The London heat island and building cooling design

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ABSTRACT

London's urban heat island increases the mean air temperature which affects the demand for heating and cooling buildings. The simultaneous hourly air temperature in London has been measured continuously for a year. These data have shown that central areas of London are significantly warmer than the surrounding areas. The measured data have been used as input to a thermal simulation model to assess the heating and cooling load of a standard air-conditioned office building positioned at 24 different locations within the heat island. Eight urban contexts were defined to represent the range of sites from rural to central urban areas. It is found that the urban cooling load is up to 25% higher than the rural load over the year, and the annual heating load is reduced by 22%. The effect of raised temperature and urban context are assessed separately, and the sensitivity of the net impact to the internal gains in a building is determined. For the estimation of peak cooling demand, we propose hourly temperature corrections based on radial distance from London's centre to be applied to standard published temperatures for the region.

1. INTRODUCTION

Heat islands are well-established consequences of the urban environment. In general, urban centres are warmer than the surrounding area and this can be beneficial, or not, in terms of the energy used in providing comfortable conditions in buildings. In hot or cold climates the annual balance of the impact of a heat island may be clear, but in temperate regions such as London the reduced heating season loads may significantly offset the higher cooling loads in the summer.

Chandler, using data from 1951-60, found a reduction in annual heating degree days (base 15.6°C) of about 10% between central London and a rural area (Chandler 1965). In Munich, Bründl reported that annual heating degree days (base 15.0°C) were 14% lower in a central urban area compared to a suburban one (Brundl and Hoppe, 1984). Energy use for cooling was not considered because summer cooling was not prevalent. Energy requirements for air-conditioning are considered higher than for heating (Landberg, 1981), and both Landsberg (1981) and Taha (1997) concluded that the elevation of urban temperatures imposes a net energy penalty in several American cities because of increased cooling requirements. Shading effects of surrounding buildings are often neglected in calculating the loads in a building. This can lead to over-sizing of plant, and in general, neglects a basic aspect of urbanization. In central Athens, the annual cooling load for an apartment block with windows shaded 50% of the time was found to be 15-50% higher than when modelled using weather data from an open site on a hill 2km away (Hassid et al, 2000). Also in Athens, where the mean heat island intensity exceeds 10°C, it was found that the cooling load of urban buildings may be doubled and the peak electricity load for cooling purposes may be tripled especially for higher set point temperatures. During the winter, the heating load of central urban buildings is found to be reduced up to 30% (Santamouris, 2001).

This paper reports the results of a study of the effects of the London heat island over a year. The heating and cooling loads for a building have been assessed using measured hourly data. Based on these measured data, the energy performance of a standard office building has been modelled in a variety of urban contexts to determine the balance of the effect of the heat island over a year.

A commercial building simulation tool (TAS) has been used to predict the impact of the heat island and the urban environment on energy use. Some results have been reported in (Watkins et al., 2002; Kolokotroni et al., 2004). In this paper, additional data on proposed temperature corrections suitable for summer cooling design assessment are presented.

2. ENERGY DEMAND MODELLING

2.1 External conditions

One year's measured hourly air temperature data from 24 stations within London were combined with regional weather data to form 24 weather files for the simulation model. Wind speed and direction data were obtained from Heathrow airport, located within the monitoring array, 23 km WSW of central London, and humidity, cloud cover, and solar radiation data from the London Weather Centre, central London. These regional data were assumed to be applicable to all 24 sites – an approximation. Wind speed in urban areas can be higher than more rural areas, but in general will be lower, and can affect infiltration and convective heat transfer. In this study of an air-conditioned building, both the infiltration and ventilation rates are scheduled and are thus independent of wind-speed. The convective heat loss coefficient is varied by the model according to the hourly regional wind speed, but this is not modified here for urban settings.

2.2 Standard Office building

The dominant type of air-conditioned building in London is the office, and to represent this a standard design has been selected from a set of designs widely used in the UK in comparative energy studies. It is a standard, as distinct from prestige, air-conditioned office termed the ECON 19/3 building; taken from the Energy Consumption Guide 19 (BRESCU, 1999). It is a three storey open plan building, 9m high, 30m long and 15m wide orientated with the longer sides facing north:south, with 60% glazing on these façades. There is clear double glazing with no shading. The end walls are unglazed. Walls and roof are concrete with insulation. Intermediate floors are of concrete with false ceilings, and the ground floor is uninsulated. The walls have a solar absorptance of 40% and the roof 65%. The surrounding land was set to have 20% ground reflectance to solar radiation. An air-conditioning system (vapour compression) and heating system (gas-fired) operates from 06:00 to 18:00 (to include pre-conditioning) maintaining the internal air temperature between 20° and 24°C. Fresh air is supplied during occupied hours with a total air change rate of 1.1 /hour (including infiltration of 0.5 ach/hour at all times). Internal gain from lights, occupants and plant is 43W/m^2.

