Past and projected trends in London's urban heat island

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The urban fabric of London and abundant domestic and industrial heat sources mean that the city creates its own microclimates. In common with many other large cities, the central, built-up area experiences fewer frosty nights and higher temperatures than the surrounding countryside due to an 'urban heat island' (UHI) effect (Chandler 1965; Lee 1992). For example, average peak temperature differences between the British Museum and a rural reference station in Langley Country Park (about 30 km to the west) were 3 degC over the summer of 1999 (Graves *et al.* 2001). Higher urban temperatures are of concern because they exacerbate summer heatwaves, leading to increased mortality amongst sensitive members of the population (Kunst *et al.* 1993; Laschewski and Jendritzky 2002) as evidenced by the summers of 1976 and 1995 (Rooney *et al.* 1998).

Detailed monitoring indicates that London's UHI is most pronounced at night, that it weakens with increasing wind speed and distance from central London, and that the location of the thermal maximum shifts with changes in wind direction (Graves *et al.* 2001). Figure 1 shows the diurnal cycle in UHI intensity at four sites with increasing distance from the British Museum along a westerly axis, compared with a reference station at Bracknell. The magnitude and timing of the nocturnal maximum UHI intensity at the two inner sites (Westminster and Hammersmith) clearly contrasts with the timing of the maximum at the two outer sites (Kew and Heathrow). At Westminster, the UHI attained a maximum intensity of over 7 degC by 0600 GMT, compared with less than 1 degC at Kew and Heathrow at the same time.

Temporal and spatial variations in the UHI reflect modifications to the radiation and energy balance at the earth's surface by the extensive urban and suburban landscape relative to more densely vegetated rural sites (Oke 1982, 1988). Building materials tend to store solar energy during the day, but have lower rates of radiant cooling during the night com-

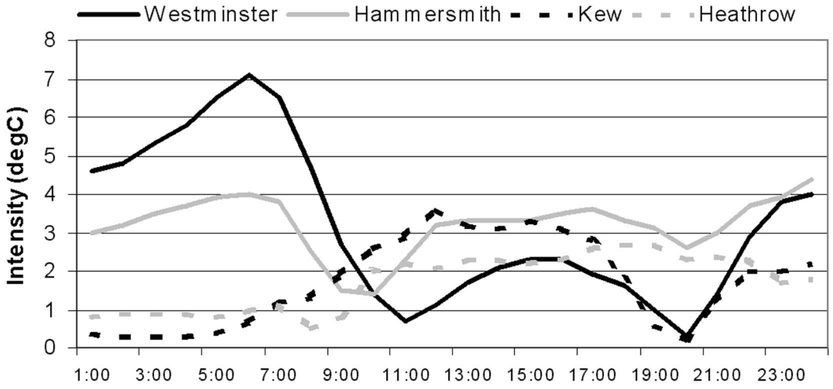

Fig. 1 Hourly variations in London's urban heat island intensity at selected sites with respect to Bracknell, during six days in July and August 1999 and 2000. The approximate distances from central London are: Westminster (~2 km), Hammersmith (~6 km), Kew (~13 km) and Heathrow (~26 km). All plots were generated from data supplied in Graves et al. *(2001).*

pared with rural areas. Lower levels of evapotranspiration from paved areas relative to soil and vegetation also mean that more net radiation is available for surface heating. Furthermore, urban canyons formed by tall buildings trap radiant energy in their walls. Comparisons of the UHI of European and North American cities suggest that the density and height of buildings are significant factors affecting the steepness of the urban–rural temperature gradient (Oke 1982). Dense urban structures also tend to reduce average wind speeds, modifying patterns of airflow over the city and reducing convective heat losses from buildings. Although urban air pollution can reduce solar radiation during the day, it absorbs and re-emits outgoing terrestrial radiation at night, thereby promoting higher nocturnal temperatures than in rural areas. Finally, there is anthropogenic heat production from a range of human activities such as space heating, air-conditioning, transportation, cooking, and industrial processes.

There has been renewed interest in the UHI of London because projected increases in solar radiation and decreasing cloud cover in summer over southern parts of the UK (Hulme *et al.* 2002) could favour the intensification of the UHI (ACChILES 2002). An intensified UHI could, in turn, compound the impact of heat-waves which are expected to increase in frequency and severity in a warmer world (Intergovernmental Panel on Climate Change 2001). This paper updates an earlier analysis of trends in London's UHI (Lee 1992), and investigates possible links between large-scale atmospheric circulation and humidity, and the UHI gradient. These relationships are then used to project changes in London's nocturnal UHI under two greenhouse-gas emission scenarios. Selected mitigation and policy implications are then considered in the concluding section.

