Keeping London a Cool Place to Be: The Role of Greenspace

Abstract

The term urban heat island (UHI) describes a phenomenon where cities are on average warmer than the surrounding rural area. Combined with the impacts of a changing climate, the assessment and mitigation of UHIs in the UK is important to the health and comfort of urban dwellers. Empirical data is required on the role of greenspaces in mitigating UHIs to inform predictions on cooling by urban greenspaces, guide urban planning and maximise the cooling of urban populations. We describe a five-month study to measure the spatial and temporal variability in air temperature across one of central London's large greenspaces (Kensington Gardens) and in two surrounding streets. Comparison of measured values with data from meteorological stations in St James Park, London and Wisley, Surrey was used to map the UHI across the study area and to determine the extent to which the greenspaces reduced UHI intensity. The results demonstrate that Kensington Gardens reduced UHI intensity by up to 6°C in the immediate vicinity of the greenspace. Statistical modelling showed that the cooling decayed exponentially with increased distance from the greenspace. The distance over which cooling was observed varied between modelled 24-hour periods, ranging from 20 to 300 m. The average cooling distance is in agreement with similar studies from outside the UK, although it is unclear which factors govern the extent to which cooling is observed. The results support claims that urban greenspace is an important component of UHI mitigation strategies.

Keywords:

green infrastructure,
parks,
trees,
urban cooling,
urban planning

Kieron J. Doick[1], Tony R. Hutchings[1] and Vicki Lawrence[1]

[1] Land Regeneration and Urban Greenspace Research Group, Forest Research, UK

Introduction

Cities frequently demonstrate higher mean average temperatures than surrounding rural areas, a phenomenon termed the 'urban heat island' (UHI) (Oke, 1987). The UHI is a result of the complex built environment (thermal properties, height and spacing of buildings), differences in land cover (including the lack of vegetation) and human activities (including emission of waste heat energy and air pollution) that lead to a very different energy balance in cities compared with the countryside (Oke, 1987). Larger, more populous cities tend to have a more intense UHI effect than cities with less densely grouped centres, although even small urban areas demonstrate the phenomenon. UHI intensity varies diurnally and seasonally (Watkins *et al*., 2002) and can be as much as 9°C in the UK (GLA, 2006).

Global temperatures are set to rise as a consequence of anthropogenic activities (Stern, 2006). Current climate change projections for south-eastern England are warming of 2.5-4°C by the 2080s (Davies *et al*., 2008; Defra, 2012). This is significant, because there is a direct impact of heat on human health. The Department of Health has identified threshold temperatures for each region within the UK that are detrimental to health when exceeded (DoH, 2008). The frequency of days with temperatures above these regional thresholds is set to increase under the changing climate predicted for the UK. Heat-related stress already accounts for *c*. 1,100 premature deaths and an estimated 100,000 hospital patient-days per year in the UK. Respiratory and cardiovascular diseases are particularly aggravated by high temperatures, thus the elderly and those who are already ill are particularly at risk. The Health Protection Agency (2012) reported that heat-related mortality will increase tenfold, to around 11,000 per year, by 2080. While London and the east and south-east of England are projected to be most vulnerable, excess deaths due to heat are also forecast to increase in the Midlands, Scotland and Wales (HPA, 2012).

The risks are greatest in large metropolitan areas such as London, Manchester and Birmingham (Defra, 2012).

The urban climate can be effectively modified by altering the amounts of heat energy absorbed, stored and transferred, and by adopting cooling strategies. Vegetation can be very effective, delivering several mechanisms of cooling simultaneously, namely, evaporative cooling, the reflecting of solar energy and shading. The surface temperature within a greenspace may be 15-20°C lower than that of the surrounding urban area, giving rise to 2-8°C cooler air temperatures and a cooling effect that extends out to the surrounding area (Saito *et al*., 1990; Taha *et al*., 1988). There are, however, few published examples of this cooling effect in the UK. In a study in 1963, Chandler (1965) compared the air temperature on a sunny day in Hyde Park with that in surrounding streets. He found a maximum contrast of 1.3°C and a cooling effect that extended up to 200 m (Chandler, 1965). Watkins (2002) reported that temperatures were on average 0.6°C cooler (maximum 1.1°C) in a 50 ha park in Primrose Hill, London than in the surrounding streets. The study was limited by its 13 -hour duration, however, and by the low distribution of monitoring stations, which resulted in the park's cooling influence being broadly estimated at 200-400 m.

There is a need for UK-based empirical data to demonstrate the cooling potential of trees and greenspaces in towns and cities. Such data would support the modelling of:

- the role of trees and greenspaces in mitigating the effects of UHIs
- the severity of the UHIs of cities across the UK under a changing climate
- tree survival in a changing climate and related work on the development of decision support tools for tree species selection for future planting in the urban environment
- the value of vegetation in reducing heat-attributable mortality.

Such data would also enhance the case for trees and greenspaces in the UK's urban environment at a time when large trees are being replaced with small ornamental varieties and budgets for the maintenance of urban trees are limited.

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

- measure and describe the hourly, daily and monthly temperature profile of one of central London's large greenspaces and surrounding streets
- determine the UHI intensity across the study area
- determine the extent to which the greenspace mitigates the UHI (magnitude of temperature reduction and distance cooled).

Methodology

Study Area

The study area was centred on Kensington Gardens in Central London, England. Covering an area of 111 ha, Kensington Gardens abuts Green Park (19 ha) and St James' Park (23 ha) and lies immediately to the west of Hyde Park (142 ha). Kensington Gardens contains lawns, tree-lined formal avenues, two large stretches of water – Long Water (4.9 ha) and the Round Pond (2.8 ha) – and several formal gardens containing fountains. Approximately one third is under tree-canopy cover.

