URBAN WARMING? – AN ANALYSIS OF RECENT TRENDS IN LONDON'S HEAT ISLAND

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CURRENT interest in global warming as a consequence of the greenhouse effect has led to the construction of several long-term temperature time-series which attempt to demonstrate the magnitude of this warming over the last century (*e.g.* Jones 1988; Jones *et al.* 1986; Hansen and Lebedeff 1987; Vinnikov *et al.* 1987). One possible criticism of these time-series (*e.g.* Kukla *et al.* 1986) is that many land-based temperature records have been affected by urban warming as cities have expanded, often engulfing airport observing sites. Even with sites situated near city centres, many cities in both Europe and North America have experienced an increase in the urban heat island effect as both population and city area have increased. For example, in London, Moffit (1972) suggested that about 1 deg C of the temperature change at Kew Observatory between 1878 and 1968 could be attributed to urbanisation. However, Jones *et al.* (1989) argue that the maximum warming bias in the temperature time-series is approximately 0.1degC per 100 years.

Urban heat islands, which in London cause mean annual temperatures to be about 1.5degC higher in the city than in the rural surroundings, are caused by a complex combination of factors. These include changes in the radiation and energy balance of the Earth's surface as vegetation is replaced by materials such as concrete and tarmac; modification of the atmospheric composition by air pollutants which affect the radiation balance; anthropogenic heat production from human activities such as heat loss from space heating; and motor vehicle emissions.

The relationship between city size and urban heat island intensity is not straightforward and certainly not linear (Chandler 1965, p.176). Studies by Oke (1973; 1987, p.291) showed that the relationship between population as a measure of city size and the maximum urban heat island appeared to be different in North American and European cities, perhaps as a function of city structure and population density. Almost all the cities reported in the literature to have experienced long-term increases in urban heat island intensity have also been subject to large population increases (Cayan and Douglas 1984; Kukla *et al.* 1986; Nasrallah *et al.* 1990).

However, in many older towns and cities in western Europe and North America the process of counter-urbanisation had led to a decline in population. A notable example of this trend is Greater London, where the population has been declining steadily for some years. Over the period of this study, population has fallen from just over 8 million in 1962 to approximately 6.8 million in 1988. The purpose of this study is to examine trends in London's heat island over this period of declining population.

There are, however, problems in relating any observed trend in heat island intensity solely to population change, as several other important factors may also have changed over time (Chandler 1965, p.176). The most important of these are the synoptic conditions which favour heat island formation. It is well known that factors such as small amounts of cloud, light winds and strong atmospheric stability all favour the formation and development of intense heat islands, and so any change in the seasonal or annual frequency of suitable synoptic conditions, especially the frequency of anticyclones, will affect observed long-term trends in heat island intensity irrespective of any population growth or decline. Despite such reservations, there is clear evidence from many cities around the world (*e.g.* Landsberg 1981, pp.87–98) which suggests that population growth is a major factor in heat island development.

There are several reasons to anticipate rather different temperature responses to population decrease than to increase. Population expansion is invariably accompanied by large increases in the surface area of cities as housing, roads, public transport and other services expand to accommodate greater population numbers. Thus the surface radiation and energy balances are significantly altered by the replacement of natural or semi-natural surfaces by a variety of materials which constitute the urban fabric and by changes in anthropogenic heat production (*e.g.* Oke 1988).

Population decrease, on the other hand, certainly in the case of London, is not accompanied by a corresponding decrease in the surface area of the city. Much of the population decrease in London has occurred as a result of migration from the densely built-up inner city residential areas to the outer suburbs, overspill towns and new towns located around the south-east of England. The redevelopment of inner city areas to accommodate the expansion of commercial and financial sectors has not resulted in any significant decrease in the volume of the building fabric. Therefore the process of population decrease is unlikely to lead to any substantial change in the surface radiation and energy balances.

Other factors associated with population change and urban redevelopment which may have an influence on urban temperatures include changes in space heating requirements, changes in fuel usage, improved standards of insulation in newer buildings and changes in the volume of motor-vehicle traffic which has increased dramatically in London in recent years.