Data and methods

Following Lee (1992), maximum (T_{max}) and minimum (T_{min}) temperatures were obtained for two sites indicative of rural (r) and urban (u) conditions. St. James's Park (Westminster) was used to represent temperatures in central London, and Wisley (32 km to the south-west of London) was chosen as the rural 'control'. This choice was based largely on the homogeneity and consistency of available records (Lee 1992). However, it is acknowledged that temperatures within St. James's Park differ from those in surrounding streets, and that the site is not located in the area that normally experiences the maximum UHI (Graves *et al.* 2001). Furthermore, urban–rural comparisons involving just two sites provide little indication of spatial variations in UHI characteristics (see Chandler 1965). In fact, recent monitoring has highlighted the mobility of the peak in relation to hourly shifts in wind direction; the thermal centre typically moves by several kilometres in line with the change in wind direction, but during August 1999 was located approximately 2.5 km south-east of the British Museum (Graves *et al.* 2001). This implies that data for St. James's Park will provide a conservative estimate of the UHI intensity.

In the original analysis, Lee (1992) employed monthly means of daily maximum, minimum and mean temperatures for the 28-year period 1962–89. In the present study, nocturnal (daytime) UHI intensity is estimated for every day in the 40-year period 1959–98 by subtracting daily T_{min} (T_{max}) at Wisley from daily T_{min} (T_{max}) at St. James's Park. Second, average values of the resulting nocturnal, $\Delta T(u\text{–}r)_{\mathrm{min}}$, and daytime, $\Delta T(u\text{–}r)_{\mathrm{max}}$, temperature gradients were calculated for each month. The number of days with $\Delta T(u\text{–}r)_{\mathrm{min}}$ and $\Delta T(u\text{–}r)_{\mathrm{max}}$ >4 degC were also counted in each year (as an arbitrary index of the most intense UHI episodes). Third, linear trends were fitted to the annual means of $\Delta T(u\text{–}r)_{\mathrm{min}}$ and $\Delta T(u\text{–}r)_{\mathrm{max}}$ to determine average decadal rates of change by season. Fourth, correlation analysis was used to explore the association between daily variations in $\Delta T(u\text{–}r)_{\mathrm{min}}$ and $\Delta T(u\text{–}r)_{\mathrm{max}}$ and indices describing the circulation, thickness, and moisture content of the atmosphere at three levels (surface, 850 mbar and 500 mbar) over eastern England. All atmospheric variables originated from the National Centers for Environmental Prediction re-analysis dataset (Kalnay *et al.* 1996), but were processed to conform to a 2.5° latitude × 3.75° longitude grid box (Wilby and

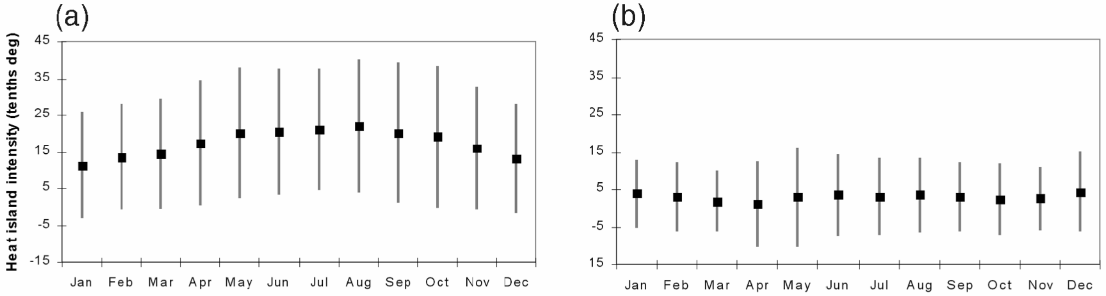

Fig. 2 Monthly variations in (a) nocturnal urban heat island (UHI) intensity calculated from minimum daily temperatures, and (b) daytime UHI intensity calculated from maximum daily temperatures, at St. James's Park minus those at Wisley, 1961–90. Vertical lines indicate ± 1 standard deviations.

Dawson 2001). Finally, the strongest associations were used as the basis for a multivariate statistical model of the nocturnal UHI.

