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# Strategies for the modification of the urban climate and the consequent impact on building energy use ☆

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ABSTRACT

It is well established that urbanisation has a significant effect on the local climate. The climate of an urban area will differ from that of a nearby rural area. Modifications to the relevant properties of the urban environment will amplify or reduce these differences. This paper briefly summarises the literature and reports on the impact of these changes.

A series of international studies has indicated that modifications to the urban environment have a significant effect on the energy use of buildings. Detailed studies of these issues with regard to the UK are now under way and these new studies are briefly discussed. There is much current interest in attempting to ameliorate potential summer overheating in cities, focusing on the consequences of heatwaves. However, the wider picture should also be considered. In summer in the UK, the urban heat island (UHI) will tend to result in an increased cooling load and an increased number of excess deaths due to overheating. But in winter, the UHI will tend to result in reduced heating loads and a reduced number of cold-related excess deaths. The net effects of these impacts must be borne in mind in the consideration of large-scale urban modifications.

## 1. Introduction

One of the best-known effects of urbanisation on the local climate is urban warming. This phenomenon is commonly referred to as the 'urban heat island' (UHI). A range of factors vary between rural and urban areas and contribute to the UHI, including the thermal properties of materials, the height and spacing of buildings, and air pollution levels. These factors result in more of the Sun's energy being captured, absorbed and stored in urban surfaces than in rural surfaces during the day, and a slower loss of this energy at night, resulting in higher air temperatures in urban areas. In addition, less evaporation takes place in the typically drier urban areas, with a reduction in associated cooling. Finally, urban areas also have greater inputs of heat as a result of the high density of energy use in cities. All this energy, used in buildings and for transport, ultimately ends up as heat. Strategic planning is required which takes account of these factors, particularly in the context of climate change.

The intensity of the UHI for a particular city will have significant spatial and temporal variations. Its maximum intensity is typically reached several hours after sunset (Oke, 1987). During the August 2003 heatwave in London the temperature difference between urban and adjacent rural locations reached 9 °C on occasions (Greater London Authority, 2006b). Watkins et al. (2002) reported on an extensive series of measurements, made in London in the period 1999–2000, which demonstrate in detail the behaviour of London's UHI.

It should be noted that for certain cities a 'negative' UHI can instead be dominant. In arid regions, cities with large amounts of irrigated green space may actually be cooler than the surrounding dry areas (Grimmond, 2007). We do not observe this effect in the UK, where cities appear to exhibit features of a 'conventional' UHI, as might be expected, and thus this paper focuses on cities with conventional UHIs.

Although the main role of this paper is to explore the implications for energy use of modifications to the urban climate, the associated health consequences should also be noted. While the lowering of urban temperatures in summer is likely to reduce rates of heat-related mortality, the number of cold-related deaths is far higher in the UK than the death toll due to excessive summer heat. This should be borne in mind before any major intervention in a city is contemplated.

## 2. Modifying factors

Attempts to modify the urban climate can take place on a range of physical scales. The UHI is a city-scale effect and research

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is currently being undertaken to examine modification strategies that can be implemented at levels ranging from street to city-wide. At a local scale these include the modification of surface properties ('cool roofs', 'green roofs' and 'cool pavements'), planting trees and vegetation, and the creation of green spaces. The geometry of the built environment, and anthropogenic (man-made) heat emissions, are also issues to consider. A useful guidance document is available that provides further details of these issues with a specific focus on a UK city (London) (Greater London Authority, 2006b). A brief discussion of all of these factors follows.

Several studies have shown the effect of anthropogenic heat emissions on the urban climate (see Coutts et al., 2007; Ichinose et al., 1999; Klysik, 1996; Taha, 1997). The Ichinose et al. (1999) study of Tokyo used a detailed survey of energy consumed to quantify the increase in temperatures within the urban environment at up to 1.5 °C within areas of high anthropogenic heat emission. The influence was strongest during winter months and weakest during summer, as the short-wave radiation varied along with seasonal daily temperature profiles. The Taha (1997) analysis of several US, Canadian and European cities indicated that anthropogenic heat emission was strongest in cold-climate city centres, but was nearly negligible in suburban areas. This study suggested that an increase of 2–3 °C could be due to the impacts of anthropogenic heat.

