The urban heat island in Central London and urban-related warming trends in Central London since 1900

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Cities create their own microclimates and their sites are almost always warmer, compared to a nearby rural location, than if the city were not there. The effect on temperatures measured in the city has been termed the 'urban heat island' (UHI). In this study we assess the strength of the UHI within and around London based on monthly and seasonal maximum, mean and minimum temperatures. The purpose of the study is not to look at UHI extremes on individually conducive days, but to show that the effect has a certain magnitude on monthly and seasonal averages, and assess whether this magnitude of UHI for Central London has increased over the twentieth century compared to rural locations around London (Jones *et al*., 2008).

London is possibly the longest-studied UHI of any city; Luke Howard (1833) was probably the first scientist to suggest that the temperature recorded in a city was likely to be higher than that in the surrounding countryside. The major studies of urban-related warming in London since then have all recognized the importance of homogeneous temperature series and the need to look at long time series, as opposed to the effects on individual days or short periods. Moffitt (1972) compared the long Kew (KEW) record with that from Rothamsted (ROTH), remarking that this rural site is unlikely to be affected by any development at Harpenden (a mile to the northeast of the site). A study was conducted (in 1925) concerning a site move that took place in 1915. Although the study is no longer available, a letter in the station metadata files states that there was good agreement between readings at the two sites and that there was no regular pattern in the minor variations (Moffitt, 1972). Some additional discussion of this site move is given by Tyrrell (1972) and Moffitt (1973). ROTH is used as one of the three key sites in England for the Central England Temperature (CET) series, and no adjustments to its data have been made (Parker *et al*., 1992). Moffitt (1972) concluded that KEW warmed relative to ROTH between 1878 and 1968 by about 0.8 degC, slightly more in winter and summer and slightly less in spring and autumn. Moffitt (1972) also showed that KEW (for annual average temperature) was warmer than ROTH in the 1880s by 0.74 degC, which agreed well with the height difference (123 metres) between the stations, assuming a standard lapse rate of 0.6 degC per 100 metres. This value will be important later when we assess the magnitude of Central London's UHI. We will also assess whether this value should be applied equally to maximum and minimum temperatures.

Later work by Lee (1992) and Wilby (2003) used the more central London site of St James's Park (SJP) and replaced the ROTH rural record with Wisley (WIS). The periods of record were reduced to 1962–1989 and 1958–1998, respectively, and the emphasis changed to the magnitude of UHI. Lee (1992) considered whether the urban-related warming trend had increased over his period of analysis, but was only able to find that minimum temperatures had risen while maxima decreased at SJP compared to WIS with no overall change in mean temperatures. Wilby (2003) found similar results to Lee (1992) and correlated counts of daily extreme UHI values (SJP warmer than WIS by more than 4 degC) against a number of synoptic indices. In this study we will use an additional site in Central London (London Weather Centre, LWC) and one in a more suburban location (Heathrow Airport, LHR), and use the full length of digitally available daily and monthly average records.

Data and periods used

We use monthly mean maximum (Tx), minimum (Tn) and mean (T) temperatures measured at sites in and around London. Table 1 gives the locations of the sites and periods of record used. These site records

Table 1

Site details for locations in the London area.

Station	Name in text	Elevation (m)	NGR (E)	NGR (N)	Distance/direction from LWC (km)	Start	End	Digitized from
Rothamsted	ROTH	128	5132	2134	35 (NNW)	1872	–	1916[1]
Wisley	WIS	38	5063	1579	34 (SW)	1904	–	1931
Heathrow	LHR	25	5077	1767	23 (W)	1947	–	1949
Kew Observatory	KEW	5	5171	1757	15 (SWS)	1857[2]	1980	1881
Kew Gardens	KEW	6	5185	1773	15 (SWS)	1910	–	1981
St James's Park	SJP	5	5298	1800	2 (SW)	1903	–	1907
Camden Square	CAM	37	5296	1845	3 (NW)	1858	1969	–
London Weather Centre	LWC	42	5302	1800		1929	–	1974[3]

[1] Rothamsted Tmean data are digitized from 1872. Tmax and Tmean are available from 1916.

[2] Earlier data back to the eighteenth century are believed to exist from references to the building of the Observatory.