Temperature Profiling

Air temperatures were was monitored using Lascar Temperature Data Loggers (model: EL-USB-1) purchased from Lascar electronics (Whiteparish, UK). The sensors have an operating range of -35 to 80°C, a stated accuracy of 31°C and monitor continuously (50 Hz).

The 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), the data loggers were housed in plastic boxes containing 14 ventilation holes and coated in self-adhesive reflective foil (Scotch™ Pressure Sensitive Tape by 3M) to minimise the effects of solar warming. The accuracy of the sensors in their housing units was tested at the Meteorological (Met) Office's synoptic weather station at Alice Holt, Surrey prior to the field monitoring campaign. The temperatures recorded by the sensors were accurate (≤4% error relative to the Met Station data) and precise (standard deviation ±0.5°C) at the temperature range investigated (0.5 to 26°C), and the sensors were therefore considered fit-for-purpose for the intended study.

A field study was conducted from 1st August to 28th December 2011. Air temperatures were recorded by mounting a sensor within its housing unit at eight locations across Kensington Gardens. Four sensors were mounted south facing in an area of open grassland; two on immature trees (*Tilia* species, diameter at breast height (DBH) 12 cm) and two on the bandstand. The other four were mounted on mature *Platanus* × *acerifolia* (London plane; DBH > 60 cm) trees along the glade known as Lancaster Walk. All were mounted using plastic cable ties at *c*. 2.5 m above ground level (Yu and Hien, 2006; Upmanis *et al*., 1998). This height allowed the sensors to be readily accessed for data collection while reducing the risk of theft or vandalism.

Temperature profiles were also monitored along transects in two streets radiating out from Kensington Gardens, namely, Gloucester Terrace and Queensway. Gloucester Terrace is an 'unclassified' road (residential street) situated to the north of Kensington Gardens with a north-west orientation away from the park. Twelve sensors were situated along Gloucester Terrace (Figure 1) with a configuration that enabled the following variables to be considered with respect to the air temperature recorded: north versus south side of street, street canyon versus end of street and lamp post (open position) versus street tree (shaded position). The sensors were mounted south facing at a height of *c*. 2.5 m. The Gloucester Terrace transect was 340 m in length. Queensway is situated to the north of Kensington Gardens and west of Gloucester Terrace. Queensway heads due north from the boundary of the Gardens. Sensors were mounted at a height of *c*. 2.5 m on lamp posts at 100, 200, 400 and 800 m distances from Kensington Gardens, avoiding factors such as street intersections and street trees to help ensure like-for-like comparison along this transect. Queensway is a 'B' category road. Every six weeks, data was downloaded, the battery replaced and the sensor memory cleared.

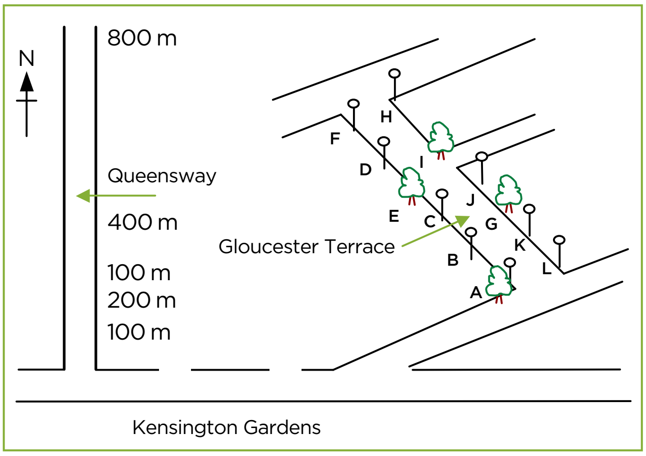

Figure 1: Schematic showing the location of the sensors along the Queensway and Gloucester Terrace transects relative to Kensington Gardens

UHI Evaluation

UHI intensity is defined as the difference between air temperatures measured in the urban space and those measured in the rural space surrounding it (Oke, 1987). UHI intensity is calculated as:

$$\text{UHI Intensity} = T_{(Urban)} - T_{(Rural)} \quad \text{(Equation 1)}$$

To determine the UHI intensity and its characteristics throughout the monitoring period, data was obtained for the Met Office's automated synoptic weather station at Wisley, Surrey (i.e., UHI intensity = $T_{(study\ area\ location)} - T_{Wisley)}$. 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. The Wisley data was obtained from the MIDAS Land Surface Stations 1853-current database, with permission from the British Atmospheric Data Centre (UK Meteorological Office, 2012). Data was also obtained from the Met Office's automated synoptic weather station at St James Park (City of Westminster, London) for the calculation of UHI intensity based upon Met Office data only (i.e., UHI intensity = $T_{St\ James} - T_{Wisley)}$. St James Park was selected as it is the nearest automated Met Office weather station to Kensington Gardens. Data for St James Park was also obtained from the US National Oceanic and Atmospheric Administration's National Climatic Data Centre (NCDC, 2012).

The cooling effect of Kensington Gardens on temperatures along Gloucester Terrace was modelled by fitting a standard non-linear model. It was hypothesised that an asymptotic model in the form of Equation 2 would describe the relationship between UHI intensity and distance. This is an exponential model with a final asymptote to reflect the diminishing cooling effect expected with increased distance from the gardens. Prior to modelling, 24-hour mean UHI intensity values were calculated from data collected at each point along the Gloucester Terrace transect and within Kensington Gardens. UHI intensity was calculated by subtracting the average air temperature recorded at Wisley over the matching time period. The model (Equation 2) was fitted to each 24-hour period within the study period (i.e., 148 nights; three November nights were omitted due to missing values) and collated using summary statistics. The effect of sensor position on a lamp post verses on a tree was also investigated by modelling the discrete datasets independently.

