air temperatures over an 8-week period and the data collected was compared to the dry-bulb air temperature recorded in the Met Office's Stevenson screen. Within the range investigated (0.5 to 26 °C), the 24 h average error was found to be −0.01 °C to 1.5 °C (std. dev. ±0.5 °C). The linear regression correlating the data is: $T_{logger} = 1.05{*}T_{Met\ Station} + 0.16$ ($R^2 = 0.98$).

A field study was conducted from August 1st to December 28th 2011. Air temperatures were recorded by mounting a sensor within its housing unit at eight locations across the Kensington Gardens. Four were mounted South-facing in an area of open grassland, two on immature trees and two on the bandstand. The other four were mounted on mature London planes (*Platanus × acerifolia*, diameter at breast height (dbh) > 60 cm) situated along the approximately north-south orientated glade known as Lancaster Walk. All were mounted using cable ties at ca. 2.5 m above ground level (after Yu and Hien, 2006 and Upmanis et al., 1998). This height allowed the sensors to be readily accessed for data collection while remaining unobtrusive, reducing the risk of theft or vandalism.

The temperature profile outside of Kensington Gardens was monitored along a street transect positioned in Gloucester Terrace. This street is situated to the north of Kensington Gardens and runs from Lancaster Gate on the boundary of the Gardens in a north-west orientation away from the park. Twelve sensors were positioned at distances ranging from 70 to 340 m, eight on lamp posts and four on street trees (*Ginkgo biloba*, dbh < 15 cm) (Fig. 1). Gloucester Terrace is an ‘unclassified’ road (residential street). Every 6 weeks, data was downloaded, the battery replaced and the sensor's memory cleared.

Gloucester Terrace was selected as it most closely met the selection criteria for the street transect, namely it is not a major arterial route, it has few street trees and those that are present are small, it is one of the longest straight streets in the vicinity that is not intersected by a major arterial route, the width of the street and the height of the buildings lining the street are approximately equal throughout, there are no other greenspaces adjoining the street or within 1 block. The aspect ratio (building height to street width ratio) along Gloucester Terrace ranges 0.8–1.1 (average 0.9). Sky-view factor is the proportion of the sky visible in a 180° field of view. While not determined for this study, sky-view factor is dependant on the aspect ratio (Shashua-Bar and Hoffman 2003) and can therefore be considered to vary little along the street canyon, only opening up at the intersections. There are no areas of grass/vegetation and, therefore, surface sealing is considered to be constant along the road.

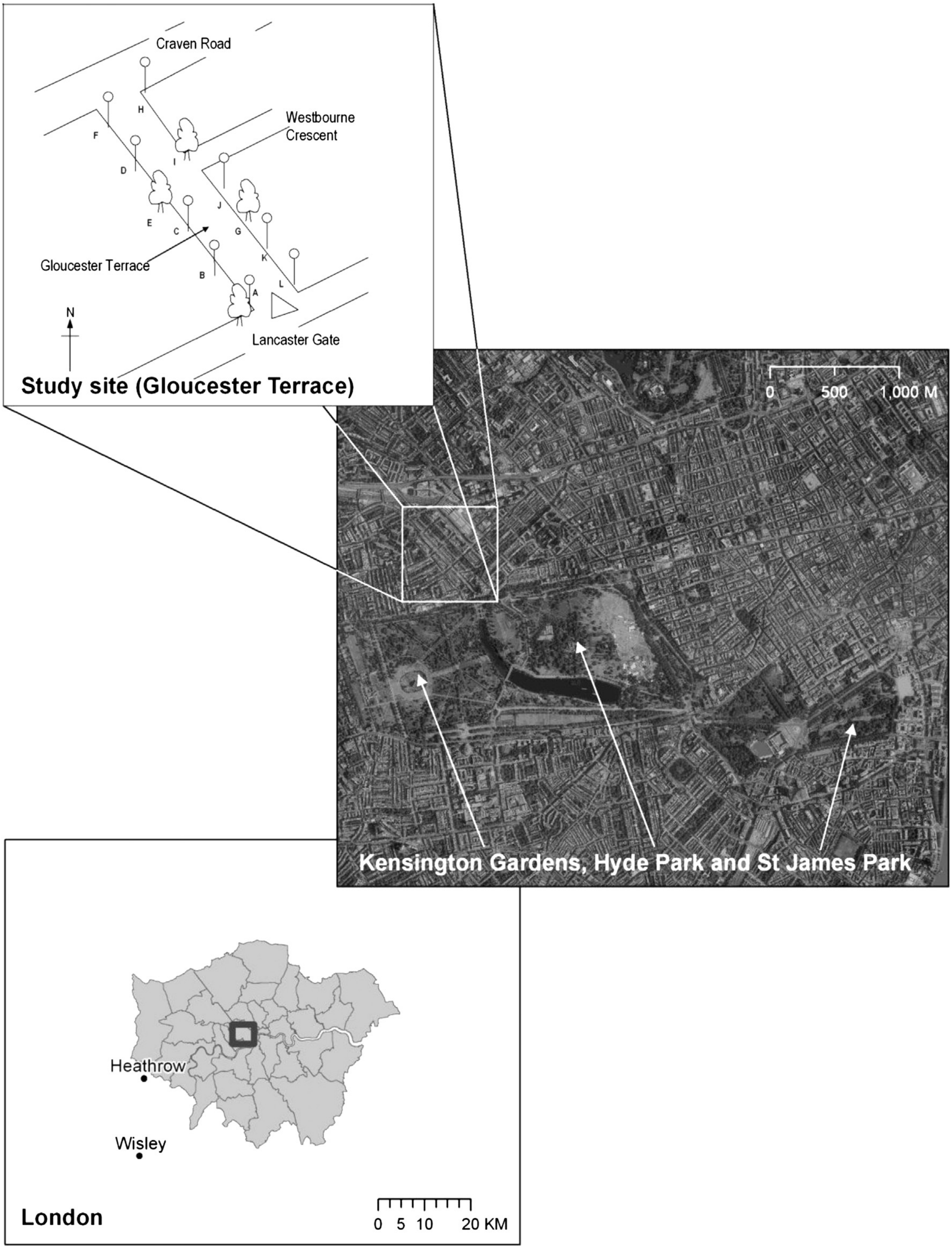

Fig. 1. Maps showing the location of the study site, the Met Stations, and the positions of the twelve sensors in the Gloucester Terrace transect.

2.3. Evaluation of the UHI effect

Urban heat island intensity is defined as the difference between air temperatures measured at an urban location and those measured at a rural reference location (Oke, 1987); see Eq. (1).

$$\text{UHI intensity} = T_{(\text{Urban})} - T_{(\text{Rural})} \tag{1}$$

To determine UHI intensity and its characteristics throughout the monitoring period, data were obtained for the Met Office's automated synoptic weather station at Wisley (Surrey, UK). Wisley was selected as a suitable rural reference point as it was the nearest automated Met Office weather station outside of the Greater London Area. Wisley data were obtained from the MIDAS Land Surface Stations 1853-current database, by permission of the British Atmospheric Data Centre (UK Meteorological Office, 2012). Data were also obtained for the Met Office's automated synoptic weather station at St James' Park (City of Westminster, Central London) for the calculation of UHI intensity based upon Met Office data only (i.e. UHI intensity $= T_{\text{St James' Park Met Station}} - T_{\text{Wisley Met Station}}$). St James' Park was selected as it is the nearest automated Met Office weather station to Kensington Gardens. Data for St James' Park were obtained from the US National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Centre (NCDC) (http://gis.ncdc.noaa.gov/map/cdo/).