A recent study (Hamilton et al., 2008) estimated the anthropogenic heat emission from buildings in London at a range of spatial and temporal scales. An example of the data is shown in Fig. 1. A wide spread of annual average heat emissions was identified, with 50% of London by area emitting less than 10 W/m$^2$, 25% emitting between 10 and 18 W/m$^2$, 20% emitting 18–30 W/m$^2$, and 5% emitting above 30 W/m$^2$. The annual average building-related heat emission for the whole of London is estimated at approximately 9 W/m$^2$. In comparison, the London Energy and CO$_2$ Emission Inventory (LECI) database (Greater London Authority, 2006a) estimates the annual average energy delivered for transport in London as approximately 2 W/m$^2$.

The highest levels of annual heat emission from buildings in London are concentrated in central London, although there are a few isolated high-emitting areas in outer London. This pattern follows the concentration of domestic and non-domestic buildings, their clustering, and the density of the development.

This study also compared the anthropogenic heat emissions and total incident net short-wave solar radiation balance at four representative London sites. In those urban areas with deep canyons and high densities, anthropogenic energy constitutes a significant portion of the total energy input. A study of London's UHI phenomenon indicated that the centre of the island sits above the Old Street and Farringdon Road area within the City of London (Watkins et al., 2002). This location is also where the anthropogenic heat emission is greatest. It indicates that reducing energy use in such areas may be particularly relevant to the UHI.

In the future it is likely that our use of energy will reduce and that the sources from which this energy is supplied will alter, due to the pressures of meeting our climate change obligations and to maintain security of supply. This may involve the decentralised distribution of energy as greater use is made of combined heat and power, and as local authorities increasingly demand that new buildings generate a percentage of their energy locally, as with the Merton Rule. These changes may have an impact on anthropogenic heat emissions. If conventional power stations were moved into cities, they would emit heat there. But if the power stations