Historical trends

In midlatitude regions UHIs are generally stronger in summer than in winter because of higher levels of solar energy absorbed by building materials during the day and subsequent nighttime radiation. The UHI is also more marked at night (see Fig. 1) because reduced nocturnal turbulent mixing keeps the warmer air near the surface. Conversely, the urban–rural contrast is generally weaker during winter because solar energy absorption is lower and hence there is less energy to radiate, despite higher levels of anthropogenic space heating. The net effects of these physical processes are clearly evident for London's monthly average $\Delta T(u{-}r)_{\mathrm{min}}$ and $\Delta T(u{-}r)_{\mathrm{max}}$ (Fig. 2). The nocturnal UHI is on average strongest in August (+2.2 degC) and weakest in January (+1.1 degC), although there is considerable daily variability within any given month (as denoted by the standard deviations). In contrast, the seasonal pattern and intra-month variability of London's daytime UHI is less marked, with average $\Delta T(u{-}r)_{\mathrm{max}}$ being greatest in December (+0.4 degC) and least in April (+0.1 degC).

Differences in the behaviour of the nocturnal and daytime UHI are also apparent from annual trends (Fig. 3). Despite considerable interannual variability, the strength of the nocturnal UHI is consistently greater than that of the daytime, and this difference has increased in all seasons except winter. The decadal average rate of change in the nocturnal and daytime UHI and accompanying significance levels are shown in Table 1. The most rapid intensification of the nocturnal UHI has occurred in spring and summer with changes averaging +0.13 degC/decade and +0.12 degC/decade respectively. Conversely, the most significant change in the daytime UHI has been the reduction in winter of 0.081 degC/decade.

The UHI changes shown in Fig. 3 and Table 1 reflect relative rates of change in temperatures at St. James's Park and Wisley. Although nocturnal warming was greatest in winter, Table 2 indicates that the rate of warming was slightly greater at Wisley than St. James's Park, resulting in a net weakening of the nocturnal UHI intensity during this season (see Fig. 3). Daytime warming in winter (and in autumn) has also been more rapid at Wisley than St. James's Park, but less rapid in spring and summer. This could be a historical artefact of lower concentrations of air pollution in winter at the rural site, allowing higher levels of daytime solar radiation receipt and hence more rapid warming (see Wilby and Tomlinson 2000). Conversely, spring, summer and autumn nocturnal warming was more rapid in central London than at the rural site. This was attributed to the presence of polluted air in the urban atmosphere, absorbing then re-emitting outgoing terrestrial radiation during the night (Lee 1992). Greater use of air-conditioning may be a factor in recent decades.

Trends in the average nocturnal and daytime UHI intensity affect the annual frequency of occurrence of the most extreme urban–rural temperature differences. Figure 4 shows the

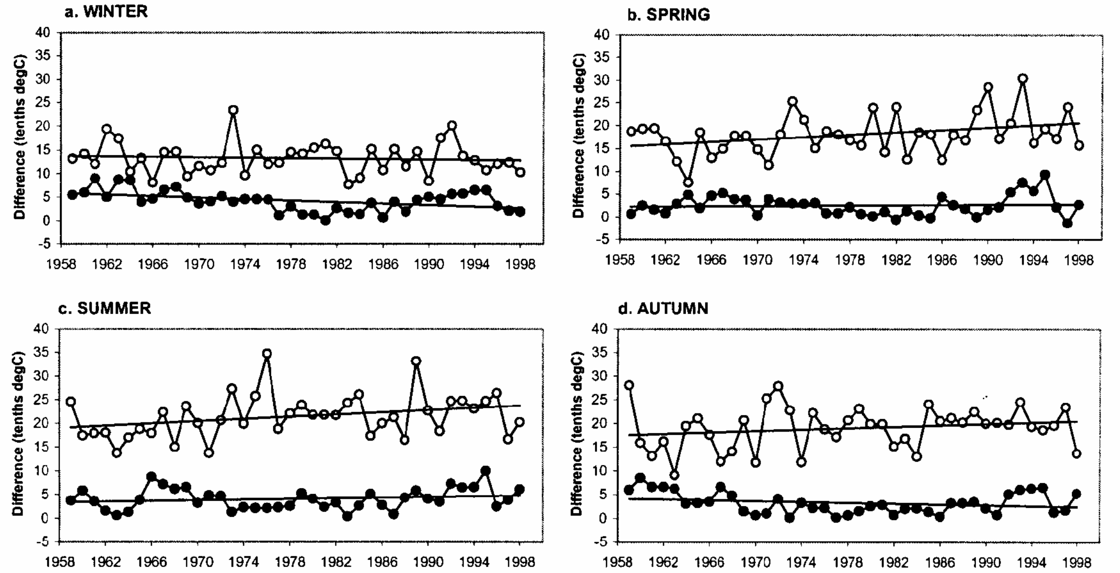

Fig. 3 Seasonal trends in urban heat island intensity calculated from T_{max} *(solid circles) and* T_{min} *(open circles) at St. James's Park minus Wisley, 1959–98*