2.4. Evaluating UHI cooling by greenspace

It was hypothesised that an asymptotic model of the form of Eq. (2) would describe the relationship between heat island intensity in Gloucester Terrace and distance from Kensington Gardens, where lower intensity values indicate cooling of the UHI by the greenspace and the asymptote reflects the diminishing cooling effect with increased distance from Kensington Gardens. Prior to modelling, average nightly temperatures were calculated from data collected between 20 h00 and 07 h00 at each point along the Gloucester Terrace transect and within Kensington Gardens and used to calculate UHI intensity by subtracting the average air temperature recorded at the Wisley reference site over the matching time period. Night-time was chosen because Watkins et al. (2002) had previously shown that when modelling changes in mean air temperatures across London, a high degree of the variance could be accounted for when modelling night-time data. However, only 25% of the variance was accounted for when modelling daytime data because the temperature pattern was more complicated.

The model (Eq. 2) was fitted to 148 nights within the period August 1st until December 28th (three November nights were omitted due to missing values). One of three outcomes was observed in the modelling process of each night's data:

a) All parameters were estimated to a good degree of precision and the convergence criterion of the model was met. Model fit was significant ($p < 0.01$) and the coefficient of variation (CV) of parameter *a* was < 30%. We define this as a Type 1 night.
b) Imprecise asymptote identified (CV > 30% for parameter *a*). Estimation of cooling effects was imprecise. Convergence criterion of the model fitting process was often not met. We define this as a Type 2 night.
c) Asymptote not identified. The model either failed to converge in the fitting process or parameters with inflated standard errors were estimated. We defined this as a Type 3 night.

$$t_i = a + lp + b \,.\, r^{\text{distancei}} + e_i \qquad (2)$$

where:

- ti refers to the recorded temperature at sensor *i* sited at distance_i from Kensington Gardens.
- a estimates the maximum asymptotic temperature with increased distance along Gloucester Terrace from Kensington Gardens.
- lp is the estimated effect of positioning the sensor on a lamppost rather than under a tree.
- b in combination with parameter a (namely a + b) estimates the temperature at Kensington Gardens, a distance of zero metres.
- R is the estimated rate of increasing temperature as one moves away from Kensington Gardens, and
- ei is the error in the model estimate for sensor *i*.

Eq. (2) is intuitively an appropriate model, it can be parameterised to estimate the maximum cooling effect at the edge of Kensington Gardens and it reflects the expected non-linear relationship between temperature and distance from the Gardens where beyond a certain distance all cooling effects would expect to have been lost. The suitability of this asymptotic curvilinear model was tested against other forms of linear and non-linear models; comparisons were based upon successful model convergence, the residual sum of squares and number of model parameters and used Aikake's Information Criteria to identify the best fitting model. Shashua-Bar and Hoffman (2000) used a similar exponential relationship to model the cooling effect of urban areas with trees. Our data did not demonstrate a 'boundary effect' as parameterised by Shashua-Bar and Hoffman (2000) but otherwise, for our Type 1 nights, the models are equivalent.

As urban heat island formation is influenced by synoptic weather conditions (Wilby, 2003), classification of 148 nights into either a Type 1, 2 or 3 night was further investigated by fitting a tree classification model to the observed weather data for the corresponding night or, for solar input values, in the preceding 12 h. The meteorological factors considered were wind direction, wind speed (knots, herein reported as m s^{-1}), cloud cover (octants), air pressure (at mean sea level, station and altimeter heights; in hPa), measured sunshine (hours), MMS (Meteorological Monitoring System) global radiation (derived; in minutes), global solar radiation amount (kJ m^{-2}) and rainfall (mm). Meteorological data was for the Heathrow Met Office station, London. The selected tree classification model was chosen to partition the target variable into a number of nodes, with each node containing, as far as possible, a single level of the target variable – in this case, nodes containing only Type 1, Type 2 or Type 3 nights. The full dataset of 148 nights was separated into a training dataset (60%) and a validation dataset (40%), each containing an approximately equal distribution of Type 1, 2 and 3 nights. Subsequently, the training dataset was used to select variables and cut-off values that significantly improved the separation of nights into one of the 3 Types. Finally, the validation dataset was used to cross validate the tree classification model and remove variables selected in the model building process which were no longer significant.

On Type 1 nights, the temperature range between Kensington Gardens and distance along Gloucester Terrace is both estimable and precise. These nights are therefore useful to estimate the UHI cooling effect of the Kensington Gardens. We defined the maximum distance at which cooling is observable as that distance where 10% of the UHI effect is still present and applied this definition to the 97 Type 1 nights to estimate parameters *a* – the maximum asymptotic temperature, and *r* – the rate of increasing temperature with increased distance from the Kensington Gardens, for each night.

Relationships between meteorological variables and UHI intensities for Wisley and St James' Park (30 km apart) were tested for by fitting a stepwise general linear model to the 148 nights of the study. Stepwise general linear models were also used to test for significant relationships in the nightly UHI effect between Kensington Gardens and Gloucester Terrace (300 m apart). As before, the meteorological factors considered were wind direction, wind speed, cloud cover, air pressure, sunshine and global radiation, and rainfall. Meteorological data was for the Wisley Met Office, Surrey.

All statistical analyses, including descriptive stats, analysis of variance (ANOVA) and mathematical modelling, were undertaken either in VSN International's Genstat 13 for Windows or SAS Institute's SAS/STAT 9.3.

3. Results

3.1. Air temperature

Air temperatures were recorded within Kensington Gardens and along the Gloucester Terrace transect between August and December, 2011. Temperature profiles exhibited a biphasic pattern differentiating night and day. Maximum and minimum temperatures recorded and the time of day at which they were observed varied between months. For example, in August maxima were observed from 13 h00 through to 16 h00 while in November maxima were observed between 12 noon and 13 h00 (data not shown). Minima were observed at ca.

Table 1
Range in daily mean average air temperatures at different London locations (monthly averages shown in parentheses). Range of hourly urban heat island intensity values presented for St James' Met Station, Kensington Gardens and Gloucester Terrace (Heat island intensity = $T_{(location)} - T_{(Wisley)}$); average day and night (20 h00–07 h00) time heat island intensity shown in parentheses.

