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Designing urban spaces and buildings to improve sustainability and quality of life in a warmer world[☆]

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ABSTRACT

It is in cities that the negative impacts of a warming climate will be felt most strongly. The summer time comfort and well-being of the urban population will become increasingly compromised under future scenarios for climate change and urbanisation. In contrast to rural areas, where night-time relief from high daytime temperatures occurs as heat is lost to the sky, the city environment stores and traps heat and offers little respite from high temperatures. This urban heat island effect is responsible for temperature differences of up to 7 °C between cities and the country in the UK. We already have experience of the potential hazards of these higher temperatures. The majority of heat-related fatalities during the summer of 2003 were in urban areas.

This means that the cooling of the urban environment is a high priority for urban planners and designers. Proven ways of doing this include altering the urban microclimate by modifying its heat absorption and emission, for example through urban greening, the use of high-reflectivity materials, and by increasing openness to allow cooling winds. Buildings themselves can also deliver improved comfort and higher levels of sustainability by taking advantage of exemplary façade, glazing and ventilation designs. In addition, changed behaviour by building occupants can help keep urban areas cool. The technology to reduce the future vulnerability of city dwellers to thermal discomfort is already largely in existence. But there is a need for complementary policy and planning commitments to manage its implementation, especially in existing buildings and urban areas.

1. Introduction

The unique microclimate of cities is the product of their complex built environment, their lack of cooling vegetative surfaces, and their increased anthropogenic activity. These combine to create a thermal contrast between urban and rural areas. This distinctive temperature pattern is at its most pronounced during the night, when the release of stored heat and the containment of outgoing long-wave radiation in urban areas combine to make them systematically warmer than the countryside (Oke, 1987). This 'urban heat island' (UHI) effect is well documented (Landsberg, 1981), and can lead to temperature differences of up to 7 °C between the centres of large conurbations in the UK and their surrounding rural areas (Wilby, 2003).

As a consequence, the inhabitants of cities have difficulty in finding respite from high summer temperatures, and this threat to human comfort and well-being poses a significant challenge for urban planners and designers. The European summer heatwave in August 2003, the warmest August on record in the northern hemisphere, was estimated to be responsible for some 35,000 heat-related fatalities, over 2000 of which were in the UK (Larsen, 2003). The impacts of this event were felt most strongly in urban areas, because of a lack of night-time relief from high temperatures. Recent research has focused on identifying and reducing the vulnerability of high-risk individuals within the urban environment to future heatwave events (e.g. Fouillet et al., 2006; Lindley et al., 2006).

This problem will become increasingly heightened under future climate change scenarios and projections of urbanisation. The urban population of Europe is predicted to increase from 73% of the total population in 2000 to 80% in 2030 (United Nations, 2005) and temperature increases of 0.1–0.5 °C per decade are expected across the UK and Europe during the 21st century (Hulme et al., 2002; IPCC, 2007a). While the use of mechanical cooling in buildings enables a reduction in internal temperatures and restores the comfort level for occupants, it is not a desirable solution overall. It produces waste heat that is emitted directly to the surrounding environment of the building, which in turn intensifies the UHI effect. Moreover, the increased use of air-conditioning conflicts (Levermore et al., 2004) with current national policies to curb CO_2 emissions (DTI, 2003; Defra, 2006).

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Adaptive strategies for the built environment are to be preferred to the increased use of air conditioning. The building sector is currently responsible for over a third of global greenhouse gas emissions, and has been cited by the IPCC (2007b) as the sector with the greatest potential for carbon saving. The typical design life of 20–100 years for buildings means that their designers and developers have a responsibility to anticipate future climates and to avoid changes prejudicing the structural integrity, external fabric and internal environment of buildings (GLA, 2005). Such a forward-thinking approach to 'climate-proofing' can reap significant benefits in the long term, including substantial economic savings (UKCIP, 2004). Furthermore, detailed risk assessment and appropriate planning for adaptation can minimise risk and exploit opportunities, by seeking optimal options, which are mutually beneficial (Lindley et al., 2007). These approaches avoid mal-adaptation, such as the use of air conditioning, and encourage the development of buildings that improve thermal comfort while having lower energy use.