$t_i = a + lp + b.r_{distancei} + e_i$ (Equation 2)

where:

- t_i 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 lamp post rather than under a tree;
- b in combination with parameter a (namely a+b) estimates the temperature at Kensington Gardens, a distance of 0 m;
- r is the estimated rate of increasing temperature as one moves away from Kensington Gardens; and
- e_i is the error in the model estimate for sensor *i*.

Data Analysis

All statistical analyses, including the descriptive statistics, analysis of variance (ANOVA) and mathematical modelling, were undertaken in VSN International's Genstat 13 for Windows.

Results

Air Temperature

Air temperatures were recorded across Kensington Gardens and along two street transects between August and December 2011. The temperature profiles exhibited a biphasic pattern differentiating night and day (minimum and maximum temperatures recorded, respectively). The amplitude of the biphasic pattern varied with month. For example, in August, maxima were observed from 13h00 through to 16h00. In November and December, maxima were observed between 12 noon and 13h00 (data not shown). Minima were observed at *c.* 05h00-06h00 (August, September) and 07h00 (October, November, December; data not shown). The range in daily mean average air temperatures across Kensington Gardens, Gloucester Terrace and Queensway are presented in Table 1; the monthly average air temperatures are also provided. Statistically, i) the daily mean air temperature in Queensway was warmer than in Gloucester Terrace in all months ($p<0.01$; data not shown); ii) Gloucester Terrace was warmer than the grassland and tree-lined glade areas of Kensington Gardens in August, September and October ($p<0.05$; data not shown); and iii) during August and September, the grassland area was significantly warmer than the tree-lined area in Kensington Gardens ($p<0.05$; data not shown).

The 24-hour mean air temperatures recorded for the intersections were often cooler, but not significantly so, than within the street canyon (ANOVA-unbalanced design, $p>0.05$). For example, the 24-hour mean air temperature on 8th August was 16.7°C at intersection point L and 17.3°C within the street canyon. Similarly, the 24-hour mean air temperatures recorded on the north and south sides of the street were not found to be significantly different ($p>0.05$).

Table 1: Range of daily mean average air temperatures at the monitored locations, monthly average also shown

Month	Temperature (°C)					
	Kensington Gardens		Gloucester Terrace		Queensway	
Aug	14.3 - 23.0	(17.4)	14.7 - 23.7	(17.8)	14.3 - 24.3	(18.0)
Sept	11.9 - 21.1	(16.7)	12.5 - 22.2	(17.2)	12.2 – 22.9	(17.5)
Oct	7.9 - 21.3	(14.2)	8.6 - 22.6	(14.7)	8.1 - 23.0	(14.8)
Nov	6.9 - 15.5	(11.0)	7.5 - 15.8	(11.5)	7.5 - 15.7	(11.6)
Dec	2.3 - 11.8	(7.2)	2.8 - 12.2	(7.5)	3.0 - 12.7	(7.9)

Effect of Greenspace on the Urban Heat Island

To characterise the UHI, heat island intensity is often quoted. Variables that affect heat island intensity include location, weather, time of day and season. Thus, heat island intensity values require a qualifier, such as a frequency distribution or time interval. Hourly mean heat island intensity values, for example, are useful to demonstrate variability in the phenomenon, such as negative and positive values, whereas 24-hour mean values are invaluable when investigating the impacts of the UHI on human health. Figure 2 shows the range in hourly heat island intensity values for Gloucester Terrace for the month of August; the mean for each hour of the day is also shown. Values range from -3.6 to 5.2°C during the day and -0.2 to 7.5°C during the night (20h00 – 07h00). The mean values show that the heat island is, on average, positive (0.9°C day; 2.8°C night). The variability in the data is comparable for day and night (standard deviations: 1.4°C and 1.7°C, respectively). Figure 3 shows the variation in heat island intensity by time of day within Kensington Gardens, Gloucester Terrace and Queensway for the months of September, October, November and December. In each case, the heat island is positive and is more pronounced within the streets (Gloucester Terrace and Queensway) than in the greenspace (Kensington Gardens). Figure 3 also shows that in September, the heat island reached its maximum intensity by *c.* 20h00 then decreased gradually until *c.* 09h00. The heat island intensity was then observed to be variable until around 14h00 before starting to build again. In October, November and December, a peak in nocturnal UHI intensity is less apparent (Figure 3). The intensity of the UHI observed in October (Figure 3B) is a result of the record-breaking temperatures experienced in England during this time (peaking at 29.9°C in Kent, making it the warmest October on record; UK Met Office, 2011). Figure 4 presents the frequency distributions of daytime and night time heat island intensity in Gloucester Terrace (Figures 4A and 4B) and Kensington Gardens (Figures 4C and 4D) for the month of August. At both locations, the heat island was always positive at night and negative for up to 10% of the daytime. Furthermore, the heat island was more intense during the night: up to 8°C compared with up to 6°C during the daytime. Kensington Gardens, the study's greenspace, also demonstrated the influence of a UHI relative to the rural reference site, although the site was cooler than the surrounding streets and acted as a cooling source for those streets (see below).