Month	Location						
	Wisley	St James'		Kensington Gardens		Gloucester Terrace	
	Air temp	Air temp	UHI	Air temp	UHI	Air temp	UHI
Aug	13.0–20.9 (16.0)	14.3–22.5 (17.2)	−5.4–6.1 (0.6; 1.9)	14.3–23.0 (17.4)	−3.4–6.6 (0.8; 2.0)	14.7–23.7 (17.8)	−3.6–7.5 (0.9; 2.8)
Sept	11.0–18.7 (15.2)	7.4–20.1 (16.4)	−2.1–6.3 (0.7; 1.8)	11.9–21.1 (16.7)	−2.1–7.5 (1.1; 1.9)	12.5–22.2 (17.2)	−2.3–9.1 (1.2; 2.8)
Oct	4.7–18.2 (12.7)	7.4–20.1 (14.0)	−2.1–8.7 (0.7; 1.9)	7.9–21.3 (14.2)	−2.3–8.6 (1.0; 2.1)	8.6–22.6 (14.7)	−2.2–10.5 (1.2; 2.8)
Nov	4.5–14.8 (10.1)	6.8–15.6 (10.9)	−2.7–6.5 (0.7; 1.0)	6.9–15.5 (11.0)	−2.1–6.4 (0.9; 1.0)	7.5–15.8 (11.5)	−1.8–7.8 (1.2; 1.7)
Dec	0.8–11.2 (6.6)	2.4–11.8 (7.2)	−2.6–3.4 (0.5; 0.6)	2.3–11.8 (7.2)	−1.9–2.8 (0.6; 0.6)	2.8–12.2 (7.5)	−2.1–3.5 (0.9; 1.0)

05 h–06 h00 (August, September) and 07 h00 (October, November, December; data not shown). Comparison of the daily mean air temperatures (Table 1) for each location revealed that Gloucester Terrace was warmer than Kensington Gardens throughout each month (ANOVA-unbalanced design, $p < 0.001$).

Air temperature within a city is affected by the synoptic weather conditions. Local scale climate variability also arises, as determined by landscape features and urban development. Extraneous microclimate signals such as caused by a vehicle with a hot engine will also impact the air temperatures recorded over short interval periods (Oke, 2004). Data from Gloucester Terrace intersection sensor H (Fig. 1) was unreliable and influenced by unknown variables: sometimes it was much higher than nearby sensors and sometimes it was much cooler. Sensor H data were thus excluded from further analysis. The height at which sensors where placed (ca. 2.5 m) may have been a compounding factor. In a comparable study, Watkins et al. (2002) used a height of 6 m, away from localised heat sources (stationary cars) and temporary shading (stationary lorries), both of which are likely to be commonplace at this traffic-light controlled intersection. Street geometry may also have been a compounding factor, with greater ventilation expected at the intersection due to changes in street orientation and aspect ratio. With a larger sky-view factor, the intersection is also less susceptible to UHI formation as more long-wave radiation will be emitted to the sky than to the street canyon.

3.2. Quantifying the UHI

To characterise the UHI, heat island intensity is often quoted. Heat island intensity is affected by location, weather, time of day and season. Heat island intensity values therefore require a qualifier, such as a frequency distribution or a time interval. Hourly mean heat island intensity values are useful to demonstrate variability in the phenomenon, such as negative as well as positive values. Night-time and mean 24-h values are valuable when investigating the impacts of the UHI on human health. Mean hourly, night-time and 24-h values are used below.

Fig. 2 shows the variation in hourly heat island intensity at a central location in Gloucester Terrace for the month of August; mean and standard deviation for each hour of the day are also shown. Values range −3.6 to 5.2 °C during the day and −0.2 to 7.5 °C during the night (20 h00–07 h00), with UHI development occurring predominantly during the early night-time hours, reaching a maximum by ca. 21 h00. UHI intensity values for the months of August through to December are presented in Table 1 for the locations: Gloucester Terrace, Kensington Gardens and St James' Park. Data presented is the range in

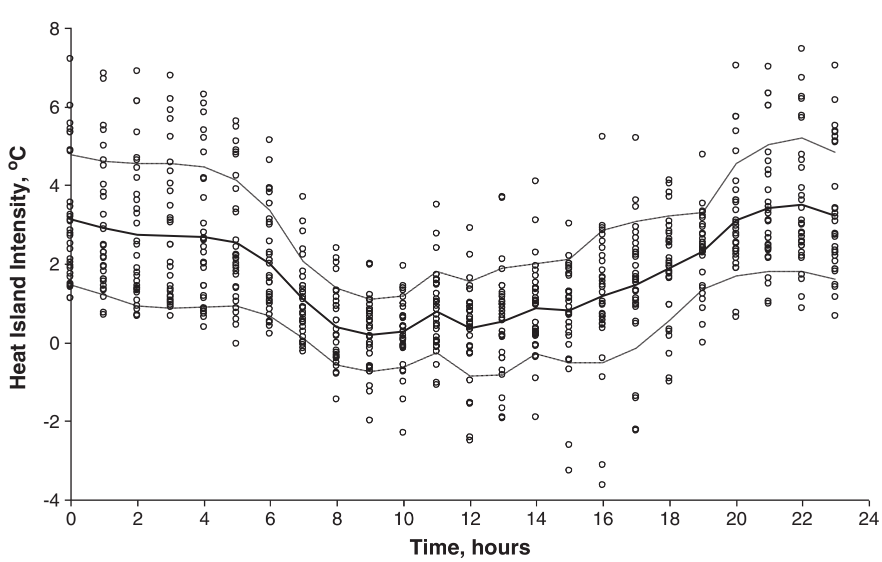

Fig. 2. Hourly variation in heat island intensity in August, at a central location in Gloucester Terrace. The mean (solid line) and standard deviation (dashed line) for each hour are also shown.

hourly means, as well as daytime and night-time (20 h00–07 h00) averages for each month. At each location and for each month of the study, mean UHI intensity is positive both during the day and night. Comparing St James' Park and Kensington Gardens (both greenspace locations) with the street location (Gloucester Terrace), shows that the heat island is, on average, more intense within the street during the night-time (2.8 °C in August, September and October). The intensity of the UHI observed in October is a result of the high temperatures experienced in England at this time (peaking at 29.9 °C in Kent making it the warmest October on record; Met Office, 2011).

3.3. Local mitigation of the UHI by Kensington Gardens

To investigate the cooling influence of Kensington Gardens, changes in heat island intensity along the Gloucester Terrace transect were calculated and their relationship to distance from Kensington Gardens modelled. Fig. 3 shows examples of the Type 1, 2 and 3 nights observed in the modelling process. Table 2 provides a summary of the frequency of Type 1, 2 and 3 nights as well as the average temperature, wind speed and UHI intensity for the months August to December. A Type 1 night was more likely to occur than either a Type 2 or Type 3 night (occurring on 97 of the 148 nights, Table 2) and occurred in each month of the study period. There were 15 Type 2 nights and these occurred in August, September and October, and 35 Type 3 nights, which occurred in October, November and December.

A tree classification model was fitted to data for the 148 nights to determine which meteorological factors were significantly correlated to the 3 night Types. Radiation, wind speed and temperature were identified as key classification variables; the additional meteorological parameters considered (wind direction, cloud cover, air pressure, MMS, and

Table 2
Summary statistics for Type 1, 2 and 3 nights.