Table 1 Seasonal trends in daily urban heat island (UHI) intensity, 1959–98

Season	UHI (degC/decade) Nocturnal ($\Delta T(u\text{–}r)_{\min}$)	UHI (degC/decade) Daytime ($\Delta T(u\text{–}r)_{\max}$)
Winter	–0.023†	–0.081**
Spring	+0.131**	+0.015†
Summer	+0.120**	+0.036*
Autumn	+0.077*	–0.046*

†Not significant, *significant at $p = 0.05$, **significant at $p = 0.01$.

number of days per year with nocturnal or daytime UHIs >4 degC. Intense UHIs occurred on average on 10.4% of nights compared with on 0.4% of days. However, intense nocturnal events were most frequent in August/September (15.9%) and least common in January/February (4.1%). Conversely, intense daytime events were slightly more common in December/January (0.6%) than in June/July (0.2%). Overall, the annual frequency of intense nocturnal UHIs has increased by 4.4 days/decade since the 1960s.

Synoptic controls

Changes in London's UHI may be linked to variations in the synoptic conditions favourable to UHI development. Table 3 shows the strongest correlations between London's nocturnal UHI intensity, $\Delta T(u\text{–}r)_{\min}$, and daily synoptic indices for eastern England over the entire year, in winter (December to February) and in summer (June to August). Note that equivalent results are not presented for the daytime UHI as the strength of the correlations was very low in most instances.

Table 2 Seasonal temperature trends at each site, 1959–98

Season	$T_{\min}$ (degC/decade) St. James's	$T_{\min}$ (degC/decade) Wisley	$T_{\max}$ (degC/decade) St. James's	$T_{\max}$ (degC/decade) Wisley
Winter	+0.347**	+0.379**	+0.400**	+0.484**
Spring	+0.208*	+0.078†	+0.236*	+0.213*
Summer	+0.308**	+0.189**	+0.351*	+0.319*
Autumn	+0.256**	+0.063†	+0.093†	+0.114†

†Not significant, *significant at $p = 0.05$, **significant at $p = 0.01$.

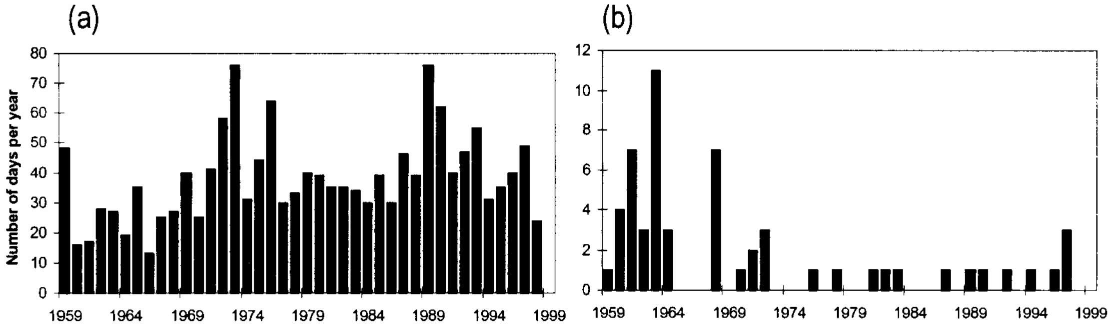

Fig. 4 Annual frequency of days between 1959 and 1998 with (a) nocturnal and (b) daytime temperature difference between St. James's Park and Wisley >4 degC

Table 3 Strongest annual, winter and summer correlations (R) between London's nocturnal urban heat island and synoptic indices for eastern England, 1961–90

Predictor	Description	Annual R	Winter R	Summer R
FSUR	Near-surface wind strength	–0.40	–0.32	–0.38
F850	Wind strength at 850 mbar	–0.38	–0.31	–0.33
H850	850 mbar geopotential height	+0.36	+0.24	+0.41
MSLP	Mean sea-level pressure	+0.35	+0.28	+0.41
RSUR	Near-surface relative humidity	–0.35	–0.18	–0.37
ZSUR	Near-surface vorticity	–0.33	–0.28	–0.36
H500	500 mbar geopotential height	+0.31	+0.13	+0.34
Z850	Vorticity at 850 mbar	–0.30	–0.24	–0.39
U850	Westerly wind at 850 mbar	–0.28	–0.28	–0.27
F500	Wind strength at 500 mbar	–0.28	–0.22	–0.24
USUR	Near-surface westerly wind	–0.27	–0.23	–0.27
U500	Westerly wind at 500 mbar	–0.26	–0.28	–0.21
TEMP*	Mean daily temperature at 2 m	+0.15	–0.27	+0.21

*Results for TEMP are provided for comparative purposes only. All correlations are significant at $p = 0.01$.