2.3 Urban contexts

In urban areas buildings usually experience a degree of over-shadowing which reduces solar gain. This effect has been modelled by surrounding the test building with neighbouring blocks to the same height (9m) at a varying distance depending on the appropriate site categorization (Table 1). The spaces formed between the buildings, the street gorges, were given a height to width ratio that varied from zero (no over-shadowing) to 2.0 (heavy over-shadowing for category 8 – Table 1).

2.4 Internal gains

Internal gains affect the ratio of heating to cooling load, and the relative significance of a change in solar gain with over-shadowing. To determine the effect of this the building was modelled with four alternative levels of internal gain. Base 43W/m^2, +25% 54W/m^2, +50% 65W/m^2 and -25% 32 W/m^2. These higher and

Table 1: Criteria used for categorizing sites

Ct	H/W ratio of street, x	Description
1	x=0	Rural fields, or large park, or trees
2	x=0	Housing near park or field
3	x=0	Urban derelict or unbuilt area
4	0<=x<0.3	Low density residential area
5	0.3<=x<0.5	Medium density urban area
6	0.5<=x<1	High density urban area
7	1<=x<2	Very high density urban area
8	>=2	Exceptionally high density urban area

lower gains are not artificial and are quite likely to be found in practice.

3. RESULTS

3.1 Main results – base gain

Figure 1 shows the model predictions of annual heating and cooling loads for the ECON 19/3 building when located at each of the 24 sites. Base internal gain is used. The rural site has the highest heating load and lowest cooling load. Compared to this, across the range of differently urbanized sites, heating load decreases by 22% and cooling load increases by 25%. The highest cooling load, and lowest heating load, is at a site two miles south east of the focus of the monitoring array. This is a dense urban area (a category 5 site), but with little vegetation, and without tall buildings.

Air temperature is an important determinant of load and this varies with radial distance from London. Figure 2 shows the variation of mean temperature for daytime and night-time in the summer of 1999. The relationship is much stronger at night-time (r^2 = 0.75) than in the daytime (r^2 = 0.38).

The residual variance apparent in the relationship with radial distance is found to be associated with site category. Overlying a general urban heat island gradient from urban centre to rural periphery, individual sites modify

the micro-climate. This is particularly so in the daytime when, for instance, evapotranspiration is active and can differentiate sites. In the one-way analysis of variance test (ANOVA) results shown in Figure 3, radial distance is con-

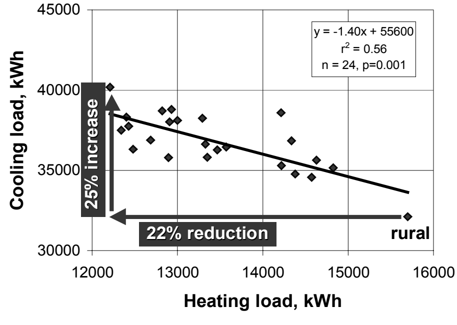
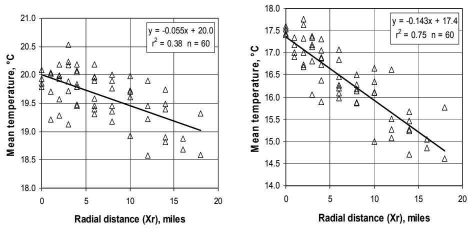


Figure 1: Predicted annual loads for the ECON 19/3 office at 24 sites (Watkins et al., 2002b).



(a) (b)

Figure 2: The variation of mean air temperature with radial distance, Xr, for DAY (a) and NIGHT (b).

trolled (Xr = 3 or 13 km), and the mean group temperature differences, dT, (local-rural reference) are shown for each site category. These plots are the annual means of daytime, daily data. The bars show the 95% confidence limits in the means.

There is a trend of increasing air temperature (and local heat island intensity, dT) seen with urbanized sites, when controlling for radial distance. From these example figures and an examination of other radial distances, there is some evidence that a peak is reached at category 5, (circled in Fig. 3), when the temperature starts to fall. The fall of category 5 may be associated with increasing over-shadowing, the increasing proportion of solar radiation that is intercepted at higher surfaces of buildings in nar-

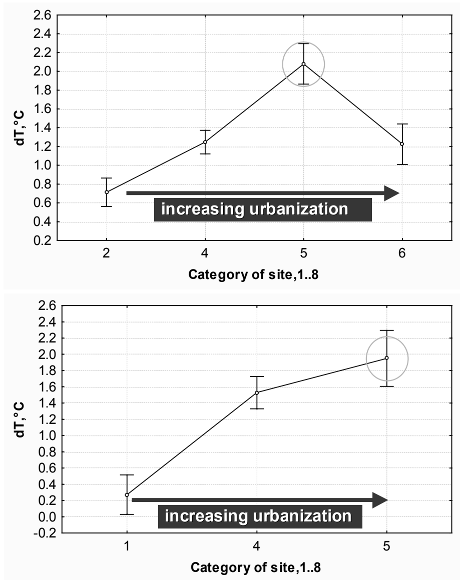


Figure 3: The variation of mean daytime dT when grouped by site category, for Xr=3 km (a) and Xr=13 (b)

rower street gorges, and the greater total gorge surface area/plan area to be warmed by the solar flux.