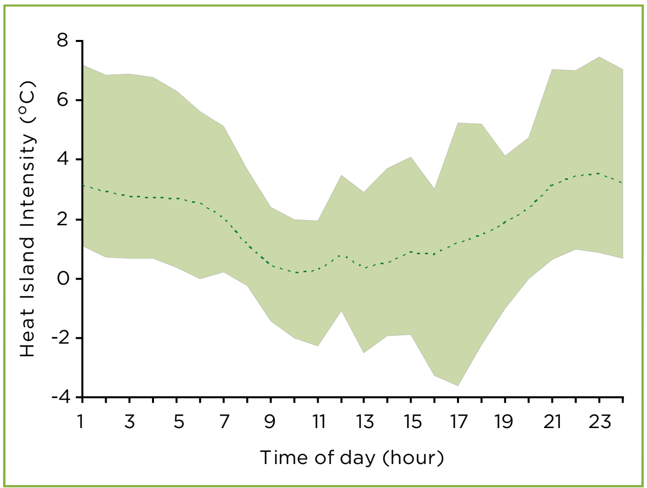

Figure 2: Average (dashed line) and range (grey-area) in UHI intensity in Gloucester Terrace by time of day for the month of August

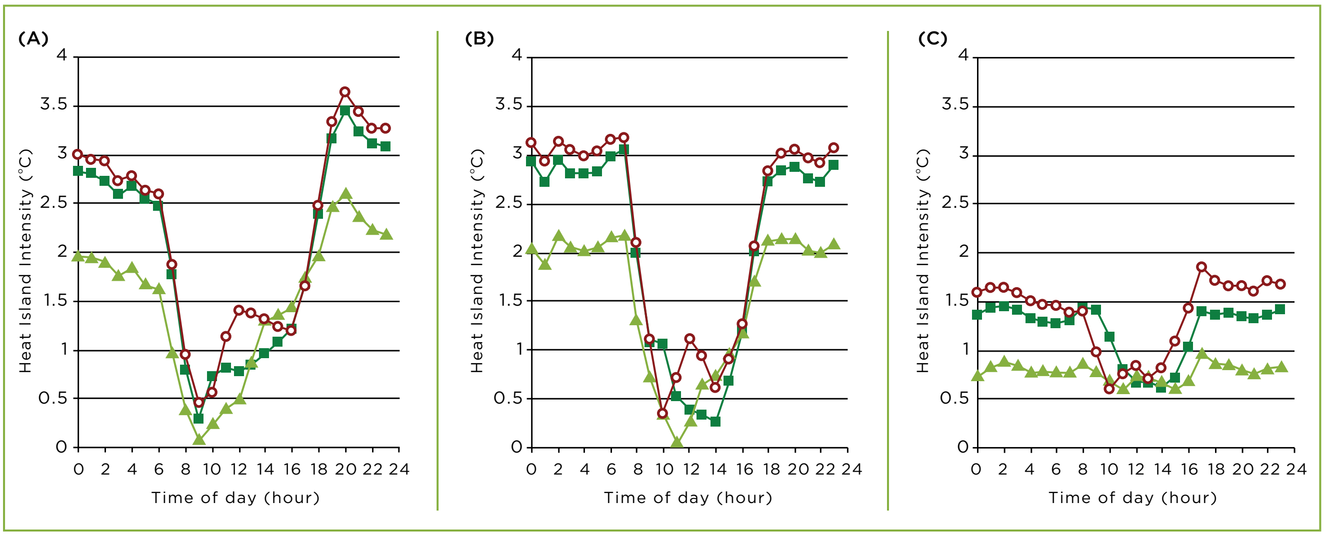

Figure 3: Variation in UHI intensity by time of day, average for A) September, B) October, C) November and December combined