Month	Data	Type		
		1	2	3
August	Count	28	3	–
	Temperature* (°C)	15.2	17.2	–
	Average UHI intensity (°C)	2.0	1.2	–
	Average wind speed (m s^{-1})	2.7	4.4	–
September	Count	24	6	–
	Temperature* (°C)	14.3	15.7	–
	Average UHI intensity (°C)	2.1	0.4	–
	Average wind speed (m s^{-1})	3.2	5.2	–
October	Count	24	6	1
	Temperature* (°C)	12.6	12.5	15.5
	Average UHI intensity (°C)	2.0	1.3	0.6
	Average wind speed (m s^{-1})	3.8	4.1	3.8
November	Count	14	–	13
	Temperature* (°C)	8.7	–	11.3
	Average UHI intensity (°C)	1.6	–	0.4
	Average wind speed (m s^{-1})	2.2	–	4.6
December	Count	7	–	21
	Temperature* (°C)	3.8	–	7.3
	Average UHI intensity (°C)	1.0	–	0.5
	Average wind speed (m s^{-1})	3.6	–	5.2

* Refers to average night-time temperature in Kensington Gardens

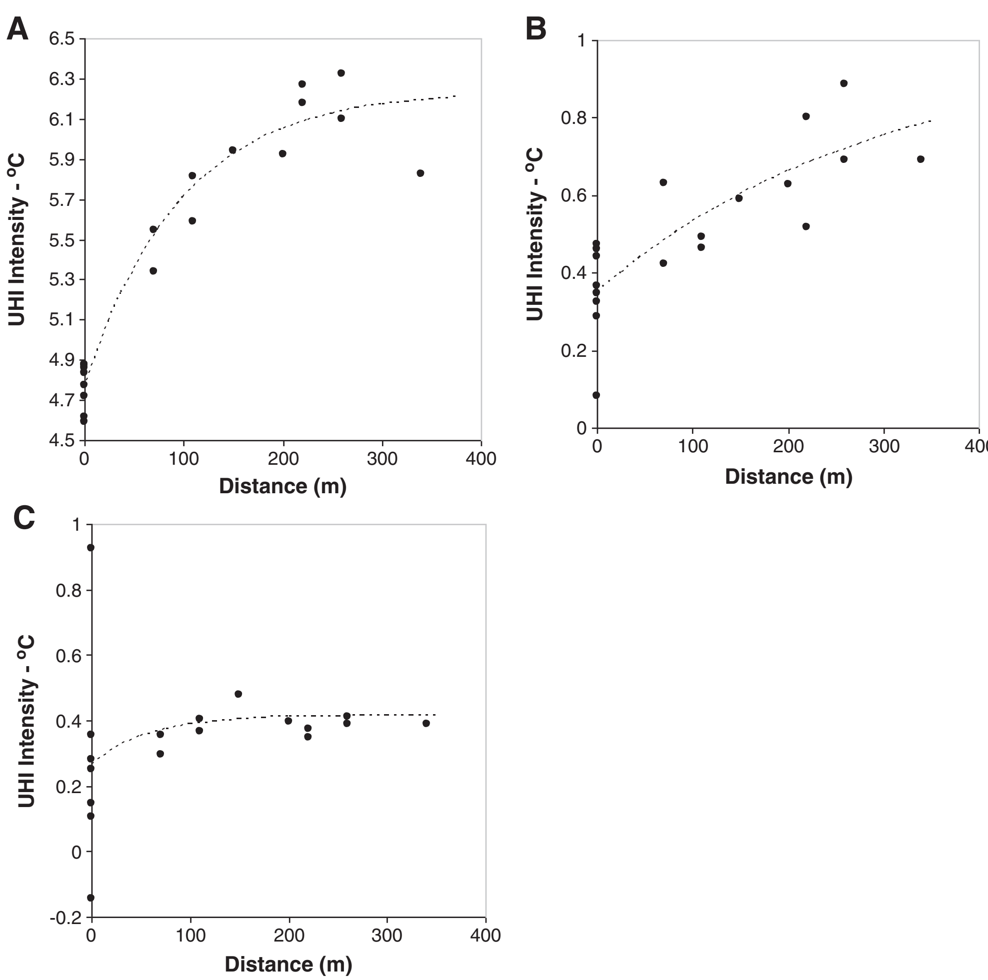

Fig. 3. Relationship between urban heat island intensity and increased distance from Kensington Gardens on Type 1, 2 and 3 nights. Typical profiles given for A) Type 1 – August 9th, B) Type 2 – September 7th, and C) Type 3 – November 30th nights.

rainfall) were not significant in the modelling process. When cumulative radiation values in the preceding 12 h were greater than zero, a night was always classified as either a Type 1 (when an asymptotic temperature increase could be precisely estimated) or Type 2 night (when an asymptotic temperature increase existed but could only be imprecisely estimated). A night was most likely to be classified as a Type 1 when, as well as having a positive cumulative radiation score, the average night-time temperature was less than 15.7 °C. When cumulative radiation values were zero, a night was most likely to be a Type 3 (57%) or a Type 1 (40%), with only a small likelihood of being a Type 2 (3%). For cumulative radiation values of zero and average wind speeds of less than 2.3 m s^{-1} (4.5 knots), nights were more likely to be classified as Type 1. Above 2.3 m s^{-1} a classification of a Type 3 night was most likely. Meteorological explanations for the occurrences of a Type 1, 2 or 3 nights are thus: positive cumulative radiation values are indicative of conditions favourable to UHI formation throughout the day and a Type 1 or Type 2 night will follow. Type 1 nights occurred when the average night-time temperature was less than 15.7 °C; above this average temperature a Type 2 night was observed. Bohnenstengel et al. (2011) simulating London's UHI in May 2008, describe a positive sensible heat flux to the atmosphere at 22 h00 and continued warming of the air that maintained a well-mixed and up to 5 times deeper boundary layer over London than over the surrounding rural area. Vertical mixing of the air will aid cooling along the street canyon leading to weaker trends in horizontal cooling (i,e, a Type 2 night). Similarly, vertical mixing increases in a street canyon with increasing wind speed and helps explain why the UHI was not observed during this study when wind speeds exceeded 2.3 m s^{-1} (see Discussion Section 4.1 for further details).

Type 3 nights represent those nights when measurable cooling of the UHI is not recorded. The observation that a night was more likely a Type 3 when cumulative radiation values are zero is logical as cloudy days (little or no cumulative radiation, often windy and rainy also) are not favourable to UHI formation. When the UHI was not very intense (1 °C or less; Table 2) a Type 2 or Type 3 night was modelled; this is likely an artefact of the methodology. With a ±0.5 °C error, the compound error between two sensors is 1 °C; this error will mask any trends in modelling. The methodology is therefore not sensitive enough to detect cooling of a weak UHI and a Type 2 or Type 3 night is modelled. The observation that a Type 1 night followed days with zero cumulative radiation points to the importance of anthropogenic heat in the energy balance of a street. On these nights, which occurred in late October, November and December, the average UHI intensity was 1.5 °C. Given that a heat island formed in the absence of solar input in the preceding 12 h, it had to be the result of anthropogenic energy inputs.