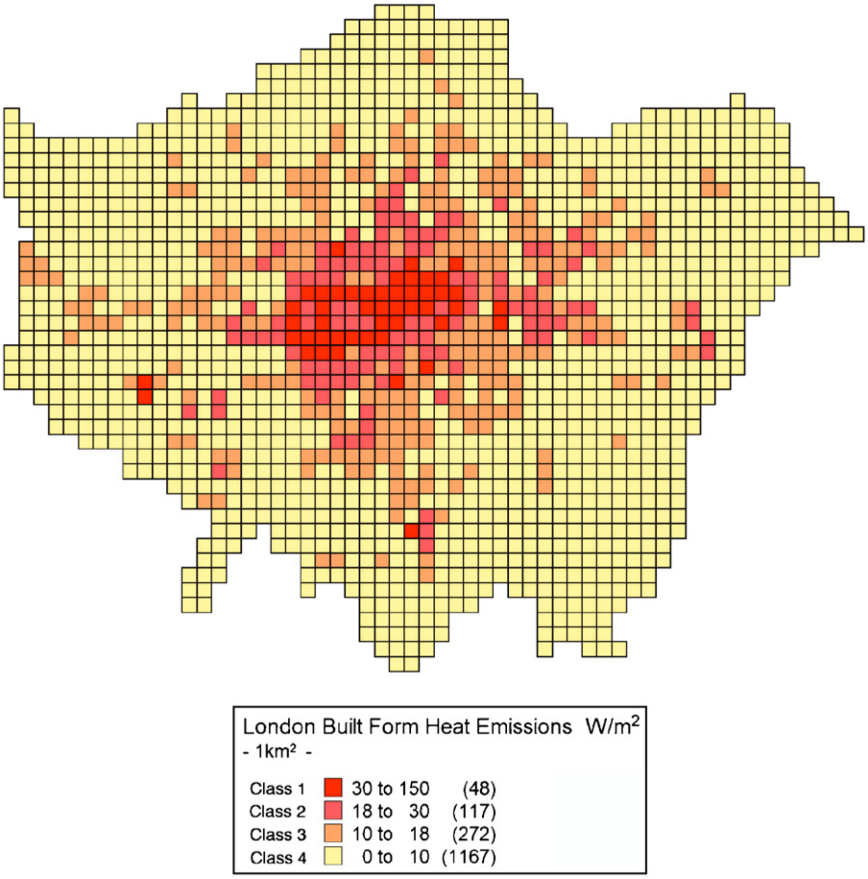

**Fig. 1.** Annual average anthropogenic heat emission from buildings in London (Hamilton et al., 2008).

were instead used for combined heat and power generation, the effect on heat emissions could be negligible. Notice that the future move to decarbonised electricity in its own right is unlikely to make a major change since it does not matter how energy is generated. The energy, whether low carbon or high carbon, all ends up as heat at the place of use.

However, it is worth considering the implications of a widespread move to the capture of solar energy because of its potential impact on the reflectance of roofs. The reflectance (albedo) of a roof surface will have a significant impact on its temperature. Changing the albedo will affect energy flows, both directly to the building and indirectly to the nearby environment. There may be a conflict between solar panels as an energy-gathering technology and the desire for highly reflecting roofs to mitigate the UHI. Additionally, while green roofs offer the potential benefit of associated evaporative cooling if they have appropriate access to water, the use of such roofs may conflict with the placement of solar panels.

Just as a modification to the albedo of roofs will impact on the energy balance of that surface and the surrounding environment, the same issues apply to other urban surfaces such as pavements and parking areas. If they are made more reflective, the UHI effect will be reduced, and if this modification to the albedo is combined with improved water permeability, evaporative cooling will also be enhanced. Highly reflective roads and pavements may also be advantageous for night-time street lighting.

Other modification strategies can make use of the fact that air temperatures in and around green spaces can be several degrees lower than their surroundings (e.g., Spronken-Smith and Oke, 1998). Trees and vegetation are good modifiers of climate. They provide shade and also offer enhanced evaporative cooling, as long as they have enough water. Gill et al. (2007) demonstrate the potential of green space, using Manchester as a case study.

Finally, a key factor that differentiates the energy balance of rural and urban areas is the tendency of the urban area to reduce the emission of long-wave radiation at night. This is due to the reduced view of the sky from urban surfaces. The orientation of streets will also impact on local wind velocities. Issues of sky view and orientation could be considered and addressed at the planning stage. However, clear evidence needs to be provided of their potential impact.

## 3. Energy use

There has been much work in this area. Here we provide only a brief summary.

### 3.1. Energy impacts of the UHI

In general, the UHI would be expected to result in an increased cooling energy demand in summer and a reduced energy demand in the heating season. The literature supports this view. For the UK, measured air temperature data have been used (Kolokotroni et al., 2007) as inputs to a building energy simulation computer program to assess the heating and cooling load of a typical air-conditioned office building positioned at 24 different locations within the London UHI. It was 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%. For this particular building and set of assumptions, the absolute gains due to the heating load reductions were outweighed by the increased cooling loads. For non-air-conditioned buildings, the UHI as described by this dataset would tend to result in net energy savings, albeit coupled with higher summer temperatures.

**Table 1**
Heating and cooling degree-days (data from USA cities adapted from Taha, 1997)

| Location | Heating degree days | | | Cooling degree days | | |
|---|---|---|---|---|---|---|
| | Urban | Airport | $\Delta$ | Urban | Airport | $\Delta$ |
| Los Angeles | 384 | 562 | −178 | 368 | 191 | +177 |
| Washington DC | 1300 | 1370 | −70 | 440 | 361 | +79 |
| St. Louis | 1384 | 1466 | −82 | 510 | 459 | +51 |
| New York | 1496 | 1600 | −104 | 333 | 268 | +65 |
| Baltimore | 1266 | 1459 | −193 | 464 | 344 | +120 |
| London | 2419 | 2779 | −360 | 248 | 207 | +41 |
| Seattle | 2493 | 2881 | −388 | 111 | 72 | +39 |
| Detroit | 3460 | 3556 | −96 | 416 | 366 | +50 |
| Chicago | 3371 | 3609 | −238 | 463 | 372 | +91 |
| Denver | 3058 | 3342 | −284 | 416 | 350 | +66 |

Elsewhere, Landsberg (1981) compared heating and cooling degree-days for several US cities and at airports outside them. A modified table was published by Taha (1997), see Table 1. The relevant data for London have been added to the table for the purposes of this paper. The heating and cooling degree-days are both calculated to a base of 18.3 °C.