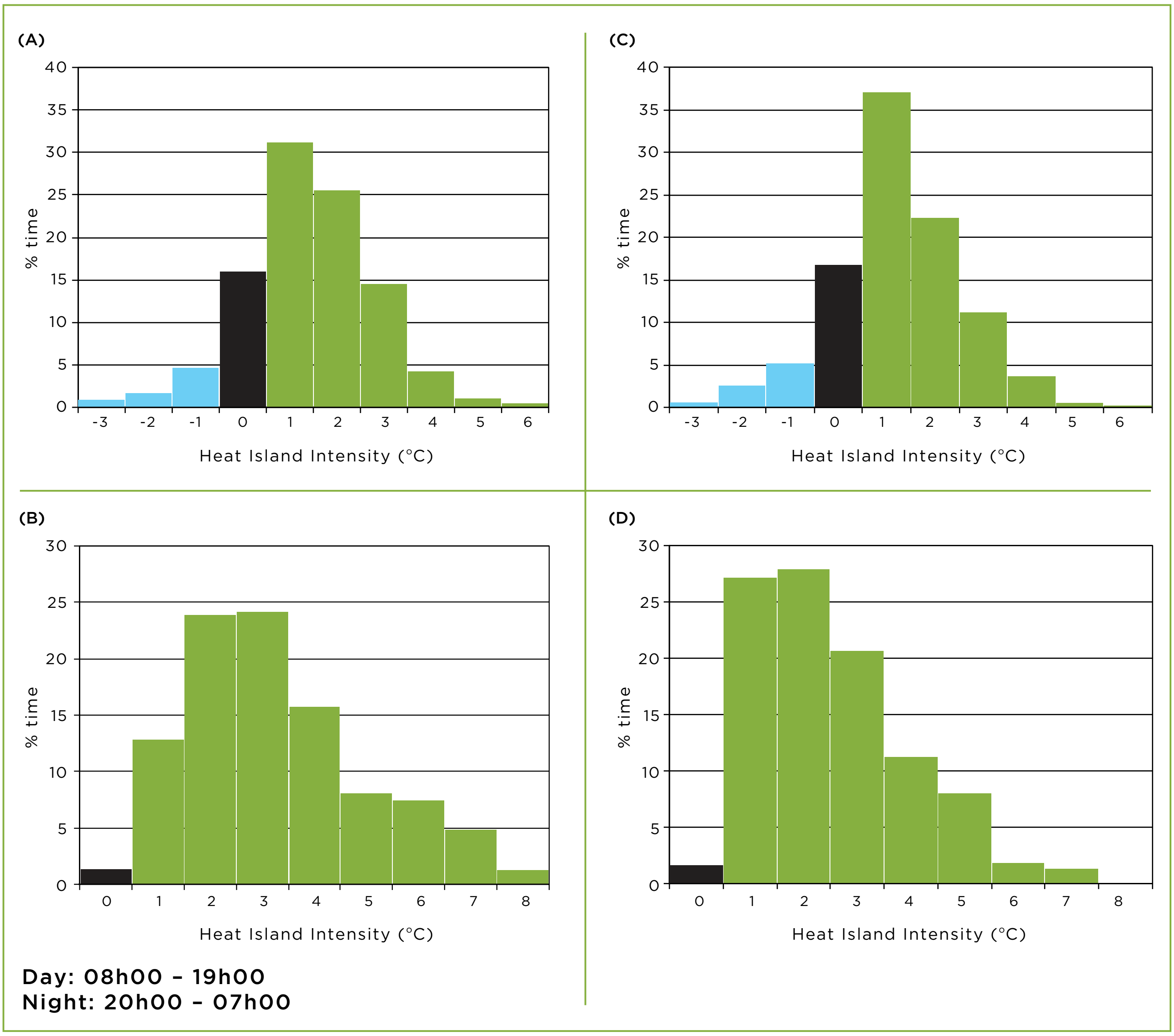

Figure 4: Frequency distribution of UHI intensity for the month of August within Gloucester Terrace and Kensington Gardens

Table 2 compares the UHI intensity at St James Park and across the study area. The largest maximum heat island intensity value observed for a single hour was +10.5°C in Gloucester Terrace and Queensway in October. The largest minimum heat island intensity value observed for a single hour was -5.4°C at St James Park in August (Table 2). The mean heat island intensity values were comparable between the two greenspaces in each month (e.g., 1.2°C in St James and 1.4°C in Kensington Gardens in August; Table 2). They were also comparable between the two streets (Table 2). Furthermore, heat island intensity observed in the two streets was significantly higher than in the two greenspaces in each month (ANOVA, $p<0.05$), with two exceptions. The UHI intensity in Kensington Gardens averaged 1.5°C in September and October and 2.0°C in Gloucester Terrace; however, the difference was not statistically significant in these months. Overall, the heat island intensity averaged +1-2°C across the study area throughout August, September and October (Table 2).

To investigate the cooling influence of Kensington Gardens, changes in the 24-hour mean heat island intensity along the Gloucester Terrace transect were investigated. It was hypothesised that the heat island would be less intense near Kensington Gardens. A non-linear model of exponential form was consistently found to account for more of the variability in temperature gain with increased distance from Kensington Gardens than a linear model. Two outcomes were prevalent in the model fitting exercise: i) all of the parameters were estimated to a good degree of precision and the convergence

Table 2: Comparison of UHI intensity at different locations

Heat Island Intensity	(°C)	St James	Kensington Gardens	Gloucester Terrace	Queensway
		Location			
August	Max	6.1	6.6	7.5	7.9
	Mean	1.2 a	1.4 a	1.8 b	2.1 c
	Min	-5.4	-3.4	-3.6	-4.1
September	Max	6.3	7.5	9.1	9.2
	Mean	1.2 a	1.5 a	2.0 b	2.2 b
	Min	-2.1	-2.1	-2.3	-2.1
October	Max	8.7	8.6	10.5	10.5
	Mean	1.3 a	1.5 a	2.1 b	2.2 b
	Min	-2.1	-2.3	-2.2	-2.2
November	Max	6.5	6.4	7.8	8.1
	Mean	0.8 a	0.9 a	1.4 b	1.6 b
	Min	-2.7	-2.1	-1.8	-1.8
December	Max	3.4	2.8	3.5	4.1
	Mean	0.6 a	0.6 a	0.9 b	1.1 b
	Min	-2.6	-1.9	-2.1	-1.1

Heat island intensity = T(location)–T(Wisley).
Values in rows (for Mean) followed by the same letter are not significantly different (ANOVA, p>0.05).

criterion of the model was met; the model fit was significant (p<0.01) and the coefficient of variation (CV) was < 30%; and ii) an imprecise asymptote was identified (CV > 30% for parameter *a*), the estimation of cooling effects was imprecise and the convergence criterion of the model fitting process was often not met. From the 148 nights modelled, an example of modelling outcome i) (all of the parameters estimated to good degree of precision) is shown in Figure 5B. An example of modelling outcome ii) (asymptote imprecisely identified) is shown in Figure 5A. Comparing only 24-hour periods where the asymptote could be predicted with a good degree of precision (i.e., modelling outcome i), the distance over which the gradient in UHI was evident varied between 20 and 300 m (mean: 185 m) and the maximum value of the gradient ranged from 0.3 to 6.5°C (mean: 1.9°C). In other words, the 24-hour