On Type 1 nights, the temperature range between Kensington Gardens and distance along Gloucester Terrace is both estimable and precise. These nights are therefore useful to estimate the UHI cooling effect of Kensington Gardens where, in the fitted model, parameter *a* – the estimated maximum asymptotic temperature – provides an estimate of the night-time reduction in the UHI by the greenspace, and parameter *r* – the estimated rate of increasing temperature with increased distance from Kensington Gardens – provides an estimate of the horizontal distance over which this cooling is measurable. Fig. 4A shows a histogram of the maximum cooling values (parameter *a*) observed for Type 1 nights (values range between 0.4 °C and 4.0 °C; mean of 1.1 °C and median of 0.9 °C; upper and lower quartiles are 0.6 °C and 1.2 °C, respectively). For these nights, variability in cooling values was significantly explained by wind speed with stronger winds leading to a reduction in cooling (Max Cooling $= -0.76 \text{Log}_{10}(\text{wind speed}) + 2.27$, $R^2 = 0.62$, $p < 0.001$; data not shown). Fig. 4B shows a histogram of the maximum distance over which cooling was measurable on Type 1 nights (values range between 20 m and 440 m; mean of 125 m and median 99 m; upper and lower quartiles are 162 m and 67 m respectively). The value of parameter *r* (the rate of temperature change with distance factor and equivalent to the decay rate b_d of Shashua-Bar and Hoffman (2000): $b_d = -\ln r$) ranged from 0.946 to 0.997 (mean: 0.986; median: 0.988). Fig. 5 shows a scatterplot of the distance to which cooling was observable on Type 1 nights. The mean distance of cooling on these nights was 125 m; it extended beyond 250 m on more than 10% of occasions. The cooling distance effect was significantly

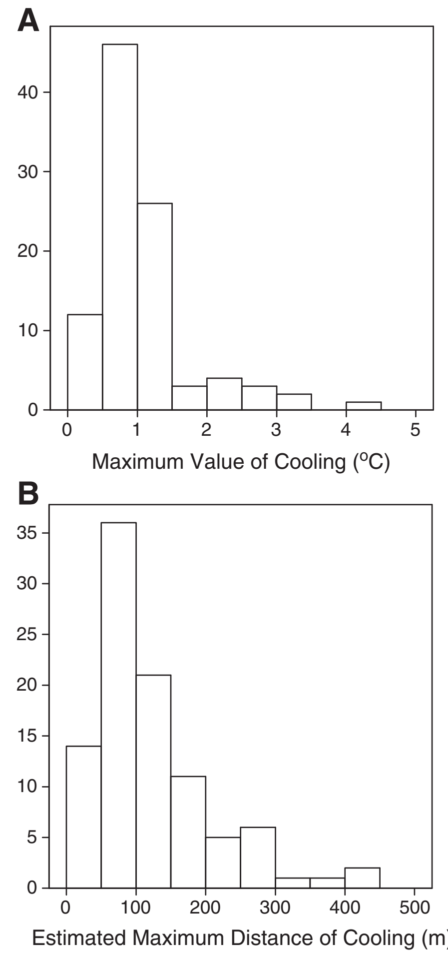

Fig. 4. Histogram plots showing the estimated maximum cooling of the UHI in Gloucester Terrace by Kensington Gardens (Fig. 4A) and the estimated maximum distance to which cooling by Kensington Gardens is observed in Gloucester Terrace (Fig. 4B) for Type 1 nights.

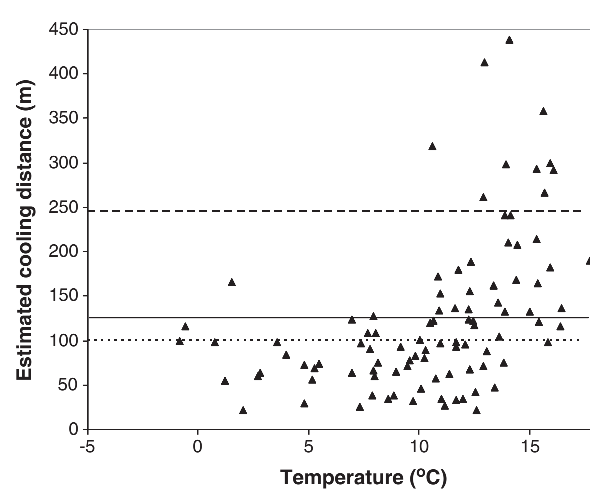

Fig. 5. The relationship between overnight temperature at Wisley and cooling effect for Type 1 nights (short-dash line represents median; long-dashed line the 90th percentile).

greater ($p < 0.001$) on warmer nights: up to 400 m when $T > 10$ °C in comparison to up to 100 m when $T \leq 10$ °C, (Fig. 5).

3.4. UHI relationships between Wisley and St James' Park (30 km distant) and between Kensington Gardens and Gloucester Terrace (300 m distant)

The intensity of the night-time UHI at St James' Park was determined relative to Wisley, the rural reference site, 30 km distant and was observed to range between −0.1 and 6.6 °C (data not shown; mean average for each month shown in Table 1). Previously, Wilby (2003) showed that a model parameterised for near-surface wind strength, westerly wind strength, vorticity, relative humidity and 850 mbar geopotential height accounted for 60% of the variance relating daily synoptic atmospheric variations to nocturnal UHI intensity in London in August 1995. In the current study, variation in UHI was best explained by a model parameterised for wind speed (log-transformed), cloud cover, a log-wind speed cloud cover interaction, preceding 12 h solar radiation and the base temperature at Wisley. The percentage variance accounted for by the model was 68.5%. We hypothesised that the same set of meteorological variables that explained the Wisley/St James' Park UHI might also explain the estimated night-time UHI temperature difference between Kensington Gardens and a fixed distance along Gloucester Terrace. Three hundred metres was chosen for this fixed distance as, on almost all nights, there was no observable cooling from Kensington Gardens beyond this distance (see Section 3.3). All parameters namely, wind speed (log-transformed), cloud cover, a log-wind speed cloud cover interaction, earlier daytime radiation and the base temperature at Wisley remained significantly important in explaining the Kensington Gardens/Gloucester Terrace UHI effect. The model accounted for 82.6% of the variance in this dataset with parameters differing in size but not sign relative to the Wisley/St James' Park model.

The relationship between the Wisley/St James' Park UHI model and the Kensington Gardens/Gloucester Terrace UHI model is shown in Fig. 6. There is a strong positive correlation between the UHIs observed at the two spatial scales. The UHI effect between Kensington Gardens and Gloucester terrace is estimated to be 45% of the UHI effect between Wisley and St James'. For example, if St James' Park (and equally Kensington Gardens) is 5 °C warmer than Wisley then 300 m along Gloucester Terrace would be expected to be 2.25 °C warmer than Kensington Gardens and the UHI effect for 'non-greenspace' London is actually 7.25 °C not 5 °C. This result suggests that previous studies that have estimated London's UHI effect by comparing temperatures between Wisley and St James' Park (see for example, Wilby, 2003; Greater London Authority, 2006) have underestimated 'urban' heat island intensity and values could be in the region of 45% higher (as the greenspace is reducing the UHI effect by 31% and this percentage reduction is constant whatever the UHI value).