The data for London in Table 1 are the average heating and cooling degree-days (1993–2006) for the London Weather Centre (central London) and Northolt (near to, and at a similar radial distance from the centre of London as, Heathrow Airport). Theoretically, the heating and cooling energy used should be a linear function of the number of cooling and heating degree-days provided that the correct base temperature is used. Although the percentage change is much greater for cooling degree-days than for heating, the absolute change in heating degree-days is greater for heating than cooling in most of the locations in Table 1, and the difference becomes greater the further north the location.

### 3.2. Energy impacts of modifications to the urban environment

Strategies for the intentional modification of the urban climate can be effective, and hence can have a significant impact on the energy used by buildings. The effect on energy use may be usefully split into two components. Direct measures involve modifying the energy use of an individual building, for example with a cool roof, while indirect ones rely on modifying the energy use of all buildings by large-scale use of methods such as those outlined in the section above on modifying factors.

One study (Synnefa et al., 2007) looked at the direct impact of using cool roof coatings on the cooling and heating loads and the indoor thermal comfort conditions of residential buildings for various climatic conditions. For the locations studied (in 27 cities worldwide), the heating penalty (0.2–17 $\mathrm{kWh/m^2}$ year) was less important than the cooling load reduction (9–48 $\mathrm{kWh/m^2}$ year).

Akbari and Konopacki (2005) developed simulation-based summary tables of the effect of a range of strategies for UHI reduction, including solar-reflective roofs, shade trees, reflective pavements and urban vegetation, for approximately 240 locations in the USA, sorted by heating and cooling degree-days. They provide estimates of savings for both the direct and indirect effects on three building types—residences, offices and retail stores. The study found significant energy savings. For all building types, over 75% of the total savings were from the direct effects of cool roofs and shade trees.

## 4. Future directions

The literature demonstrates that both the UHI and relevant modifications to the urban environment have the potential to impact significantly on energy use. However, more analysis is required into what happens in practice. Research is currently being undertaken at University College London (UCL) to examine the impact of climate change on energy use. Analysis of the connection between monitored energy use and external temperature suggests that the effect is more complex than previously thought. For example, as temperatures rise the benefits of warmer external conditions are not always taken as reduced energy use, but as higher internal temperature and increased levels of ventilation. Energy use in cities is highly complex. Thus the requirement for air conditioning in cities is often driven more by traffic noise and pollution than by the UHI. Also, some new feedback mechanisms can be foreseen for the future. For example, lightweight electric cars could be quiet and less polluting while contributing less heat to the urban heat island. This could encourage the use of natural ventilation instead of energy-intensive air conditioning.

Widespread and immediate modification of the urban environment to reduce the UHI is not feasible for UK cities on a large scale. However, the collective effect of many smaller changes may be significant at a variety of scales. A number of recent projects have begun to investigate these issues with a particular focus on the UK, in particular two EPSRC funded projects, 'SCORCHIO' (Sustainable Cities: Options for Responding to Climate cHange Impacts and Outcomes) and 'LUCID' ('The Development of a Local Urban Climate Model and its Application to the Intelligent Design of Cities'). The authors of this paper are involved in the LUCID project (2007–2010) that will develop, test and apply state-of-the-art methods for calculating local temperature and air quality in the urban environment. The impact on energy use and the consequences for health of changes to the urban climate will then be explored.