Over the year as a whole, the nocturnal UHI is most negatively correlated with the near-surface wind strength (FSUR) and wind at 850 mbar (F850), supporting the view that the UHI requires stable air conditions and is weaker under stronger regional airflows. The negative correlation with the near-surface relative humidity (RSUR) is probably indicative of a weakening associated with greater cloud cover/ lower solar radiation receipt. The strengths of the westerly components of wind at the surface, 850 mbar and 500 mbar (USUR, U850, U500) were also negatively correlated with UHI intensity. Conversely, the only positive correlations were with 850 mbar geopotential height (H850), 500 mbar geopotential height (H500) and mean sea-level pressure (MSLP), indicating a stronger UHI under high pressure systems. The weak positive association with the near-surface average daily temperature (TEMP) across eastern England shows that regional temperatures are relatively poor indicators of London's nocturnal UHI intensity.

Correlations between atmospheric circulation and the nocturnal UHI are generally stronger in summer than in winter. Again, the mean sea-level pressure (MSLP) and near-surface wind strength (FSUR) figure prominently in both seasons. Figure 5 shows the nature of the association between these two indices and the nocturnal UHI during the hot, dry summer of 1995. The vertical axis shows the UHI intensity (in tenths of a degree Celsius), the horizontal axes show each synoptic index normalised by their respective long-term mean and standard deviation. Although the plots suggest that the intensity is greater under conditions of high pressure and low wind speeds (*i.e.* anticyclonic weather), there is considerable scatter. This is partly due to controls exerted by the other vari-

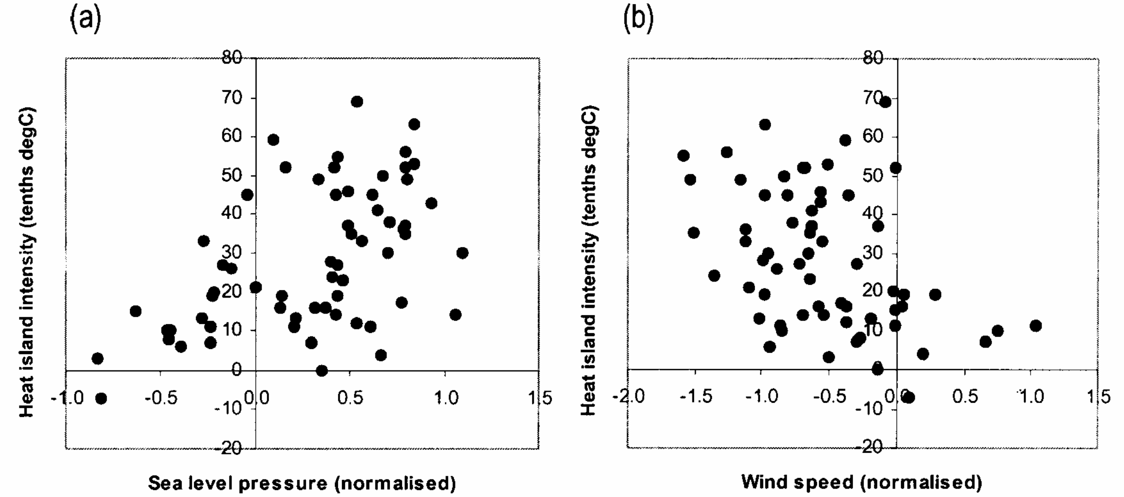

Fig. 5 Relationship between London's nocturnal urban heat island intensity and (a) mean sea-level pressure, and (b) wind speed, July to August 1995

ables listed in Table 3, and local meteorological factors that cannot be resolved at the temporal and spatial scale of the eastern England grid box (*e.g.* local cold air drainage from surrounding valleys (Eliasson 1996; Kuttler *et al.* 1996)).

UHI model

The final stage of the analysis involved the development of robust multivariate statistical models of the nocturnal UHI (Wilby *et al.* 2002). A step-wise multiple linear regression procedure was used to relate daily variations in the nocturnal UHI intensity, $\Delta T(u\text{–}r)_{\mathrm{min}}$, to daily variations in the most strongly associated atmospheric variables. For each month, the procedure begins with the strongest predictor variable and then incrementally includes additional predictors until a cut-off statistic is achieved. Unexplained behaviour was represented by the addition of a random component which yields UHI variability that better matches observations. The model was trained against daily $\Delta T(u\text{–}r)_{\mathrm{min}}$ for the period 1961–90, and evaluated against data for the period 1991–98.