DATA

It is obviously important in the analysis of long-term trends that observation sites should offer a continuous record and be subject to as little change as possible, either through relocation, or by changes in the immediate surroundings such as the encroachment of built-up areas. In London the choice of such sites is rather limited, but St. James's Park (Westminster) was selected to represent temperatures within central London. Being located within a park, the temperatures are likely to differ slightly from those experienced in the immediately surrounding streets (Chandler 1965, p.153). Also, the St. James's Park site is not located within the area which normally experiences the maximum urban heat island effect, so the real magnitude of the urban–rural temperature difference will be slightly underestimated at this site. The use of single sites to represent the heterogeneous nature of the city climate is always subject to reservations, but the longevity and consistency of the record must be balanced against this.

The use of one site outside London to represent 'rural' temperatures is also open to criticism, but the choice of Wisley, 32 km to the south-west of London was made for similar reasons. It is clear that in any urban–rural comparison involving only two sites, neither the absolute magnitude of the heat island nor its spatial variation will be represented accurately. However, the examination of long-term trends is not dependent on the absolute magnitude of the heat island, only its change over time.

Monthly means of daily maximum, minimum and mean temperatures were obtained from the *Monthly Weather Report* of the Meteorological Office, for St. James's Park and Wisley, for the 28-year period 1962–89 inclusive. Differences in maximum, minimum and mean temperatures between St. James's Park and Wisley were used to represent heat island intensity in each of four seasons. On the few occasions when data were missing, values were estimated by comparison with several nearby sites.

RESULTS

In most mid-latitude cities, there is a marked seasonal and diurnal pattern of heat island development. Heat islands are strongest on summer nights when heat which has been absorbed by building fabric from daytime solar radiation is subsequently released. Reduced nocturnal turbulent mixing allows this warmer air to remain near the surface. During winter, although the anthropogenic heat input from space heating is greater, the absorption and subsequent release of daytime solar energy by buildings is much less, and heat islands are generally weaker.

The mean daily heat island intensity, $\Delta T(u - r)_{\mathrm{mean}}$ (where u is urban and r is rural), for each season is shown in Figs. 1(a)–(d). Although there is considerable year-to-year variability, linear regression lines were calculated for each season in order to determine overall trends. It is apparent that, for mean daily temperatures, as expected, the greatest