Health models are being developed in LUCID and other projects such as the MRC-funded 'Heat waves in the UK: impacts and public health responses' project. They are intended to relate changes in temperature to mortality rates. This should enable estimates to be made of the impact of modifications to the urban climate on the overall number of deaths. An element of the EPSRC-funded 'PUrE Intrawise' (Pollutants in the Urban Environment: An Integrated Framework for Improving Sustainability of the Indoor Environment) project, of which the authors are part, will consider issues related to the internal conditions of buildings. Attempts to reduce the energy use of buildings and their associated heat emissions by increased insulation and reduced air change rates may lead to overheating and low air quality in poorly designed buildings. The associated health risks need to be borne in mind.

## 5. Conclusions

The climate of an urban area differs from that of a nearby rural area. In this paper the focus has been on the typical situation where the centre of a city is warmer on average than the fringes—the UHI. Modifications to the urban environment will amplify or reduce such differences. Such possible modifications and the likely scale of their impacts have been discussed in the paper. International studies have indicated that the impact of the urban modifications on the energy use of buildings is significant.

There is much current interest in attempting to ameliorate potential summer overheating—that is, a focus on the consequences of heatwaves. However, the wider picture should also be considered. In summer, in the UK, the UHI will tend to result in an increased cooling load and an increased number of excess deaths due to overheating. In winter, conversely, the UHI will tend to result in reduced heating loads and a reduced number of cold-related excess deaths.

For the UK it would be possible to hypothesise that the UHI may actually have a net positive energy, health and comfort effect over the year. The research challenge is to test this hypothesis both for the present day and also for the future, taking into account climate and other social and technical changes. Detailed studies of these issues as they apply to the UK are now under way. The results of this research should be fully understood before any major changes to the urban infrastructure that may impact on the UHI are undertaken.

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## References

Akbari, H., Konopacki, S., 2005. Calculating energy-saving potentials of heat island reduction strategies. Energy Policy 33 (6), 721–756.

Coutts, A.M., Beringer, J., Tapper, N.J., 2007. Impact of increasing urban density on local climate: spatial and temporal variations in the surface energy balance in Melbourne, Australia. Journal of Applied Meteorology 46, 477–493.

Gill, S.E., Handley, J.F., Ennos, A.R., Pauleit, S., 2007. Adapting cities for climate change: the role of the green infrastructure. Built Environment 33 (1), 115–133.

Greater London Authority, 2006a. London Energy and $CO_2$ Emissions Inventory 2003: Methodology Manual. Greater London Authority, London.

Greater London Authority, 2006b. London's Urban Heat Island: A Summary for Decision Makers. Greater London Authority, London.

Grimmond, S., 2007. Urbanization and global environmental change: local effects of urban warming. Geographical Journal 173, 83–88.

Hamilton, I.G., Davies, M., Steadman, J.P., Stone, A., Ridley, I., Evans, S., 2008. Significance of London's anthropogenic heat emissions: a comparison against captured shortwave solar radiation. Building and Environment, in press.

Ichinose, T., Shimodozono, K., Hanaki, K., 1999. Impact of anthropogenic heat on urban climate in Tokyo. Atmospheric Environment 33, 3897–3909.

Klysik, K., 1996. Spatial and seasonal distribution of anthropogenic heat emissions in Lodz, Poland. Atmospheric Environment 30, 3397–3404.

Kolokotroni, M., Zhang, Y., Watkins, R., 2007. The London heat island and building cooling design. Solar Energy 81, 102–110.

Landsberg, H. (Ed.), 1981. The Urban Climate. Academic Press, New York.

Oke, T.R., 1987. Boundary Layer Climates, second ed. Methuen, London.

Spronken-Smith, R.A., Oke, T.R., 1998. The thermal regime of urban parks in two cities with different summer climates. International Journal of Remote Sensing 19 (11), 2085–2104.

Synnefa, A., Santamouris, M., Akbari, H., 2007. Estimating the effect of using cool coatings on energy loads and thermal comfort in residential buildings in various climatic conditions. Energy and Buildings 39 (11), 1167–1174.

Taha, H., 1997. Urban climates and heat islands: albedo, evapotranspiration, and anthropogenic heat. Energy and Buildings 25, 99–103.

Watkins, R., Palmer, J., Kolokotroni, M., Littlefair, P., 2002. The London heat island: results from summertime monitoring. Building Service Engineering Research and Technology 23 (2), 97–106.