[3] The site known as London Weather Centre has moved around over the years. It was situated in Kingsway from 1959 and moved to High Holborn in 1965. It was moved again in 1992 to Clerkenwell Road. Further information about the LWC site is given by Hunt (2007).

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were chosen to provide relatively long series and to be from sites that can be shown to be relatively homogeneous (with the exception of KEW, see later).

Study of Table 1 indicates that there are relatively few temperature series with an excess of 30 years of daily temperature data digitally available in and around London – and all are west of Central London. ROTH and WIS are considered rural locations. We note that Burt and Eden (2004) consider that the WIS site has become more sheltered in recent years. The longest-record Central London site is SJP, but as the name suggests it is not located in a highly developed area of London. LWC, a rooftop – and therefore highly non-standard – site is in a much more developed area (Table 1). The LWC site has moved once (in 1992) since digital records began in 1974 (Hunt, 2007). The effect of this change is relatively minor. Compared to SJP, LWC is warmer on an annual basis by 0.43 degC for the period 1974–1991 and 0.38 degC for 1993–2006.

The final two records considered are LHR and KEW, located west and southwest of Central London. Both sites have seen urban development during the twentieth century, particularly so at LHR over the last 50 years, and Moffitt (1972) has already indicated a warming of about 0.8 degC at KEW between 1878 and 1968 relative to ROTH. According to the Met Office site information, the thermometers at LHR have not been moved since instrumental data were digitally available in 1949. The KEW record began at the observatory from the late eighteenth century, but this site was closed in 1980. The recent data for KEW come from the Gardens site, and we will show clear evidence of a discontinuity between the two sites (which is to be expected as they are about one mile apart). We combine the records, but make no attempt to adjust one to the other because the Gardens data were not digitized before 1980. The series for KEW and LWC are included for completeness, but only the LWC record is used later to estimate UHI for a more developed part of London compared to SJP.

We considered two other 'London' sites – Northolt Airport and High Beach in Essex, but both contain considerable amounts of missing daily data. We also considered two 'outer' London sites at Gatwick and Stansted airports, but both sites are no longer (since the late 1990s) run by the Met Office, and their data (collected by the Civil Aviation Authority) now only sporadically enter the Met Office database.

Table 2

*Annual and seasonal temperature trends (for Tx, Tn and T) in degC per decade for the four selected periods. Values in **bold** are significant at the 95% level. Seasons are winter (DJF), spring (MAM), summer (JJA) and autumn (SON).*