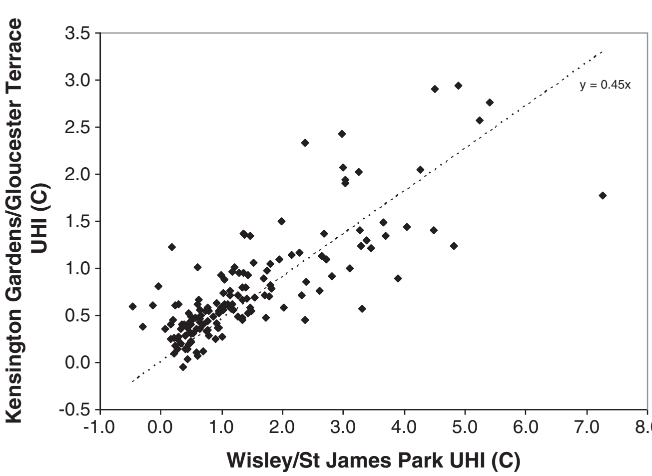

Fig. 6. Correlation between the Wisley–St James UHI model and the Kensington Gardens–Gloucester Terrace UHI model.

4. Discussion

4.1. Urban heat islands, greenspaces and urban cooling

Data presented in this study adds to the evidence that suggests that London's heat island displays diurnal and seasonal variability and is a predominantly nocturnal phenomenon. Our study has also demonstrated that hourly heat island intensity values may exceed 10 °C on individual nights. This is significant because of its implications for the thermal comfort of London's residents and because climate change projections for a warmer south-eastern England will further exacerbate the situation. Urban climate adaptation strategies typically include increased urban greening as a major component (see for example: Greater London Authority, 2010) and hence it is important to understand the role of putative components of such strategies to ensure that they work in an effective and complementary manner.

Research suggests that greenspaces have a cooling influence on their surrounding built-up area and that the extent of the cooling effect is larger for larger greenspaces (see for example Saito et al., 1990; Givoni, 1998; Ca et al., 1998; Upmanis et al., 1998; Jauregui, 1991). The average size of the cooling boundary observed within our study, however, is smaller than that observed for similar sized greenspaces: 1.5 °C to ca. 1 km distance around the 60 ha park in Tama New Town, Japan (Ca et al., 1998) and 4 °C to 775 m around the 156 ha park in Goteberg, Sweden (Upmanis et al., 1998). And while comparable to the 3 °C cooling influence that extended 200 m around Hyde Park (including Kensington Gardens; Chandler, 1965) it is smaller than the maximum 1.1 °C of cooling extending 200 to 400 m around the 50 ha park in Primrose Hill, London (Watkins, 2002). The higher density of sensors used along our Gloucester Terrace transect (eleven sensors along 340 m) in comparison to 3 sensors over 450 m in Watkins (2002) transect perhaps allowed for a more accurate quantification. However, a more likely explanation for this discrepancy is the comparison of a 13 h study (Watkins, 2002) and our 5-month study. Watkins reported undertaking their observations on a sunny day when the contrast in temperature between the air in the park and the air outside would be at it's highest (Watkins, 2002, pg 119). On equivalent days in our study, the cooling influence extended as far as 350 m, a distance comparable to that reported by Watkins (2002). Interpolation over smaller distances also enabled us to map, with confidence, an exponential decay in cooling with increased distance (Fig. 3). Our results show the importance of evaluating the cooling effect of greenspaces over a number of days, ambient temperatures, and weather conditions in order to enable appropriate cross-study comparisons and to demonstrate the full range in a greenspace cooling effect.

Studying small (up to 1.1 ha) urban green areas with trees in Tel-Aviv, Shashua-Bar and Hoffman (2000) reported a 'buffer zone' outside a green area's boundaries at which the cooling process effect starts. These buffer zones ranged in distance from 4.5 to 10.4 m. As our study site is much larger (111 ha) than those of Shashua-Bar and Hoffman (2000) a larger boundary zone could be expected, though none was detected and experimental design is likely to be a constraining factor. The minimum distance between Kensington Gardens and the Gloucester Terrace transect was 70 m. To establish whether a buffer zone exists around Kensington Gardens, the transect would need to start closer, say 10 to 20 m from the boundary, and employ a higher frequency of sensors over the first 100 m.

For Eq. (2), parameter r is equivalent to the decay rate reported by Shashua-Bar and Hoffman (2000) (see Section 3.3). Shashua-Bar and Hoffman (2000) reported an average decay rate of 0.02313; r is therefore calculated as 0.977. In our study, r was determined for each day of the study and averaged 0.986 (our decay rate is thus calculated as 0.0141). In order words, the cooling effect drops by an average of

2.3% per metre (100*(1–0.977)) in the study by Shashua-Bar and Hoffman (2000) and 1.4% per metre in our study. The discrepancy is to be expected because the cooling effect depends on the size of the greenspace, its orientation and its configuration (Shashua-Bar and Hoffman 2000) and, as noted above, Kensington Gardens is a much larger greenspace. Interestingly, Shashua-Bar and Hoffman (2000) calculate that for the 500 ha Chapultepec Park (see Jauregui, 1991) the rate of change in cooling factor (parameter r) is 0.986, the same value as calculated for parameter r in this study and indicates that a higher proportion of the cooling effect maintained per metre moved away from a large greenspace than from a small green area.

The size of the cooling boundary around a greenspace reportedly approximates to the width of the greenspace (Jauregui, 1991; Spronken-Smith, 1994; Upmanis et al., 1998). Given that Kensington Gardens ranges ca. 800 to 1100 m in width such a hypothesis is not supported by the findings of our study. Indeed, with respect to their potential to cool the urban environment, Kensington Gardens and Hyde Park could be considered as one large 253 ha greenspace (approximately 2500 m by 1000 m) separated only by The Serpentine and The Long Water (one contiguous stretch of water; see Fig. 1). Assuming an equal 125 m cooling effect on all sides of the greenspace, a total of 91 ha is cooled beyond the site boundaries, or 36% of the area of Kensington Gardens and Hyde Park. Furthermore, using the average value for parameter r as 0.986, only 41% of the total cooling effect (100*(0.986^63)) is experienced between the greenspace boundaries and 63 m distant (i.e. half of the 125 m average cooling distance). In other words, on average, 42 ha receive half of the average 1.1 °C cooling. This area would be reduced further after periods of extended warmth or drought as such conditions reduce the cooling effectiveness of greenspaces (Gill et al., 2013). When the maximum of 4.0 °C cooling is experienced, however, people living within these 42 ha would experience 2 °C cooler air temperatures than those living further from the greenspace and when r is at its maximum calculated value (0.997) 83% of the cooling is still experienced 63 m from the greenspace; these are sizeable levels of cooling with respect to human health. Further research is required in to the factors that determine r for a given size of greenspace.

Vidrih and Medved (2013) combine tree age and tree planting density into a specific dimensionless leaf area index LAI_{sp} to model the vegetation impact on a park's cooling effect relative to park size. The tree age and planting density of Kensington Gardens is approximately equal to Vidrih and Medved's $LAI_{sp} = 1.52$ indicating that the optimum size for this park in respect to urban cooling is 130 m width. While the model of Vidrih and Medved (2013) has not been tested for park widths >140 m, the putatively optimum size of 130 m and our above observations on the relatively small size of Kensington Garden's cooling boundary agree with recommendations for networks of small (2–3 ha) greenspaces for effective cooling of urban environments (Honjo and Takakura, 1991; Shashua-Bar and Hoffman 2000, 2003).