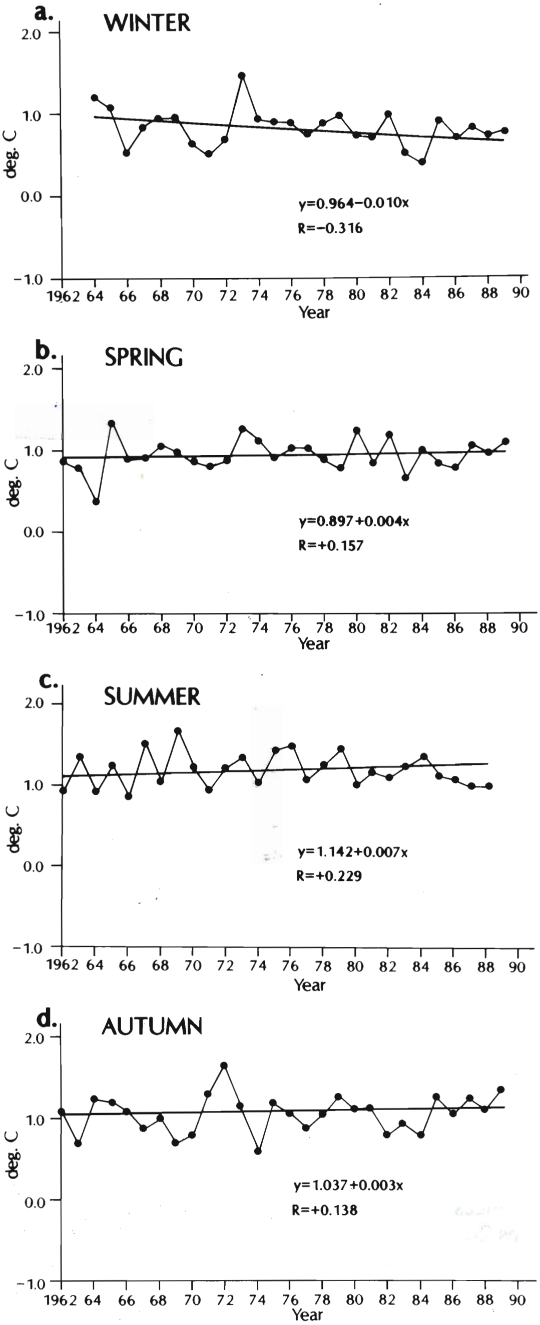

Fig. 1 *Seasonal trends in heat island intensity calculated from daily mean temperatures* ($\Delta T(u-r)_{mean}$), *St. James's Park–Wisley, for 1962–89 (1964–89 for winter). The linear regression equations, where* y = *heat island intensity (degC) and* x = *time in years after 1962 (or 1964 for winter) indicate the change in heat island intensity over time. The correlation coefficients,* R, *indicate the strength of the linear trend.*

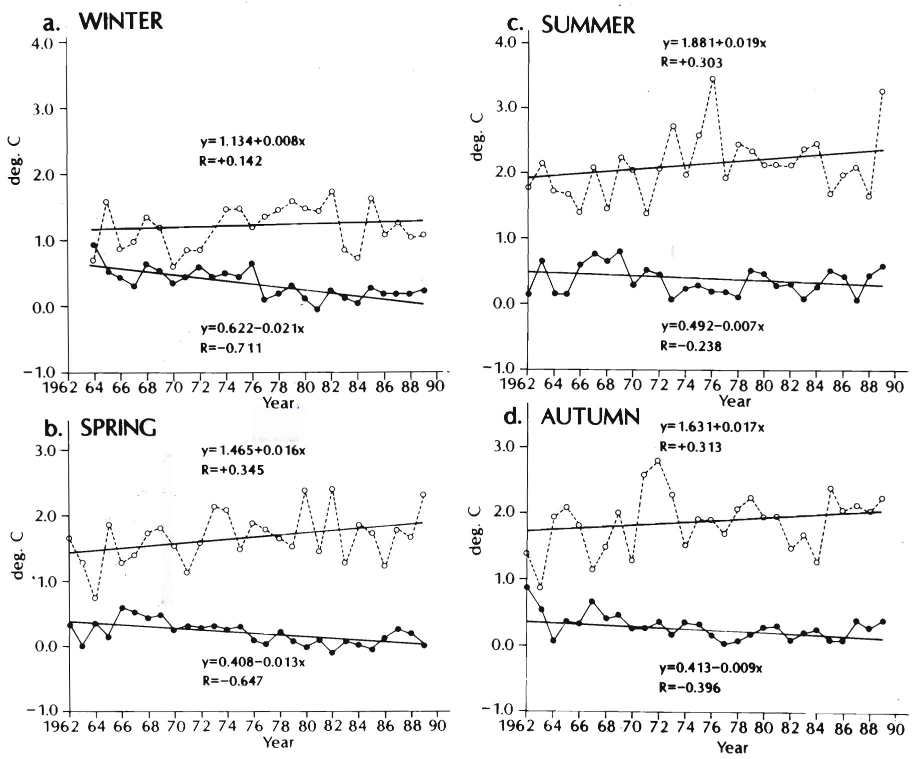

Fig. 2 Seasonal trends in heat island intensity calculated from daily maximum (solid line) and minimum (dashed line) temperatures ($\Delta T(u-r)_{max}$) *and* ($\Delta T(u-r)_{min}$)*, St. James's Park–Wisley, for 1962–89 (1964–89 for winter). The linear regression equations and correlation coefficients are as explained in Fig. 1.*

differences exist in summer and the smallest in winter with mean differences of 1.24 and 0.83degC respectively. Linear trends over the 28-year period are relatively small with spring, summer and autumn showing slight relative urban warming of +0.03 to +0.07degC per decade. Winter, on the other hand, displays a quite different trend, with a marked urban cooling of −0.10degC per decade. Possible reasons for such seasonal differences are discussed later.

Mean daily urban–rural temperature differences may, however, conceal patterns of change in daily maximum, $\Delta T(u-r)_{\text{max}}$, and minimum, $\Delta T(u-r)_{\text{min}}$, temperature differences. The intensity of the daytime heat island, as represented by differences in maximum temperatures, may respond to a different combination of synoptic, radiation and energy balance influences compared to nocturnal urban–rural differences in minimum temperatures. Figures 2(a)–(d) therefore illustrate separate seasonal trends $\Delta T(u-r)_{\text{max}}$, and $\Delta T(u-r)_{\text{min}}$ over the same period.