The most robust statistical model was based on just five atmospheric variables: the near-surface wind strength (FSUR), westerly wind strength (USUR), vorticity (ZSUR), relative humidity (RSUR) and 850 mbar geopotential height (H850). This combination of predictors yielded correlation coefficients as high as $R = +0.6$ (August) for observed versus modelled nocturnal UHI. For example, Fig. 6 compares the observed and modelled daily UHI intensity during the summer of 1995. It is apparent that the model correctly emulated the short-lived UHI peak in early May, and the longer episode from mid-July to mid-August.

A notable deficiency of the model was the overestimated frequency of low or negative UHI intensities. This is clearly evident when the distributions of observed and modelled intensities are compared for data not previously used in model calibration (Fig. 7). The modal class of the model is also slightly warmer than observations. These deficiencies arise because the statistical modelling assumes that the daily UHI intensities are normally distributed. In fact, the intensities are slightly skewed to the left. The net effect is a relatively poor description by the model of the negative UHI episodes, but a reasonable representation of the intense UHI events (*i.e.* >4 degC). Overall the model yields a rather conservative estimate of the average nocturnal UHI (1.70 degC ± 0.03 degC) compared with observations (1.91 degC ± 0.03 degC). With this in mind, the penultimate section focuses only on model projections of the future frequency of intense UHI events ($\Delta T(u\text{–}r)_{\mathrm{min}}$ >4 degC) and on mean intensities.

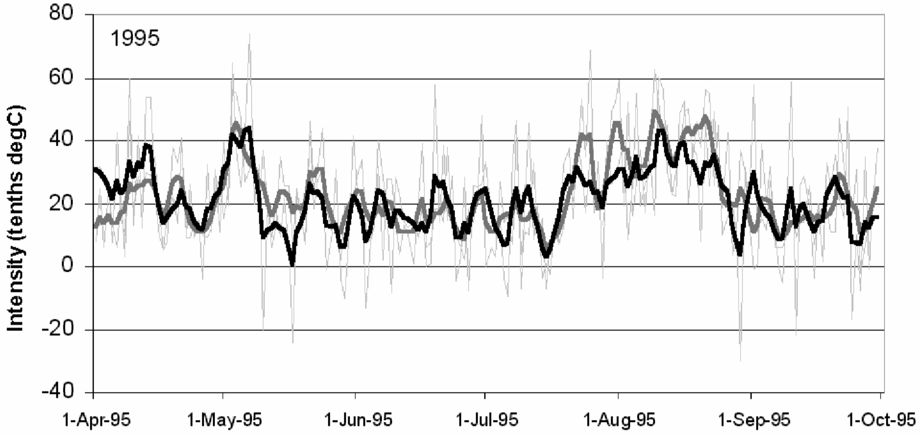

Fig. 6 Observed (grey lines) and modelled (black lines) nocturnal urban heat island intensity during the summer of 1995. Thin lines denote daily values; thick lines are seven-day weighted averages.

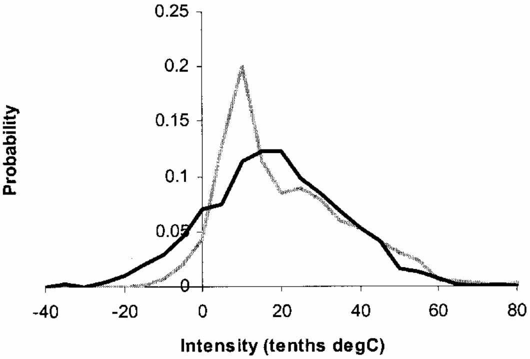

Fig. 7 Comparison of observed (grey line) and modelled (black line) distributions of summer nocturnal urban heat island intensities, 1991–98

Future UHI

The statistical model was used to produce future estimates of the nocturnal UHI. This was accomplished by driving the historical relationships with atmospheric predictors for eastern England supplied by the Met Office's coupled ocean–atmosphere general circulation model HadCM3 for the period 1961–2099. Sets of atmospheric predictors were available for the future climate under Medium–High Emissions and Medium–Low Emissions scenarios (Hulme *et al.* 2002). All projected changes in London's UHI were calculated with respect to the period 1961–90.

Under the two emissions scenarios there are progressive increases in both the intensity (*i.e.* annual average temperature difference between the sites) and number of days on which the nocturnal UHI exceeded 4 degC (Table 4). For comparison, the averages for 1961–90 were +1.8 degC and 38 days/year respectively. In line with observations, there remains considerable interannual variability in both UHI indices (Fig. 8). In fact, projected changes in the mean intensity and frequency of intense events under the Medium–High and Medium–Low Emissions scenarios do not exceed natural variability until the 2050s.