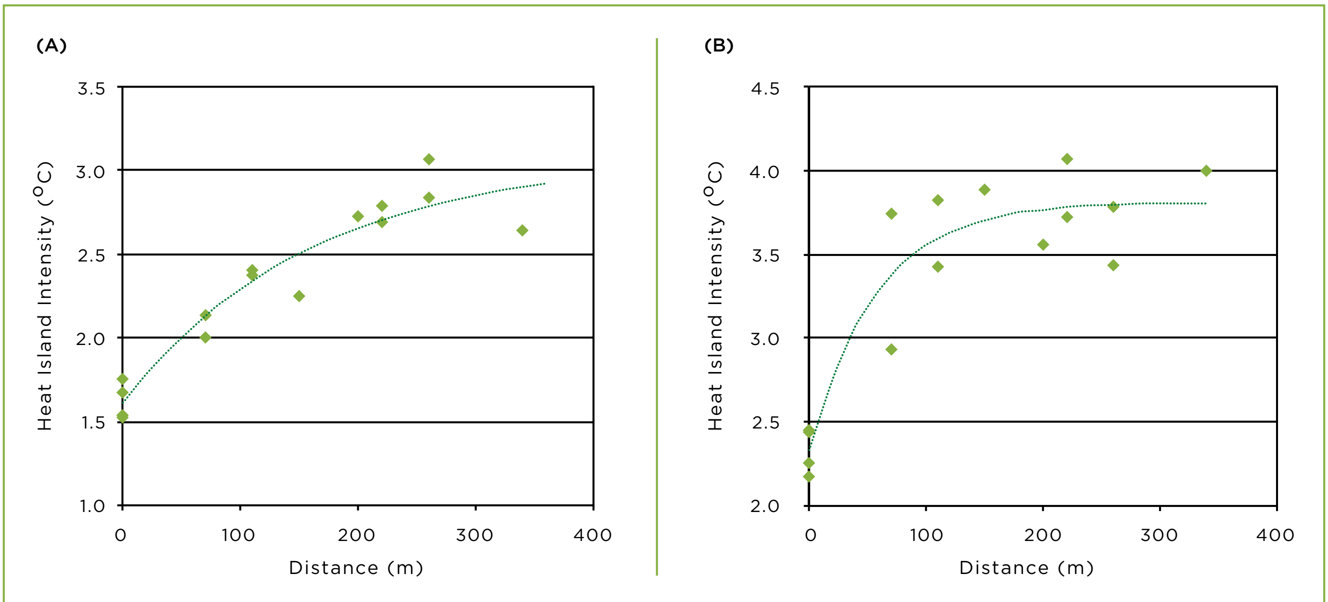

Figure 5: Variation in UHI intensity with distance from Kensington Gardens.

mean average heat island was 1.9°C more intense at a distance of 185 m from Kensington Gardens than within or immediately surrounding the greenspace.

A non-linear model of exponential form was fitted to investigate whether the temperature gain at a given position within Gloucester Terrace was statistically correlated to its position on a lamp post or under a tree. Temperature gain was assessed relative to the daily average air temperature in Kensington Gardens. The models demonstrated that i) the temperatures recorded by the sensors attached to street trees and lamp posts were warmer than those observed in the gardens, and the temperature difference was larger on warmer days relative to cooler days; ii) the temperatures recorded by the sensors on lamp posts were significantly warmer than those recorded by the sensors attached to trees, except when the absolute mean temperatures were low (8°C or less), in which case the temperatures recorded on lamp posts were marginally cooler than those under trees (i.e., it was warmer under the trees); and iii) for both lamp post and street tree positions there was a clear and significant ($p<0.001$) increase in temperature with increased distance from Kensington Gardens.

Discussion

Trends in London's Heat Island

The Gloucester Terrace transect was designed to enable the mapping of heat island intensity by considering factors putatively influential in air circulation and temperature control, namely, orientation and location. Data from intersection sensor H was unreliable and influenced by unknown variables: sometimes it was much cooler than nearby sensors and sometimes it was much warmer. Sensor H data was thus excluded. The height at which the sensors were placed (*c*. 2.5 m) may have been a compounding factor. In their London 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 may be commonplace at our sensor location H (a traffic-light controlled intersection). A working height of 2.5 m has previously been adopted by Yu and Hien (2006) and Upmanis *et al*. (1998).

A city's propensity to form a UHI is governed strongly by its size, density and built environment design. UHI intensity, however, is governed by synoptic weather conditions. As a consequence, inter-annual variations in heat island intensity may be substantial (Lee, 1992). Despite these variations, London has, like many cities, shown a progressive intensification of its heat island since the late 19th century (Chandler, 1964; Lee, 1992; Watkins *et al*., 2002). Watkins *et al*. (2002) reported that in the summer of 1999, London's heat island was approximately 0.8°C during the day and 2.5°C at night, exceeding 5°C on 10% of nights. Our study demonstrated that the summertime (August-September) heat island averaged 2.0°C in the streets (1.2°C daytime; 2.8°C night time) and 1.4°C (0.9°C daytime; 2.0°C night time) in Kensington Gardens, was greater for maxima (up to 9.2°C) than for minima (minus 5.4°C) and was zero or negative in the streets for 14-19% of the time (negative UHI intensity values are often referred to as the "cool island" effect). Given the inter-annual variability in heat island intensity our study cannot, on its own, demonstrate a long-term change in the intensity or prevalence of London's heat island. However, it does add to the literature and to the evidence that suggests that:

- London predominantly displays a heat island, rather than a cool island, effect
- London's heat island displays diurnal and seasonal variability
- the intensity of London's heat island may exceed 7°C on individual nights.

Taha *et al*. (1990) showed that heat islands can develop in pockets around single buildings, and that temperature differences of 4°C can develop along a single street. Such micro-environments vary by how much they exhibit characteristics of urbanisation in terms of increased heat capacity, reduced albedo and sky view, reduced vegetation and restricted air movement. In our study, Queensway demonstrated a heat island effect more frequently and occasionally more intensely than Gloucester Terrace (Table 1). Possible explanations for this observation include: i) Queensway is a major road in comparison to Gloucester Terrace. With a more substantial flow of traffic and many shops present, the mean anthropogenic heat emissions are likely to be higher in Queensway than in Gloucester Terrace. Higher volumes of traffic and higher anthropogenic heat emissions in Queensway support the formation of a more intense UHI (Santamouris, 1998, cited in Watkins, 2002). ii) Turbulent mixing is an important mechanism for urban cooling (Oke, 1987) and, as a consequence, the preferred orientation of streets for minimum solar heating in the northern hemisphere and maximum cooling by the wind is 45° to the prevailing wind (Coronel, 1997, cited in Watkins, 2002). Gloucester Terrace is orientated north-west–south-east. Buildings lining the street partially buffer the prevailing south-westerly winds and, as the wind travels over these buildings, lee-side eddies form. The ensuing turbulent mixing and dissipation of air cool along Gloucester Terrace would account for the reduced heat island. Queensway, by contrast, is not perpendicular to the prevailing wind and, as such, will experience less cooling by turbulent mixing. It is unclear from the present study whether the warmer temperatures in Queensway were caused by a stronger potential to form a heat island or because this street was cooled less, or a mix of both. Mapping the 360° cooling effect around Kensington Gardens using numerous transects radiating out from the greenspace and monitoring over an extended period of time to average out day-to-day weather effects would help to answer this question.