Site	Tx					Tn					T				
	Ann	*DJF*	*MAM*	*JJA*	*SON*	*Ann*	*DJF*	*MAM*	*JJA*	*SON*	*Ann*	*DJF*	*MAM*	*JJA*	*SON*
1931–2006															
SJP	**0.13**	0.17	0.07	0.14	**0.12**	**0.15**	**0.19**	**0.16**	**0.10**	**0.13**	**0.14**	**0.18**	0.12	0.12	**0.12**
KEW	**0.29**	**0.32**	**0.24**	**0.28**	**0.32**	–0.04	–0.01	0.00	**–0.09**	–0.06	**0.12**	**0.16**	**0.12**	0.10	**0.13**
WIS	**0.14**	**0.23**	0.05	0.10	**0.17**	**0.12**	**0.19**	**0.13**	0.06	0.11	**0.13**	**0.21**	0.09	0.08	**0.14**
ROTH	**0.15**	**0.20**	0.06	**0.16**	**0.16**	**0.12**	**0.16**	**0.13**	0.07	**0.13**	**0.13**	**0.18**	0.10	0.11	**0.14**
1949–2006															
SJP	**0.24**	0.23	**0.22**	**0.27**	**0.20**	**0.24**	**0.24**	**0.24**	**0.26**	**0.20**	**0.24**	0.24	**0.23**	**0.26**	**0.20**
KEW	**0.43**	**0.41**	**0.40**	**0.51**	**0.41**	–0.05	–0.07	–0.09	–0.08	–0.15	**0.17**	0.17	**0.18**	**0.21**	0.13
LHR	**0.28**	**0.34**	**0.20**	**0.34**	**0.24**	**0.31**	**0.35**	**0.29**	**0.32**	**0.30**	**0.29**	**0.35**	**0.25**	**0.33**	**0.27**
WIS	**0.26**	0.29	0.18	**0.29**	**0.26**	**0.20**	**0.27**	**0.19**	**0.16**	0.16	**0.23**	**0.29**	**0.18**	**0.23**	**0.21**
ROTH	**0.19**	0.23	0.11	**0.26**	0.15	**0.24**	0.25	**0.23**	**0.25**	**0.22**	**0.22**	0.24	**0.17**	**0.25**	**0.19**
1951–1980															
SJP	0.03	0.28	–0.25	0.10	0.03	0.10	0.33	–0.07	0.13	0.08	0.05	0.29	–0.17	0.11	0.04
KEW	0.19	0.36	–0.08	0.32	0.20	–0.02	0.23	–0.10	–0.04	–0.07	0.09	0.29	–0.09	0.14	0.07
LHR	0.11	0.39	–0.26	0.16	0.20	0.20	0.44	0.02	0.18	0.21	0.15	0.42	–0.11	0.17	0.20
WIS	0.06	0.37	–0.30	0.06	0.18	–0.04	0.29	–0.16	–0.19	–0.04	0.01	0.33	–0.23	–0.06	0.07
ROTH	–0.02	0.24	–0.36	0.07	0.07	0.06	0.31	–0.05	–0.03	0.05	0.02	0.28	–0.21	0.01	0.06
1981–2006															
LWC	**0.63**	0.46	0.66	**0.78**	0.57	**0.60**	0.63	0.59	**0.56**	**0.55**	**0.61**	0.54	0.63	**0.67**	**0.57**
SJP	**0.62**	0.57	0.62	0.63	**0.64**	**0.50**	0.58	0.47	**0.44**	**0.49**	**0.56**	0.58	0.53	0.53	**0.56**
KEW	**0.76**	0.82	**0.77**	0.80	**0.77**	0.27	0.45	0.34	0.17	0.18	**0.52**	0.63	0.56	0.49	0.48
LHR	**0.58**	0.51	0.54	0.64	**0.60**	**0.69**	0.72	0.67	**0.60**	**0.70**	**0.63**	0.62	0.61	**0.61**	**0.64**
WIS	**0.69**	0.56	0.64	0.77	**0.73**	**0.55**	0.66	0.51	**0.46**	0.49	**0.61**	0.60	0.57	**0.60**	**0.62**
ROTH	**0.64**	0.63	0.62	0.63	**0.64**	**0.66**	0.69	0.59	**0.70**	**0.61**	**0.65**	0.67	0.60	**0.65**	**0.62**

To increase the amount of data used in the study, we add to the length of some of the existing sites from Met Office publications giving average temperatures for 'standard' periods: 1901–1930, 1921–1950 and 1931–1960 (Anonymous, 1933, 1953, 1963). WIS has longer records than those that are digitally available (back to 1904 but digitally only from 1931). We also add the Central London site of Camden Square (CAM), from these sources, to give a site in a more built-up part of the city (like LWC today).

We consider trends and averages over selected periods. The periods are constrained by the length of records and also the early 30-year standard periods. For trends, we consider four periods: 1931–2006, 1949–2006, 1951–1980 and 1981–2006. In the first of the two periods for trends in Table 2, the fact that 1980/1981 discontinuity between the two series at KEW is within the first two periods should be borne in mind. For the 30-year averages, we also consider four periods: 1901–1930, 1931–1960, 1951–1980 and 1981–2006 (the last only 26 years).

Temperature trends

Figure 1 shows annual time series in the three temperature measures (Tx, T and Tn) from the earliest digitally available, and it is clear that all six series show common year-to-year variations and similar trends to higher temperatures during the twentieth century. KEW differs from the others, with an obvious discontinuity around 1980, which can be related to the merging of the Observatory site (up to 1980) with the Gardens site since. Trends in Tx and Tn at KEW seem quite different (Tx greater and Tn much smaller) at the Gardens location compared to the other sites, but are similar for T. Figure 1 clearly shows a greater spread of the Tn, as opposed to the Tx series. For example, Tn is always highest at LWC, but for Tx, the warmest years (and seasons, not shown) could be found at any of the sites apart from ROTH. Earlier work (Burt and Eden, 2004; Jones *et al*., 2008) indicates that the highest absolute daily values are more likely to be recorded west and southwest of London (LHR, WIS or KEW) than in Central London (LWC or SJP). Later we will quantify the UHI, but it is clearly larger for Tn than for Tx.