Table 4 Changes in the annual average nocturnal urban heat island intensity (ΔUHI), regional temperature change projected by the UK Climate Impacts Programme (ΔUKCIP02) and change in the frequency of intense (>4 degC urban–rural difference) UHI days (Δfrequency) in central London, under the UKCIP02 Medium–High Emissions and Medium–Low Emissions scenarios, for the 2020s, 2050s and 2080s. All changes are with respect to the 1961–90 average.

	Medium–High Emissions			Medium–Low Emissions		
Scenario	ΔUHI (degC)	ΔUKCIP02 (degC)	Δfrequency (days)	ΔUHI (degC)	ΔUKCIP02 (degC)	Δfrequency (days)
2020s	0.07	0.5–1.0	5	0.03	0.5–1.0	3
2050s	0.16	2.0–2.5	9	0.17	1.5–2.0	10
2080s	0.26	3.5–4.0	15	0.19	2.5–3.0	11

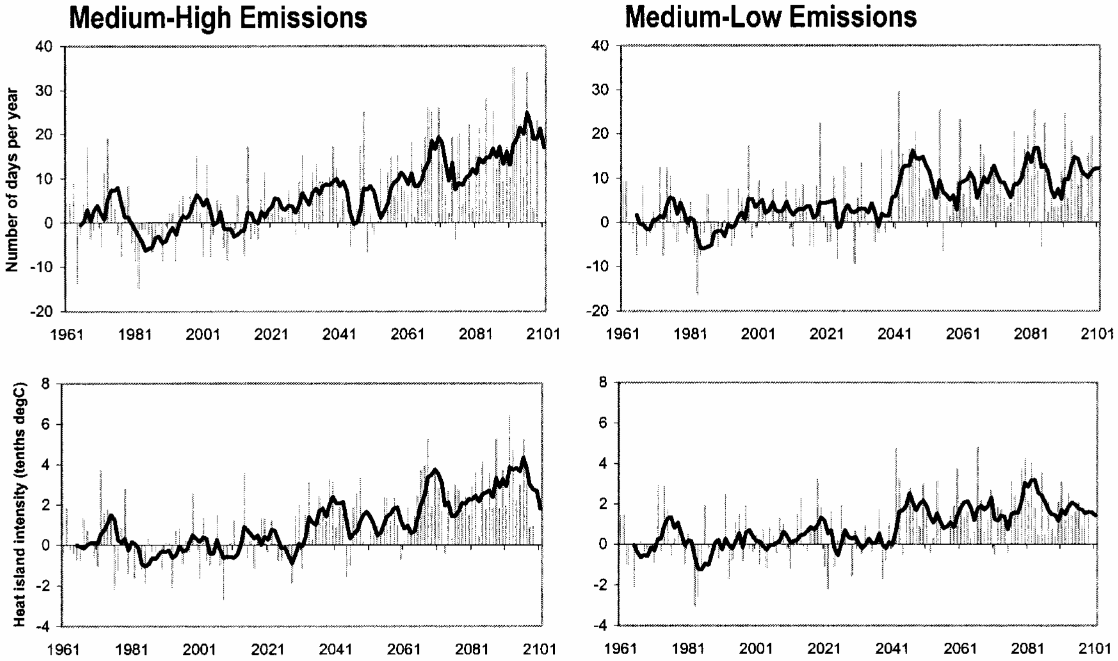

Fig. 8 Changes in the annual number of intense (>4 degC urban–rural difference) nocturnal urban heat island (UHI) days (top row) and average nocturnal UHI intensity (bottom row) in central London (under Medium–High Emissions and Medium–Low Emissions scenarios), with respect to the 1961–90 average

Under the Medium–High Emissions scenario, the nocturnal UHI changes by a further +0.26 degC, and the number of intense urban–rural temperature differences by +15 days/year (+40% relative to 1961–90) by the 2080s. The equivalent figures for the Medium–Low Emissions scenario are +0.19 degC and +11 days/year (+29%) by the 2080s. These temperature changes are in addition to the regional warming of 3.5–4.0 degC anticipated under the UK Climate Impacts Programme (UKCIP02) Medium–High Emissions scenarios (Hulme *et al.* 2002) and the UHI of 1.8 degC for the baseline period (Table 4). In other words, the additional annual average temperature increase for London attributable to the UHI would be ~2.06 degC under the Medium–Low Emissions scenario (*i.e.* 1.80 degC from 1961 to 1990 plus 0.26 degC intensification by the 2080s). However, observations have shown that the most intense nocturnal UHIs tend to develop in summer (Fig. 2). Therefore, summer episodes could have even more adverse consequences for London's citizens, including, for example, reduced night-time relief during heatwaves and reduced ambient cooling of the underground system, beyond the warming projected by UKCIP02.