All seasons show values of $\Delta T(u-r)_{\text{max}}$ to be considerably smaller than $\Delta T(u-r)_{\text{min}}$ as expected. However, it is also apparent that the long-term trends in these two values of heat island intensity diverge over time in all seasons, that is, the nocturnal heat island intensity has increased, whilst the daytime heat island intensity has decreased. The consistency of this pattern suggests that some overriding influence is acting which appears to be more important than the annual variability in synoptic conditions favourable for heat island formation, as similar long-term trends in synoptic patterns are unlikely to appear in all seasons. Individual exceptional years can be identified, for example the summers of 1976 and 1989 which were very warm and sunny show large nocturnal heat islands.

Table 1 shows the correlation coefficients and significance levels of heat island trends against time. The correlation coefficients are a measure of the strength of the linear trend and the significance levels indicate the likelihood of this trend occurring by chance. The daytime trends in all seasons except summer are significant at the 5 per cent level at least, whereas for the night-time heat island trends all seasons except winter are significant at the 5 per cent level. Not surprisingly, given the opposite sign of the trends for maximum and minimum temperature differences in all seasons, the only trend in mean heat island intensity which is significant at the 5 per cent level is that of winter, because of the strong effect of the daytime trend in maximum temperature differences. Table 2 shows the seasonal warming and cooling rates for maximum and minimum temperatures over time for Wisley and St. James's Park from which the changes in heat island intensity can be deduced.

Table 3 illustrates the mean annual warming rates and overall change in maximum and minimum temperatures at the two sites. It is apparent that at both sites there has been a warming trend although the pattern of the changes is not consistent. Mean annual maximum temperatures have increased at Wisley by a greater amount than at St. James's Park, while conversely, mean annual minimum temperatures have increased by a greater amount at St. James's Park than at Wisley.

Possible explanations of these patterns and trends must remain speculative at present as a more detailed analysis of mechanisms will be necessary. However, several possible changes in the urban radiation and energy balances may be considered. Population change

TABLE 1 Correlation coefficients and significance levels of heat island intensity against time

	$\Delta T(u-r)_{max}$	$\Delta T(u-r)_{min}$	$\Delta T(u-r)_{mean}$
Winter	−0.711*	+0.142†	−0.316**
Spring	−0.647*	+0.345**	+0.157†
Summer	−0.238†	+0.303**	+0.229†
Autumn	−0.396**	+0.313**	+0.138†

* Significant at 1 per cent level.
** Significant at 5 per cent level.
† Not significant.

TABLE 2 Seasonal values of temperature trends (degC per year)

	MAXIMUM	MINIMUM
Winter		
St. James's Park	+0.015	+0.014
Wisley	+0.048	+0.001
Spring		
St. James's Park	+0.013	+0.014
Wisley	+0.024	−0.001
Summer		
St. James's Park	+0.033	+0.031
Wisley	+0.040	+0.010
Autumn		
St. James's Park	+0.019	+0.024
Wisley	+0.033	+0.023

TABLE 3 Mean annual warming rates (degC per year) and total temperature change (degC) for maximum and minimum temperatures for 1962–89

	MAXIMUM		MINIMUM	
	Warming rate	Temp. change	Warming rate	Temp. change
Wisley	+0.037	+1.04	+0.011	+0.31
St. James's Park	+0.030	+0.84	+0.024	+0.67

does not, by itself, appear capable of explaining the trends, as population is merely a surrogate of some aspect of city size which is difficult to define. Any expectation that a decrease in population should be accompanied by a decrease in heat island intensity is simplistic for reasons outlined previously. Several other factors which may be more directly important in determining urban–rural temperature differences may also have changed over the same period, for example energy consumption and motor-vehicle traffic.