Table 2 gives seasonal trends (for Tx, Tn and T) over the four periods introduced earlier (1931–2006, 1949–2006, 1951–1980 and 1981–2006). Over the longest period, both ROTH and WIS exhibit trends for all three measures and all seasons that are essentially the same. For annual averages (for T), the warming is 0.13 degC per decade. Differences between these two sites become larger for the shorter periods and for individual seasons, but their trends are never significantly different from each other. LHR shows enhanced warming compared to

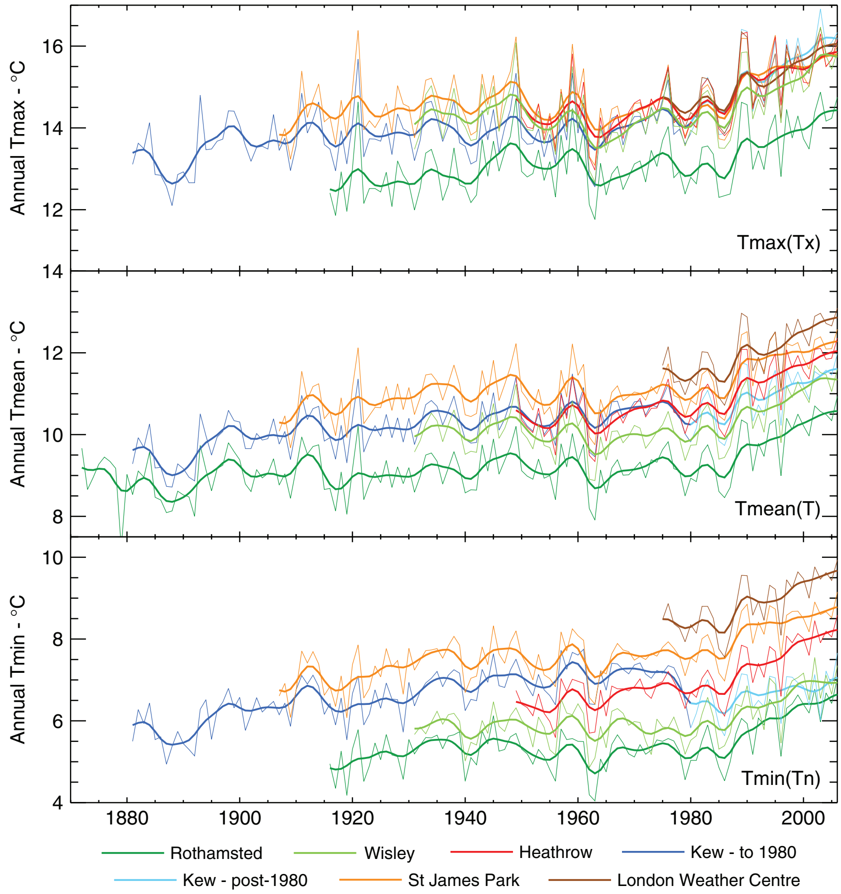

Figure 1. Annual temperature time series (for Tx, T and Tn) for the six selected key sites (LWC, SJP, LHR, KEW, WIS and ROTH). Smoothing is based on a ten-year data adaptive Gaussian filter. Note the different shades of blue used for KEW pre- and post-1980.