In the current study, the extent of the cooling boundary was noted to vary and modelling suggests that it extended to just 20 m on some days and in excess of 400 m on others. The extent of temperature reduction also varied, from 4.0 °C to 0.4 °C. A number of factors are implicated in governing the extent of UHI reduction by greenspace including the extent to which air is cooled within a greenspace, wind strength and direction, sky-view factor and the continuity of buildings and the size of the open areas in between (Chandler, 1965). For a greenspace to cool the surrounding neighbourhood, the air within the greenspace needs to be cooled (Yu and Hien, 2006) and the cool air needs to penetrate into the urban environment. Air within a greenspace tends to be cooler than in the surrounding environment because vegetation delivers several mechanisms of cooling simultaneously and in a complementary manner. These mechanisms: evaporative cooling, shading and reflectance, however are not cooling so much as warming less, viz. during evaporation (and evapo-transpiration) solar energy is used to convert water into vapour rather than warming the urban fabric; and shading and reflectance lead to less solar energy being absorbed and stored within the tree/urban fabric. Collectively, therefore, these mechanisms result in an overall reduction in the conversion of incoming solar energy to sensible heat and the air stays cooler than in the surrounding urban environment. The extent to which air is cooled (or rather, not warmed) in a greenspace depends also on its residence time within the greenspace and, hence, on wind speed. In light wind conditions, advection currents are set up as warm air in the streets rises drawing cool air from the park into the streets, causing cooling (Upmanis et al., 1998; Jansson et al., 2006). At higher wind speeds, these advection currents and the associated cooling effect of the park are disrupted (see below). UHIs and intense heat waves tend to form under anticyclonic conditions characterised by a stable air mass and low wind speeds (Wilby, 2003). Our data shows strong reduction of the UHI effect during low wind speeds and cooling over significantly greater distances on warmer nights suggesting that the cooling impact of greenspaces may in fact be strongest when it is most required. Given that the cooling effect of a greenspace extends in the direction of the prevailing wind (Oke, et al. (1989); Jauregui, 1991; Ca et al., 1998) and that our transect was not on the lee-side of Kensington Gardens relative to the prevailing south-westerly winds, the maximum extension of the cooling effect may in fact be greater than that observed in this study. However, this was not specifically tested for.

The cooling effect of Kensington Gardens was noted to all but disappear along the Gloucester Terrace transect at wind speeds greater than 2.3 m s^{-1}. This is lower than the 5 m s^{-1} wind speed reported by Brundl et al. (1986; in Upmanis et al., 1998) and the 6 m s^{-1} wind speed reported by Oke et al. (1989) and may be a function of street geometry. Oke et al. (1989) describes the air flow regimes associated with increasing aspect ratio and illustrates that for a street canyon with a 1:1 ratio, as in our study, a skimming flow regime sets up that leads to turbulent mixing across the full depth and width of the street canyon and mixing of the street canyon air with the faster winds aloft. If mixing was experienced to the full depth and width of the street canyon in this study it may help explain why the cooling effect dissipates at lower wind speeds than that reported by others; however, street canyon dimensions are not reported by Oke et al. (1989) and therefore further direct comparison was not possible.

Given the observed cooling effect of greenspaces, it is important when reporting the intensity of London's UHI that calculations are based upon 'urban' London not greenspace London. For example, in an analysis of the trends in London's UHI, Wilby (2003) acknowledged that temperatures within St James' Park differ from those in surrounding streets, although offered no values to indicate the strength of the influence of the greenspace. Our study provides empirical values to affirm Wilby's argument. London's UHI intensity is typically calculated using data from the Met Stations at St James' Park, Heathrow and Wisley (Wilby, 2003; Greater London Authority, 2006 and references therein). Our study used these stations to enable comparability to these previous works. The automated synoptic Met Office station at RAF Noltholt provides an alternative option to the Heathrow Met Station. However, also within the M25 and an airfield, and at approximately 5 miles NNE of Heathrow, we suggest that UHI intensity will be very similar whether calculated from Notholt or Heathrow data. Similarly, the Met Station at Kew Gardens offers an alternative option for the calculation of UHI intensity. Like St James', the Met Station at Kew is in a large park and calculation of the UHI intensity here would show variance in the UHI across Greater London. However, being approximately equidistant between Heathrow and St James' Park it cannot be considered rural or, therefore, a suitable alternative to the rural reference site at Wisley. Heat island intensity values are likely to be smaller if calculated from data obtained from Kew, rather than Wisley. The use of a small number of sites to represent the heterogeneous nature of the UHI across a city such as London is, therefore, subject to reservations. However, we suggest that the Met Stations used in this study are useful and representative for the purposes of this study.

4.2. Future considerations

Climate change projections of warmer and drier summer conditions will inflict particular stresses on urban vegetation that will significantly affect their vigour and appearance, as reviewed by Tubby and Webber (2010). For example, stress induced by drought combined with high temperature predisposes trees to attack by pests and diseases and expected changes in temperature and moisture availability will directly affect the development and survival of pests and diseases, their natural enemies, competitors and vectors (Tubby and Webber, 2010). Our data demonstrates that the extent of warming predicted for south-eastern England is already being experienced in London due to the UHI effect, and suggests that the implications of this warming, as considered by Tubby and Webber (2010), are already a threat to London's urban vegetation. The problem with respect to vegetative cooling of the UHI is that excessive defoliation reduces a tree's effectiveness at cooling through shading and evapo-transpiration (Tubby and Webber, 2010). While the increased use of drought-tolerant plants, such as Canary Island date palm (*Phoenix canariensis* hort. *ex* Chabaud), olive (*Olea europeae* L.) and holm oak (*Quercus ilex* L.), may be a wise precautionary measure in urban greening (Tubby and Webber, 2010), the impact of their use with respect to urban cooling merits investigation as trees with higher transpiration rates are more effective in urban cooling those that transpire less.

5. Conclusions

Our results support the inclusion of trees and greenspaces within holistic multifaceted city-level climate change adaption strategies. The extension of the cooling effect beyond the greenspace boundary was greatest during low wind speeds, as observed during the atmospherically stable conditions typical of a heat wave. The cooling impact of greenspaces thus appears to be strongest when it is most required. The factors that limit cooling boundary extension require further investigation. Given the temporal variability in the size of the cooling boundary, urban planners should seek to use small wooded greenspaces in preference to large open or grassed greenspaces and include wider forms of urban greening, including green roofs and cool pavements, in UHI mitigation strategies to ensure effective and widespread cooling.

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References

Bohnenstengel SI, Evans S, Clark PA, Belcher SE. Simulations of the London urban heat island. Q J R Meteorol Soc 2011;137(659):1625–40.

Bowler DE, Buyung-Ali L, Knight TM, Pullin AS. Urban greening to cool towns and cities: a systematic review of the empirical evidence. Landsc Urban Plan, 97(3). Elsevier B.V.; 2010. p. 147–55. [[Internet], Sep [cited 2013 May 21], Available from: http://linkinghub.elsevier.com/retrieve/pii/S0169204610001234].