Greenspaces and Urban Cooling

Trees and the wider green infrastructure are recognised for their strong potential to regulate urban air temperatures and combat UHIs. The air temperature within a greenspace has been shown to be as much as 8°C cooler than in the surrounding urban area, and this can give rise to a cooling effect that extends out beyond the boundaries of the greenspace (Saito *et al*., 1990; Taha *et al*., 1988). Research suggests that the extent of the cooled urban area relates to the size of the greenspace.

- Small greenspaces: a 0.24-ha park in Kumamoto City, Japan cooled by 1-2°C for 20 m (Saito *et al*., 1990); and a 0.5 ha park in Haifa, Israel cooled by 1.5°C to 150 m (Givoni, 1998).
- Medium greenspaces: Watkins (2002) suggested that an average 0.6°C cooling effect extended 200-400 m around a 50-ha park in London, England; and Ca *et al*. (1998) reported that a 60-ha park in Tama New Town, Japan cooled surrounding air temperatures by 1.5°C to an approximately 1 km distance.
- Large greenspaces: the 156-ha Slottsskogen Park in Goteborg, Sweden cooled the surrounding air by 5°C for 175 m at sunset (Upmanis *et al*., 1998); and the 500-ha Chapultepec Park in Mexico City was reported to cool by 4°C to distances of up to 2 km (Jauregui, 1991).

Adding to the existing literature, our study provides evidence for the specific role of one large greenspace in providing localised relief from London's heat island, and suggests a reasonable level of agreement with other studies. The extent of cooling demonstrated in this study averaged 200 m around the 111-ha greenspace of Kensington Gardens. This distance is perhaps surprisingly small given the 200-400 m cooling boundary reported by Watkins (2002) around another London greenspace, but one that, at 50 ha, is less than half the size of Kensington Gardens. However, the study by Watkins (2002) was conducted over a period of *c*. 13 hours; our 200 m is an average observation, with cooling noted up to 300 m for 24-hour periods. Furthermore, the higher density of sensors used along the Gloucester Terrace transect (12 sensors along 340 m) compared with those in the transect of Watkins (2002) (three over *c*. 450 m) perhaps allows a more accurate quantification. Interpolation over smaller distances also enabled us to map, with confidence, an exponential decay in the extent of cooling with increasing distance from Kensington Gardens (Figure 5), a relationship not previously described in the scientific literature. The variability in the size of the cooling boundary observed in our study may also be an outcome of the position of the street transects relative to the greenspace, with a more conservative expression of the greenspaces' cooling influence observed on days for transects not on the lee-side of Kensington Gardens.

In the current study, the extent of the cooling boundary was noted to vary, extending to 20 m on some days and up to 300 m on others. A number of factors are implicated in governing the extent of cooling, including the continuity and height of buildings and the size of the open areas in between (Chandler, 1965). Wind strength is another contributory factor. This is important, because heat islands (and especially intense heat islands and heat waves) tend to form under anticyclonic conditions characterised by a stable air mass and low wind speeds. Our study showed that cooling was greater when mean ambient temperatures were higher, i.e., there is more cooling when it was needed the most and when wind speeds were low (< 5 mph). While the mechanics of this observation require further investigation, our study adds to the evidence that urban greenspaces are an important component of urban climate adaptation strategies.

Pests, Pathogens and Other Threats to Greenspace Vegetation in Heat Islands

Climate change projections of warmer and drier summer conditions and a forecast 2.5 to 4°C warming in the south-eastern UK by the 2080s (Defra, 2012) will inflict particular stresses on urban vegetation. Tubby and Webber (2010) report that 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. Models used in the production of climate change scenarios, however, are based upon a rural land use and do not predict changes to urban climates (GLA, 2006). Given that the data presented herein demonstrates that the UHI effect is already causing an average warming of 2°C, the stresses of a warmer climate highlighted by Tubby and Webber (2010) may be an imminent threat to urban vegetation. The excessive defoliation caused by some pests will reduce a tree's effectiveness at cooling through shading and evapo-transpiration. Furthermore, by demonstrating that the heat island is also prevalent through October, November and December, our monitoring programme shows that the UHI leads to reduced chilling of vegetation in urban locations compared with the rural reference location (Table 2). Periods of sufficiently long chill are essential for tree health and development, including for bud vernalisation (Broadmeadow and Ray, 2005). Further reductions in the period of chilling under a warming climate may pose an additional threat to the vitality of urban vegetation over and above those described.