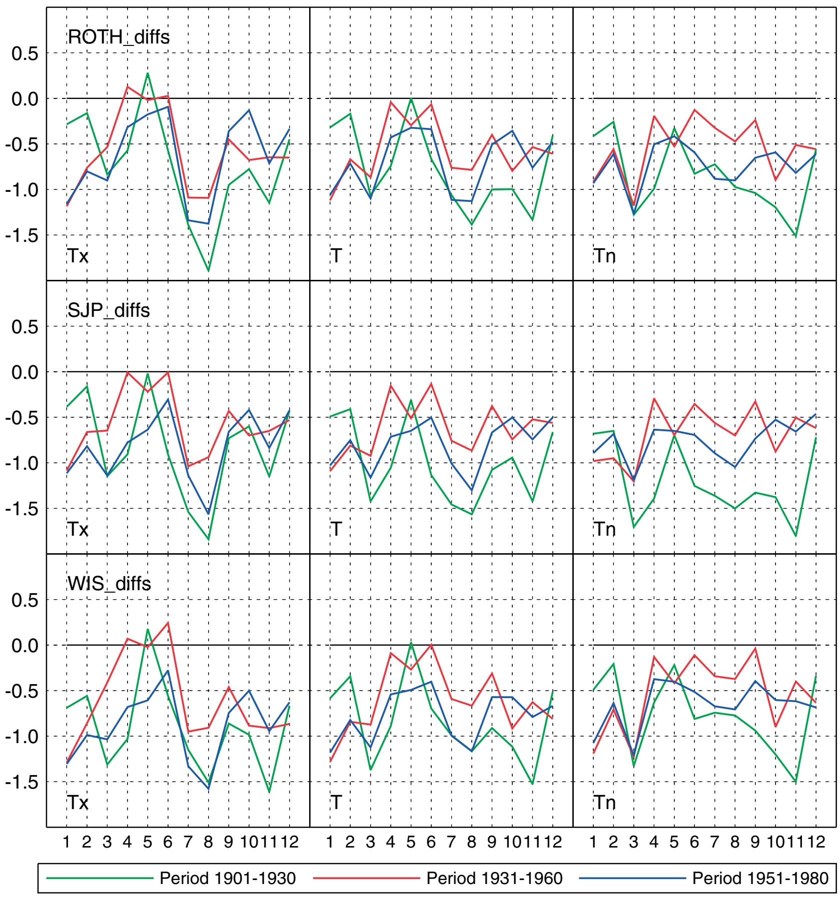

Figure 2. Monthly differences (degC) between various periods (for Tx, Tn and T) and 1981–2006 for ROTH, SJP and WIS.

Table 3

Average seasonal and annual temperatures (Tx, Tn and T in °C) for selected 30-year periods. Seasons defined as in Table 2.

Site	Tx					Tn					T				
	Ann	DJF	MAM	JJA	SON	Ann	DJF	MAM	JJA	SON	Ann	DJF	MAM	JJA	SON
1901–1930															
CAM	14.7	7.4	14.3	22.3	14.6	6.4	2.1	5.0	11.8	6.9	10.6	4.8	9.7	17.1	10.8
SJP[1]	14.4	8.1	13.7	20.9	14.7	7.1	2.7	5.6	12.3	7.6	10.7	5.4	9.7	16.7	11.2
KEW	13.8	7.5	13.1	20.7	13.9	6.4	2.3	4.9	11.7	6.7	10.1	4.9	9.0	16.2	10.3
WIS[1]	14.1	7.5	13.4	21.0	14.1	5.7	1.8	4.3	10.7	5.9	9.8	4.6	8.9	15.9	10.1
ROTH	12.9	6.6	12.4	19.6	13.1	5.1	0.9	3.6	10.2	5.6	9.0	3.8	8.0	14.8	9.4
1931–1960															
CAM	14.7	7.3	14.4	22.2	15.0	7.4	2.3	5.8	13.0	8.2	11.0	4.8	10.1	17.6	11.6
SJP	14.6	7.7	14.1	21.7	15.0	7.6	2.5	6.1	13.2	8.5	11.1	5.1	10.1	17.5	11.8
KEW	13.9	7.0	13.4	21.2	14.2	7.0	2.2	5.5	12.6	7.8	10.5	4.6	9.5	16.9	11.0
WIS	14.3	7.1	14.0	21.6	14.6	5.9	1.3	4.4	11.2	6.7	10.1	4.2	9.2	16.4	10.6
ROTH	13.1	6.0	12.6	20.2	13.5	5.4	0.6	3.8	10.8	6.3	9.2	3.3	8.2	15.5	9.9
1951–1980															
SJP	14.4	7.6	13.5	21.4	14.9	7.5	2.7	6.0	12.8	8.4	10.9	5.1	9.8	17.1	11.7
KEW	14.0	7.2	13.1	20.9	14.5	7.1	2.4	5.6	12.4	7.9	10.5	4.8	9.3	16.7	11.1
LHR	14.3	7.3	13.5	21.4	14.9	6.6	1.7	5.0	12.1	7.4	10.4	4.5	9.3	16.8	11.2
WIS	14.0	7.1	13.4	21.0	14.6	5.8	1.3	4.3	10.9	6.6	9.9	4.2	8.9	16.0	10.6
ROTH	13.0	6.1	12.3	20.0	13.7	5.2	0.5	3.7	10.3	6.2	9.1	3.3	8.0	15.1	9.9
1981–2006 (26 years)															
LWC	15.3	8.7	14.4	22.3	15.6	9.0	4.3	7.4	14.3	9.9	12.1	6.5	10.9	18.3	12.8
SJP	15.2	8.4	14.4	22.4	15.6	8.3	3.4	6.9	13.7	9.1	11.7	5.9	10.6	18.1	12.3
KEW	15.3	8.5	14.5	22.6	15.7	6.7	1.9	5.3	12.1	7.3	11.0	5.2	9.9	17.4	11.5
LHR	15.2	8.3	14.4	22.6	15.5	7.5	2.6	5.9	13.0	8.2	11.3	5.5	10.1	17.8	11.9
WIS	14.9	8.1	14.2	22.1	15.3	6.4	2.1	5.0	11.5	7.1	10.7	5.1	9.6	16.8	11.3
ROTH	13.7	6.9	12.7	20.9	14.1	5.9	1.2	4.4	11.1	6.9	9.8	4.1	8.6	16.0	10.5