3.2 Separation of the temperature and urban context effects – variable gain

There are two main factors affecting load: higher urban temperatures increasing cooling load, and higher over-shadowing decreasing it, with the opposite effects for heating. The size of these effects when operating independently is evaluated here. The sensitivity of the results to variable internal gain is also given here; the higher the internal gain the more the annual loads shift from heating to cooling, affecting the balance of the effect of the heat island.

The effect of context alone

The simulation model was run using rural weather acting on the ECON 19/3 building in each of the seven contexts. This introduces the effects of over-shadowing, while controlling for external temperature. Figure 4a shows the change in total annual load (heating + cooling) with site category with respect to rural load. Note that the first three categories are open sites and there is therefore no change for these.

For a low internal gain building, increasing over-shadowing leads to an increase in total annual load, regardless of the degree of urbanization. For the base gain building, greater over-shadowing leads to an increase in total load by about 2%, but starts to fall for the most urban site type to almost the same as at the rural site (category 1). Higher gain buildings have a reduced total load with any level of over-shadowing.

As noted, for the base and low gain buildings, increasing context density leads initially to an increase in total annual load, and then a levelling-off or reduction. This is probably because of the angle of the sun being higher during the cooling season compared to the heating season. Applying a wide context affects gain during the heating season much more than in the cooling season.

The effect of temperature alone

The simulation model was run using the measured hourly temperatures at each site, but keeping the ECON 19/3 building in the open, as if in a rural context. This introduces the effects of

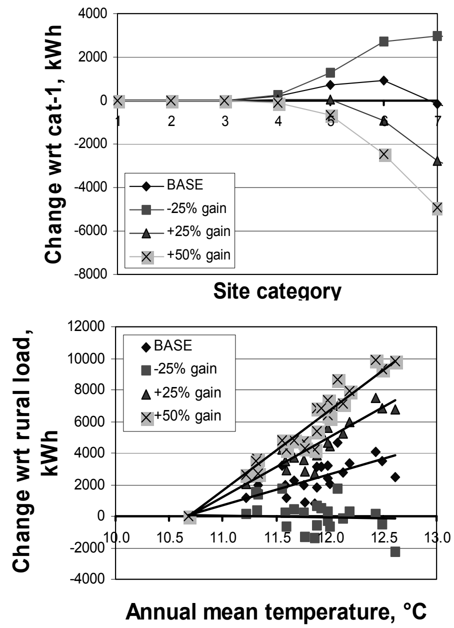


Figure 4: Change in total annual load with site category alone for different internal gains (a) Rural site category and (b) Rural Weather.

temperature, while controlling for over-shadowing. Figure 5b shows the change in total annual load with annual mean temperature, with respect to the rural load, at each of the 24 sites. The low gain building is almost insensitive to higher temperatures – they tend to have a neutral effect on total load – but at the highest temperatures total load decreases. For higher gain buildings, higher mean temperatures lead to increased total load. The base gain building’s total load increases by about 7% at the warmest sites in the heat island compared to the load at rural temperatures.

The effect of context alone – reduced solar gain

For a fixed degree of over-shadowing, the level of solar gain can also vary if the façade design of a building is different: higher or lower percentage glazing, shading features, etc. To determine the effect of reduced solar gain, the building has been modelled with reflective glass (20% reflectivity to solar radiation) and the effect of context alone re-evaluated. In this case, the higher internal gain buildings experience the greatest absolute reduction in total load change with site category, because of the dominance of cooling over heating load.

4. SUMMER DESIGN TEMPERATURE

The results presented above suggest that temperature variations within the London Heat Island should be considered in the design of buildings. In particular there are specific implications for passive cooling techniques due to increased temperatures, Santamouris (2004).

In order to estimate peak cooling loads, it is desirable to modify published temperature values (CIBSE 1999) to account for the position of a building within the London Heat Island. Such a method was first proposed in (Graves et al 2001). CIBSE (1999) includes hourly design data for typical days for each month. These days are derived from the 97.5 percentile daily global irradiation exceedence data. From available data (July and August 1999 and 2000) Graves (2001) selected 6 days (5% of data) with the highest solar radiation and calculated the temperature difference (site air temperature minus Bracknell air temperature). From these, Tables were proposed based on the proximity of 180 London sites to 80 monitored sites.