The most significant trend is the reduction in daytime heat island intensity, which could be changed by either urban temperatures being lower than expected, or rural temperatures being higher than expected. It is reasonable to postulate that some aspect of the urban environment has led to a lowering of maximum temperatures in the city compared with its surroundings. Possible mechanisms include a decrease in the receipt of solar radiation in the city as a result of atmospheric pollution or a reduction in the daytime anthropogenic heat emissions, perhaps as a consequence of increased energy efficiency or lower population density. The latter possibility is given more support by the fact that the greatest and most significant decrease is in winter, when the anthropogenic heat component of the urban energy balance is known to be greatest. The nocturnal heat island intensity has generally been increasing, notably in summer and autumn.

The presence of air pollution within the city atmosphere during a period of overall warming at both sites may offer an explanation of the diurnal differences in the trends. If it is assumed that the increase in daytime maximum temperatures at both sites is associated with a greater receipt of solar radiation, the presence of polluted air in the urban atmosphere will, by absorbing some of this radiation increase, moderate the effects on temperatures, whereas the less polluted air at Wisley will allow daytime maximum temperatures to increase at a greater rate, thus decreasing daytime urban–rural temperature differences over time. Conversely, at night, the presence of urban air pollution is known to absorb and re-emit significant amounts of outgoing terrestrial radiation, maintaining higher urban nocturnal minimum temperatures.

It must be emphasised that such explanations are tentative at present and will be confirmed only by a more detailed analysis of changes in solar radiation receipt, synoptic conditions and anthropogenic components of the energy balance.

CONCLUSIONS

The observed trends in London's heat island intensity divide clearly into two. Daytime heat islands have decreased over time and night-time heat islands have increased. The opposite sign of these trends means that conclusions regarding urban warming which are based only on daily, monthly or seasonal mean temperatures conceal important differences between daytime and night-time trends.

It is clear that any simple relationship between heat island intensity and population as a surrogate for some aspect of city size, which has proved to be reasonably successful in predicting the growth of heat islands as cities grow, cannot be expected to hold as populations decrease, as much of the urban fabric which modifies the surface radiation and energy balances remains unaffected. However, it is possible that part of the explanation for reduced daytime heat islands could lie with factors related to decreasing population such as reduced anthropogenic heat emissions, but this remains unclear at present.

More general conclusions relate to the influence of urbanisation on long-term temperature records. Whilst it may be true in some parts of the world that an urban warming bias may be present in the observed trends, it is very unlikely to be the case in many European and North American cities which have either stabilised their population numbers or in fact have been losing population over several decades. The complex nature of the urban temperature response is clearly demonstrated in London where both nocturnal urban warming and daytime urban cooling have occurred over the last three decades.

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THE ROYAL OBSERVATORY OF SAN FERNANDO (CADIZ) AND ITS PLACE IN THE DEVELOPMENT OF METEOROLOGICAL STUDIES IN SPAIN

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CADIZ claims to be one of western Europe's oldest settlements, being founded as the Phoenician port of *Gaddir* (meaning an enclosure) perhaps as early as 1100 BC. The Greeks knew it as *Gadeira* and the Romans distinguished it as *Julia Augusta Gaditana*. The Moors referred to it as *Jerizet Kádis*, but since its conquest by Alfonso the Wise in 1262 it has been known simply as Cádiz. Because of its history, inseparable association with the Spanish Navy, links with the vast Empire of the Americas and its proud defiance to the French Napoleonic invasions it has long enjoyed a special place in Spanish history. In keeping with this pedigree, meteorologists should note that it also has one of the longest instrumental weather records in the world and that the local observatory led the way in establishing a Spanish meteorological service. This paper reviews the history of this interesting observatory.

FOUNDATION AND THE MOVE TO SAN FERNANDO

This account begins in the early eighteenth century, not with the study of meteorology *per se*, but with the issue that then vexed the scientific world, namely the precise shape of the Earth. Greek philosophers had suggested the Earth to be spherical as long ago as half a millennium BC, but only following the Renaissance and the great voyages of discovery of the Portuguese and Spanish pilots was the sphericity of our planet finally and widely accepted. But as the sciences of surveying and navigation developed throughout the sixteenth century and later, it became apparent that the Earth's detailed form might not be perfect. It was Halley who, in 1677, proposed the Earth to be a geoid with polar flattening, though the idea was not immediately accepted and formed the basis of frenzied polemic. Indeed the Cassinis, father and son, proposed the Earth to be extended not equatorially but