[1]SJP and WIS records begin in 1903 and 1904, respectively.

the two rural sites for the period 1951–1980, but similar warming over the most recent period (1981–2006). An urban-related warming of 0.4 degC is therefore evident at LHR, estimated from the 1951–1980 period, but it is confined to this period as it does not continue beyond 1980. It is also likely – based on the KEW results from Moffitt (1972) – that the LHR site would have experienced some urban-related warming before the meteorological record started in 1949. The urban-related warming at LHR is very slightly greater for Tn than for Tx. For the Central London sites (SJP and LWC) warming over the most recent period (1981–2006) is also almost exactly the same as at ROTH and WIS. For the earlier periods, SJP warms at essentially the same rates as ROTH and WIS, indicating no urban-related warming at the site since 1931.

Period averages

As differences between earlier 30-year periods and the most recent slightly truncated period of 1981–2006 are generally small, compared to the annual cycle of temperature, we plot each period as a difference from the latest period (1981–2006). Figure 2 shows the results for the three sites that have all four periods: ROTH, SJP and WIS. We exclude KEW because of the discontinuity between the Observatory and the Gardens site. The courses of monthly temperature differences between each period and 1981–2006 are very similar for all three sites.

Table 3 gives annual and seasonal averages for the four periods (1901–1930, 1931–1960, 1951–1980 and 1981–2006) for Tx, Tn and T for all sites. In this Table and the subsequent discussion of differences between sites, values are all rounded to tenths of degrees, as extra precision is beyond the accuracy of the original values. WIS and SJP start in 1904 and 1903 respectively (digitally from 1931 and 1907). There were 12 missing months at SJP (four in 1918, four in 1946, two in 1958 and two in the 1960s). These were infilled with regression estimates from ROTH. Comparison of the ROTH and WIS annual T values for each of the four periods in Table 3 indicates differences of either 0.8 or 0.9 degC, a slightly higher value than the 0.67 degC estimated by Moffitt (1972) from the elevation difference of KEW and ROTH. WIS is 33 metres higher than KEW, so would be expected to be marginally cooler than KEW. The differences with ROTH, therefore, relate to the elevation difference (90 metres) and a component from the more southerly location of WIS. The annual average differences between WIS and ROTH for Tx and Tn from Table 3 are greater for Tx (1.1 degC) than for Tn (0.6 degC). This difference relates to lower relative humidity values during the day as opposed to higher values at night.

Compared to SJP, T at ROTH is lower by 1.7, 1.9, 1.8 and 1.9 degC for the four periods. These intercomparisons between ROTH, WIS and SJP extend the findings of Figure 1 and Table 2 and indicate that SJP shows no statistically significant urban-related warming since 1901 (based on ROTH and WIS). Furthermore, the annual mean temperature (T) for SJP is 0.1 degC higher than for CAM for both the 1901–1930 and 1931–1960 periods, but is 0.1 degC lower than for LWC for the final period (1981–2006).