In order to simplify the procedure for possible inclusion in the forthcoming edition of CIBSE Guide A, the authors have repeated this study with some adjustments. Heathrow air temperatures have been used instead of Bracknell's as Heathrow is the met station used for climatic data for London (CIBSE, 2001).

The London region has been divided into three concentric annular zones, and the mean heat island intensities with respect to Heathrow computed for each zone and hour. Different radii were examined for significant changes in the zone means before selecting: 0-3km (core temperature), 3-10km (semi-urban), and 10-23km (suburban). Beyond this lie rural areas. We propose these hourly temperature corrections to Heathrow data for summer peak cooling estimation based on radial distance. Table 2 presents the proposed adjustments to be *added* to Heathrow design data. Heathrow is towards the edge of the London Heat Island but significantly warmer than a rural site. The heat island air temperature corrections in Table 2 are significantly lower than if they were given relative to a true rural site. The real Urban Heat Island Intensity can be obtained by *subtracting* the rural reference column from an annular column in Table 2.

5. DISCUSSION AND CONCLUSIONS

The effect of the London heat island on energy used for heating and cooling depends on the degree of urbanization in a particular location, radial distance from the centre (depth within the heat island) and the relative contribution of solar gain to total gains in a building. Heating dominated buildings will tend to benefit from a heat island whereas the opposite is the case for cooling dominated ones. Results from an analysis of variance of daytime temperature showed a fairly consistent ordering of mean temperature (or heat island intensity) with site category, when controlling for radial distance.

It should be noted that the site categories and associated street gorge ratios (Table 1) reflect the urban densities in London, and may not be appropriate for other cities where, for example,

Table 2: Proposed air temperature corrections based on radial distance from city centre.

Hour	Distance from city centre			Rural Reference
	0-3km	3-10km	10-23km	
0	1.9	1.0	-0.9	-2.3
1	1.9	1.1	-0.9	-2.5
2	1.9	1.1	-0.7	-2.0
3	1.7	0.9	-0.7	-2.3
4	1.5	0.8	-0.7	-2.3
5	1.4	0.7	-0.6	-2.3
6	1.7	1.3	-0.4	-2.5
7	1.5	1.9	0.8	-1.3
8	1.7	2.0	1.3	-0.7
9	1.8	2.2	1.5	-0.4
10	1.6	2.0	1.4	0.7
11	1.4	1.8	1.3	0.0
12	1.7	2.1	1.3	-0.2
13	1.6	2.2	1.4	-0.2
14	0.6	1.1	0.4	0.9
15	0.9	1.4	0.5	0.0
16	0.9	1.4	0.4	-0.1
17	0.7	1.0	0.2	-0.2
18	0.4	0.8	0.0	0.8
19	0.4	0.4	-0.4	-0.5
20	0.6	0.3	-0.9	-1.9
21	1.0	0.3	-1.4	-2.7
22	1.5	0.6	-1.3	-2.7
23	1.5	0.6	-1.3	-2.8
Average	1.3	1.2	0.0	-1.1

very much narrower streets are the norm.

For a standard air-conditioned building (ECON 19/3) operating with internal gains of 43 W/m^2, the annual heating load decreases by 22% from a rural site, with cooling load increasing 25%. Mean summer daytime temperatures for different sites are found to be associated with a site categorization based on the nature of surfaces and street gorge ratio. For a given radial distance, daytime temperatures tend to peak at category 5 sites. The annual primary energy use is also associated with site category, again tending to peak at category 5 sites, and reducing at more urbanized (over-shadowed) sites, despite them being warmer.

When the ECON 19/3 building has 25% lower internal gain, total annual primary energy tends to be less sensitive to position within the heat island. This is because the heating and cooling loads are more balanced and a reduced heating load, deeper within the heat island, is matched by an increased cooling load. With higher gains, +25% and +50%, the pattern followed is similar to the base gain building.

A simplified method for adjusting temperatures based on Heathrow peak cooling calculations' design data and radial distance from the centre of the London Heat Island is proposed (section 4). However, site category (microclimate) has been shown to have a marked effect on the heat island intensity and more work is needed to enable us to include the effect of physical site characteristics into urban heat island prediction.

Recently, the UHII as affected by synoptic climatic parameters has also been studied using Artificial Neural Networks (ANNs) (Mihalakopoulou, 2002; Kim, 2002). ANN models are suited to the proposed research because they are particularly good at representing any complex non linear functions whose analytical forms are difficult or impossible to obtain. The UHII problem is complicated and some relationships between different factors are still not fully understood. Kim (2002) has compared the ANN model results to a multiple linear regression model and concluded that the ANN model gave improved predictions by up to 6.5%.

We propose to use similar techniques (ANNs) to investigate the effect of synoptic climatic conditions experienced over London. In addition, we propose to investigate the effect of *physical urban characteristics* and incorporate these into the ANN model.

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