In the UK, 80% of the population lives in conurbations. Rising temperatures and declining rainfall, which are likely to be a result of climate change, will increase the demands placed on the UK's urban greenspaces, as the favourable weather conditions will encourage people to lead a more outdoor lifestyle (Givoni, 1998). Enhanced drought summer conditions may also lead to increased demand for water for the irrigation of trees (to sustain health and promote evapo-transpirational cooling) and grass (to maintain function and aesthetic appeal). To help mitigate competition between existing demands and these new demands, greater adoption of sustainable forms of urban drainage, including green roofs and cool pavements, have been recommended (Davies *et al*., 2008). The high water permeability of cool pavements helps to maintain the soil moisture content, reducing the need to irrigate street trees and enabling evaporative cooling by trees to continue in drought periods without the need for irrigation. The loss of street trees due to drought-induced stress would be costly (for the replacement of trees) and lead to a reduction in cooling via evapo-transpiration and shading. The increased use of drought-tolerant plants, such as *Phoenix canariensis* (Canary Island date palm) and *Olea europeae* (olive) may be a wise precautionary measure in urban greening (Tubby and Webber, 2010). However, the quality of shade they offer and the quantity of evaporative cooling they provide is likely to be lower than those provided by the trees more traditionally seen in our towns and cities, as their canopies are sparser and their transpiration rates lower. The impact on urban cooling of using more drought-tolerant species merits investigation.

Large urban greenspaces offer a place of cool refuge within UHIs. By demonstrating that such places also cool the urban environment that surrounds them by an average of *c*. 2°C to a distance of 200 m, our results support the inclusion of trees and greenspaces within holistic multifaceted city-level climate change adaption strategies.

Acknowledgements

The authors thank the Royal Parks, the Royal Borough of Kensington and Chelsea and the City of Westminster for permitting the study on their land, the Forestry Commission for funding, Ros Bryant for fieldwork, and Andrew Peace and Paul Taylor for the statistical analyses.

References

Broadmeadow, M.S.J. and Ray, D. (2005) Climate change and British woodland. *Forestry Commission Information Note 69*. Forestry Commission, Edinburgh.

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

Chandler, T.J. (1964) City growth and urban climates. *Weather* 19, 170–171.

Chandler, T.J. (1965) *The Climate of London*. London, Hutchinson & Co (Publishers) Ltd.

Davies, M., Steadman, P. and Oreszczyn, T. (2008) Strategies for the modification of the urban climate and the consequent impact on building energy use. *Energy Policy* 36, 4548–4551.

Defra (Department for Environment Food and Rural Affairs). (2012) *The UK Climate Change Risk Assessment 2012 Evidence Report*. Defra, London.

DoH (Department of Health) (2008) *Heatwave Plan for England. Protecting Health and Reducing Harm from Extreme Heat and Heatwaves*. NHS Best Practice Guidance. NHS and Department of Health, London.

Givoni, B. (1998) Impact of green areas on site and urban climates. In: *Climate Considerations in Building and Urban Design*. J. Wiley and Sons, New York, pp. 303–330.

GLA (Greater London Authority) (2006) *London's Urban Heat Island: A Summary for Decision Makers*. Greater London Authority, London.

HPA (Health Protection Agency) (2012) *Health Effects of Climate Change in the UK 2012. Current Evidence, Recommendations and Research Gaps.* S. Vardoulakis and C. Heaviside (eds). Health Protection Agency, London.

Holden, A.A., Klene, A.E., Keefe, R.F. and Moisen, G.G. (2013) Design and evaluation of an inexpensive radiation shield for monitoring surface air temperatures. *Agricultural and Forest Meteorology 2* 180, 281–286.

Jauregui, E. (1991) Influence of a large urban park on temperature and convective precipitation in a tropical city. *Energy and Buildings* 15, 457–463.

Lee, D.O. (1992) Urban warming? – An analysis of recent trends in London's heat island. *Weather* 47, 50–56.

NCDC (National Climatic Data Centre) (2012) Available at: http://gis.ncdc.noaa.gov/map/cdo/ (accessed February 2012).

Oke, T.R. (1987) *Boundary Layer Climates*. 2nd Edition. Routledge, London.

Saito, I., Ishihara, O. and Katayama, T. (1990) Study of the effect of green areas on the thermal environment in an urban area. *Energy and Buildings* 15, 493–498.

Stern, N. (2006) *The Stern Review Report on the Economics of Climate Change*. HM Treasury and Cambridge Univeristy Press, Cambridge

Taha, H.G., Akbari, H. and Rosenfeld, A.H. (1988) *Vegetation Canopy Micro-climate: A Field Project in Davis, California. Lawrence Berkeley Laboratory Report No. 24593,* Lawrence Berkeley, Davis, California.

Taha, H.G., Akbari, H., Sailor, D. and Ritschard, R. (1990) *Causes and Effect of Heat Islands: The Sensitivity of Urban Microclimates to Surface Parameters and Anthropogenic Heat. Lawrence Berkeley Laboratory Report No. LBL-29864,* Lawrence Berkeley, Davis, California.

Tubby, K. V and Webber, J.F. (2010) Pests and diseases threatening urban trees under a changing climate. *Forestry* 83, 451–459.

UK Meteorological Office (2011) *Annual 2011*. Available at: http://www.metoffice.gov.uk/climate/uk/2011/annual.html (accessed February 2012).

UK Meteorological Office (2012) *MIDAS Land Surface Stations Data (1853-current).* Available at: http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_ukmo-midas (accessed: 27 June 2013).

Upmanis, H., Eliasson, I. and Lindqvist, S. (1998) The influence of green areas on nocturnal temperatures in a high latitude city (Göteborg, Sweden). *International Journal of Climatology* 18, 681–700.

Watkins, R. (2002) The impact of the urban environment on the energy used for cooling buildings. PhD thesis. Brunel University, London.

Watkins, R., Palmer, J., Kolokotroni, M. and Littlefair, P. (2002) The London Heat Island: results from summertime monitoring. *Building Services Engineering Research and Technology* 23, 97–106.

Yu, C. and Hien, W.N. (2006) Thermal benefits of city parks. *Energy and Buildings* 38, 105–120.