Quantification of the London UHI

We begin by assuming that the 0.7 degC 'height' difference between KEW and ROTH also applies to SJP as it has a similar elevation to KEW (Table 1) and is split into Tx and Tn as 0.9 and 0.5 degC, based on the earlier ROTH/WIS comparisons. Using the height difference gives an annual UHI for SJP (for T) of 1.1 degC and a value of 1.8 degC for LWC. These values were calculated as differences with ROTH averaged over as many of the 30-year periods as possible. For Tx and Tn, the UHI values for SJP are 0.6 and 1.6 degC. The value for LWC is more tentative as it is based only on 1981–2006 and a different height difference (with ROTH) of 0.5 degC (86 metres). For Tx and Tn, the UHI values for LWC are 0.9 and 2.8 degC. The larger values for LWC reflect its location in a more built-up area of London and possibly the site's non-standard rooftop location. Seasonally for SJP, there is little difference for Tx, with Tn being slightly greater in spring and summer compared to winter and autumn. The much greater UHI value for Tn for LWC explains why this site was always, in an absolute sense, the warmest 'London' location in Figure 1. The UHI value for Tx is much smaller, so 30-year Tx averages are much closer for all the sites, except ROTH (Table 3 and Figure 1).

Conclusions

In this study of the UHI within London we have used more temporally extensive datasets than in any previous study. Our aim was to quantify the UHI within Central London and to determine if there has been any urban-related warming at Central London sites compared to two rural locations outside London. The UHI for SJP for T, Tx and Tn is 1.1, 0.6 and 1.6 degC respectively, while for LWC it is larger at 1.8, 0.9 and 2.8 degC. Warming trends at SJP are not statistically different from those at ROTH and WIS for the four periods analysed, and the four 30-year-period averages indicate consistent differences. These results show that the temperatures at SJP are not increasing any more than those at ROTH and WIS since 1901. The implication of this study is that the SJP temperature series could be used in global temperature datasets (see references in Jones *et al*., 2008) as constituent series are incorporated as anomalies from a common reference period, and not as absolute temperatures. However, results for London cannot be extrapolated to other British and European cities.

The UHI for Central London (as estimated at SJP and LWC) must have developed before the start of the twentieth century. UHIs have increased and urban-related warming has occurred at the LHR and KEW sites located on the periphery of London. At LHR, mean temperature increased by 0.4 degC between the start of the record in 1949 and 1980. Since 1981 there has been no further increase in the UHI. It is expected that other sites located in the outskirts of Central London (like LHR and KEW) would show similar courses of change in their UHIs over the twentieth century, but sites within Central London would show no urban-related warming trends (i.e. constant UHIs) compared to rural stations around London.

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References

Anonymous. 1933. *Averages of temperature for the British Isles for periods ending 1930*. MO 364, Air Ministry, Meteorological Office: HMSO, London.

Anonymous. 1953. *Averages of temperature for Great Britain and Northern Ireland 1921–1950*. MO 571, Air Ministry, Meteorological Office: HMSO, London.

Anonymous. 1963. *Averages of temperature for Great Britain and Northern Ireland 1931–1960 in degrees Celsius*. MO 735, Meteorological Office: HMSO, London.

Burt S, Eden P. 2004. The August 2003 heatwave in the United Kingdom: Part 2 – The hottest sites. *Weather* **59**: 239–246.

Howard L. 1833. *The climate of London: deduced from meteorological observations made in the metropolis and at various places around it.* Harvey and Darton: London.

Hunt R. 2007. The end of weather forecasting at Met Office London. *Weather* **62**: 143–146.

Jones PD, Lister DH, Li Q. 2008. Urbanization effects in large-scale temperature records, with an emphasis on China. *J. Geophys. Res*. **113**: D16122, doi:10.1029/2008/JD009916

Lee DO. 1992. Urban warming? – An analysis of recent trends in London's urban heat island. *Weather* **47**: 50–56.

Moffitt BJ. 1972. The effects of urbanization on mean temperatures at Kew Observatory. *Weather* **27**: 121–129.

Moffitt BJ. 1973. The effects of urbanization on mean temperature. *Weather* **28**: 42–42.

Parker DE, Legg TP, Folland CK. 1992. A new daily Central England temperature series, 1772–1991. *Int. J. Climatol.* **12**: 317–342.

Tyrrell JG. 1972. The effects of urbanization on mean temperatures. *Weather* **27**: 348–348.

Wilby RL. 2003. Past and projected trends in London's urban heat island. *Weather* **58**: 251–260.

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