Ca VT, Asaeda T, Abu EM. Reductions in air conditioning energy caused by a nearby park. Energy Build 1998;29(1):83–92.

Chandler TJ. The climate of London. London: Hutchinson & Co (Publishers) Ltd; 1965.

Chang C-R, Li M-H, Chang S-D. A preliminary study on the local cool-island intensity of Taipei city parks. Landsc Urban Plan 2007;80:386–95.

Davies M, Steadman P, Oreszczyn T. Strategies for the modification of the urban climate and the consequent impact on building energy use. Energy Policy 2008;36(12): 4548–51. [[Internet], Dec [cited 2013 May 27], Available from: http://linkinghub.elsevier.com/retrieve/pii/S0301421508004801].

Department for Environment Food and Rural Affairs. The UK Climate Change Risk Assessment 2012 — Evidence Report. Defra Project Code GA0204. London: Department for Environment, Food and Rural Affairs (Defra), London; 2012. p. 488.

Department of Health. Heatwave Plan for England. Protecting health and reducing from extreme heat and heatwaves, NHS Best Practice Guidance. NHS Best Pract. Guid. London: NHS (Department of Health); 2008. p. 32.

Gill S, Rahman MA, Handley JF, Ennos ARModelling water stress to urban amenity grass in Manchester UK under climate change and its potential impacts in reducing urban cooling Urban Forestry and Urban Greening 2013;12:350–8.

Givoni B. Impact of green areas on site and urban climates. Clim Considerations Build Urban Des. New York: J. Wiley and Sons; 1998. p. 303–30.

Greater London Authority. London's urban heat island: a summary for decision makers. London, UK: London Gt. London Auth; 2006 [[Internet], Available from: http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:London%E2%80%99s+Urban+Heat+Island:+A+Summary+for+Decision+Makers#0].

Greater London Authority. The draft climate change adaptation strategy for London. In: Mayor of London, editor. Public consultation draft; 2010. p. 138. [February 2010, London].

Health Protection Agency. Health effects of climate change in the UK 2012. In: Vardoulakis S, Heaviside C, editors. Current evidence, recommendations and research gaps. London: London: Health Protection Agency; 2012. p. 242.

Holden AA, Klene AE, Keefe RF, Moisen GG. Design and evaluation of an inexpensive radiation shield for monitoring surface air temperatures. Agric For Meteorol 2013;180: 281–6.

Honjo T, Takakura T. Simulation of thermal effects of urban green areas on their surrounding areas. Energy Build 1991;16(3–4):443–6. [[Internet], [cited 2013 Jun 27], Available from: http://www.sciencedirect.com/science/article/pii/037877889090019F].

Jansson C, Jansson P-E, Gustafsson D. Near surface climate in an urban vegetated park and its surroundings. Theor Appl Climatol 2006;89(3–4):185–93. [[Internet], Dec 21, [cited 2013 Jun 27], Available from: http://link.springer.com/10.1007/s00704-006-0259-z].

Jauregui E. Influence of a large urban park on temperature and convective precipitation in a tropical city. Energy Build 1991;15-16(3–4):457–63. [[Internet], [cited 2013 Jun 27], Available from: http://www.sciencedirect.com/science/article/pii/037877889090021A].

Mayer H. Results from the research program “STADTKLIMA BAYERN” for urban planning. Energy Build 1988;11:115–21.

Met Office. Annual 2011. London: Met Office; 2011 [[Internet], Available from: http://www.metoffice.gov.uk/climate/uk/2011/annual.html].

Meteorological Office UK. MIDAS Land Surface Stations data (1853-current). NCAS British Atmospheric Data Centre; 2012 [[Internet], [cited 2013 Jun 27]. Available from: http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_ukmo-midas].

Oke TR. Boundary layer climates2nd ed. 1987. p. 435 [Routledge, London].

Oke TR, Crowther JM, McNaughton KG, Monteith JL, Gardiner B. The Micrometeorology of the Urban Forest. Philosophical Transactions of the Royal Society B: Biological Sciences 1989;324(1223):335–49.

Oke TR. Initial guidance to obtain representative meteorological observations at urban sites. Instruments and Observing Methods Report No. 81. Geneva: World Meteorological Organization; 2004.

Saito I, Ishihara O, Katayama T. Study of the effect of green areas on the thermal environment in an urban area. Energy Build 1990;15(3–4):493–8. [[Internet], [cited 2013 Jun 27], Available from: http://www.sciencedirect.com/science/article/pii/037877889090026F].

Shashua-Bar L, Hoffman ME. Vegetation as a climatic component in the design of an urban street - an empirical model for predicting the cooling effect of urban green areas with trees. Energy and Buildings 2000;31:221–35.

Shashua-bar L, Hoffman ME. Geometry and orientation aspects in passive cooling of canyon streets with trees. Energy and Buildings 2003;35:61–8.

Smith CL, Webb A, Levermore GJ, Lindley SJ, Beswick K. Fine-scale spatial temperature patterns across a UK conurbation. Clim Chang 2011;109(3–4):269–86.

Spronken-Smith RA. Energetics and cooling in urban parks. Vancouver: The University of British Columbia; 1994. p. 204.

Spronken-Smith RA, Oke TR. The thermal regime of urban parks in two cities with different summer climates. Int J Remote Sens 2010;19(11):2085–104.

Stern N. The Stern review report on the economics of climate change. Cambridge: HM Treasury and Cambridge University Press; 2006 [[Internet], Available from: http://webarchive.nationalarchives.gov.uk/+/http://www.hm-treasury.gov.uk/stern_review_report.htm].

Taha HG, Akbari H, Rosenfeld AH. Vegetation canopy micro-climate: a field project in Davis, California. Lawrence Berkeley Laboratory Report No. 24593. Davis, CA: Davis, CA.: Lawrence Berkeley; 1988.

Tubby KV, Webber JF. Pests and diseases threatening urban trees under a changing climate. Forestry 2010;83(4):451–9.

Upmanis H, Eliasson I, Lindqvist S. The influence of green areas on nocturnal temperatures in a high latitude city (Göteborg, Sweden). Int J Climatol, 18(6). John Wiley & Sons, Ltd; 1998. p. 681–700. http://dx.doi.org/10.1002/(SICI)1097-0088(199805)18:6<681::AID-JOC289>3.0.CO;2-L [Internet].

Vidrih B, Medved S. Multiparametric model of urban park cooling island. Urban Forestry & Urban Greening 2013;12(2):220–9.

Watkins R. The impact of the urban environment on the energy used for cooling buildings. Dep. Mech. Eng. Sch. Eng. Des. London, UK: Brunel University; 2002. p. 247.

Watkins R, Palmer J, Kolokotroni M, Littlefair P. The London Heat Island: results from summertime monitoring. Build Serv Eng Res Technol 2002;23(2):97–106. [[Internet], [cited 2013 Jun 27], Available from: http://bse.sagepub.com/content/23/2/97.short].

Wilby RL. Past and projected trends in London's urban heat island. Weather 2003;58: 251–60.

Yu C, Hien WN. Thermal benefits of city parks. Energy Build 2006;38(2):105–20.