Concluding remarks

London's urban landscapes and associated human activity are known to have affected many aspects of the local climate, including air quality, sunshine, precipitation and temperature. Not all impacts have been adverse. For example, wintertime mortality may have reduced due to higher average winter temperatures (Langford and Bentham 1995), and London is home to numerous flora and fauna introduced from warmer parts of the world but now flourishing in the city (see, for example, http://www.lbp.org.uk/action/statements/ssexoticflora.htm). This paper focused specifically on the thermal aspects, examining recent trends in London's UHI, and speculating about future changes under two of the UKCIP02 scenarios. However, it is recognised that London's UHI will probably affect other processes governing air quality and rainfall (see Atkinson 1968).

Temperature surveys reveal that London's UHI is most intense near the centre of the city, during night-time, in summer, under stable, anticyclonic weather. The effect diminishes with distance from the urban centre, during daytime and under windier weather. Since the 1960s, the intensity of the nocturnal UHI in spring and summer has increased by approximately +0.12 degC/decade. This has been attributed to more rapid night-time warming in the city than at outlying rural sites, possibly linked to urban air pollution, population changes, traffic volume and/or urban redevelopment (Lee 1992). Projected changes in the nocturnal UHI are of a further +0.26 degC by the 2080s. This equates to an urban warming rate of +0.04 degC/decade, compared with about +0.5 degC/decade directly due to regional warming. However, urban warming is probably a conservative estimate because (i) it reflects only the component of the UHI change that is linked to regional atmospheric variables excluding temperature (*i.e.* changes in urban population, building density, energy consumption, etc. are not included), and (ii) mid-range emissions scenarios were employed for the modelling.

Finally, there are many established but non-trivial techniques for countering UHI effects and improving human comfort (Golany 1996). These range from solutions at the scale of individual buildings to the radical proposals to construct a lattice of cooling pipes under Tokyo (Taha 1997). Conventional methods involve: reducing building densities; changing building height, spacing and street orientation to increase shade and reduce insolation receipt; enhancing natural ventilation through variations of building height and density; achieving effective solar shading using trees and vegetation; use of high-albedo (reflective) building materials; and improved building and cooling system design. It is also widely recognised that urban parks and bodies of water can create 'cold islands' within the thermal landscape (Upmanis *et al.* 1998). For example, air moving along the edge of the River Thames or within urban parks is, on average, 0.6 degC cooler than air in neighbouring streets (Graves *et al.* 2001). Under Chicago's UHI Initiative there is a programme of greening hard spaces by installing rooftop gardens and replacing hard surfaces such as school playgrounds with grassed areas (see, for example, http:// www.cityofchicago.org/Environment/AirToxPollution/UrbanHeatIsland/). However, care must be taken in the choice of species because of the ozone-forming potential of the biogenic emissions from urban plants (Benjamin and Winer 1998).

As well as countering UHI effects, more widespread green space and vegetation in London could benefit flood control by increasing travel times between rainfall, the urban drainage system, and receiving watercourses. Furthermore, the greening of the city is entirely consistent with the wider objectives of the Mayor of London's Biodiversity Strategy.

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Fifty-five years of flight – and some sights!

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Looking over the side of a Tiger Moth in 1947 and seeing that the aircraft was being blown to one side is one thing, but looking down through the bubble canopy of a Vampire, bombing along at 35 000 ft (10 668 m) and a Mach number of point 72 over Germany two years later, seeing that exactly the same thing was happening, raised my hackles. "What", I thought to myself, "exactly does the weather think it is doing to me, a jet jockey?" Fortunately, I had read of the existence of jet streams in the then 8-page only, lightweight overseas version of the *Daily Telegraph* some little while earlier. Accordingly, as the most junior pilot on 16 Squadron, I set about a mental computation of its direction and strength, and with considerable trepidation I called air traffic control at RAF Gutersloh, in effect going public, to report the result, both for their professional interest and because a number of other aircraft from the squadron would later be following me round that particular high-level cross-country.

Back in the squadron crew room after landing, I had a telephone call from the met. office to let me know that my estimates of the jet stream's direction and strength had been out by only 5 kn!

Some time later, having in the meantime taken up gliding, together with its introduction to 'thermals', I was flying at about 20 000 ft (6096 m) over the north German plain, with a