2. Current understanding

Some degree of warming in urban areas is inevitable, because of the delay between greenhouse gases being emitted and their full effect on the climate. Recognition of this reality has seen a shift in focus in the recent literature from greenhouse gas emission mitigation strategies to risk analysis and the identification of adaptive mechanisms (Lindley et al., 2006, 2007; McEvoy et al., 2006; Willows and Connell, 2003). Successful adaptation to minimise the occurrence of heat stress is, however, dependent upon a detailed understanding of the processes that lead to elevated urban temperatures. Fortunately, there exists a wealth of literature concerned with urban climatology across a range of spatial and temporal scales, extensively reviewed in recent publications by Arnfield (2003) and by Souch and Grimmond (2006).

2.1. *Urban climatology*

Urban areas contain buildings and environments with distinctive topography and bio-physical properties. This means that their energy receipts and losses are different from those of rural areas. The steepness of the urban–rural temperature gradient depends upon a range of meteorological and geomorphological variables. But maximum heat island intensity is generally observed on calm, clear nights following a day of similar conditions. In this scenario, the lack of cloud means that daytime solar radiation receipt is at its greatest. This leads to a large amount of heat being stored in the urban fabric, which is characterised by low albedo and hence by a high tendency to absorb heat. This heat is released into the surrounding environment as the external air temperature cools after sunset. But net losses of heat by long-wave radiation are at a maximum during the evening in the rural hinterland, and remain comparatively low in the city, where radiation is reflected or absorbed by buildings and by higher levels of air pollution. Under low wind conditions the difference is further accentuated, since nocturnal cooling is inhibited by the lack of ventilation to transport warmer air away from the urban environment.

The alteration of the urban radiative energy balance, and the reduction of heat loss by wind-driven turbulence in a city environment, are both consequences of urban surface geometry. The convoluted nature of the urban surface leads to radiative interaction between tall urban structures. Radiation which in a rural area would be emitted into the atmosphere is reflected instead between surfaces. This urban morphology is also responsible for lowering the 'porosity' of the city and limiting air flow through it (Britter and Hanna, 2003; Skote et al., 2005). Street canyon geometry is often measured in terms of the sky view factor (SVF) the proportion of sky visible in a 180° field of view, or of the aspect ratio, the height of the canyon divided by its width. Both are readily quantifiable measures of urban terrain (e.g. Chapman et al., 2001; Grimmond et al., 2001). They are also a surrogate for building density, which is a key variable in controlling heat island intensity. The overall size of a city, measured by population, displays a non-linear relationship with the urban–rural temperature difference (Oke, 1987). Even quite small centres are found to have a heat island effect. The gradient of this relationship differs, for example between European and North American cities, as a result of different development patterns and planning structures (Goudie, 2005). This means that SVF is generally accepted as a more robust indicator of heat island intensity than aspect ratio.

Although complex, the relationship between urban morphology and the urban–rural temperature difference has been shown to display an inverse linear association under the idealised UHI conditions outlined above, for a range of mid-latitude, developed cities (Oke, 1981). This means that more built up or denser cities have bigger heat island effects. However, spatial temperature variations within a city may not correspond quite so simply with SVF, owing to the myriad of other potential influencing factors that are present at the microscale (Eliasson, 1996). For instance, a key difference between the surface energy budget at rural and urban sites is the ratio of the latent to sensible heat fluxes. In rural areas, the surface is dominated by vegetation, from which water evaporates. In contrast, much of the surface in an urban environment has undergone waterproofing through the use of impervious materials, reducing the latent heat flux (Grimmond and Oke, 1999, 2002). Differences in land use, irrigation, wind speed and rainfall mean that evaporative cooling varies in urban environments. But even in densely populated areas the latent heat flux accounts for 20–40% of the net radiation balance (Grimmond and Oke, 2002; Grimmond et al., 2004). On a neighbourhood scale, the presence of a vegetated area or water body within a city can have a significant cooling effect on local temperatures (Graves et al., 2001; Spronken-Smith and Oke, 1999).

The day-to-day activities of city inhabitants also emit heat into the surrounding environment (Grimmond, 1992; Ichinose et al., 1999; Sailor and Lu, 2004). The energy consumed by traffic, buildings and people results in heat generation, which makes a significant contribution to the urban environment, particularly during winter. Estimates of its scale range from 71 W/m^2 in Lodz, Poland (Klysik, 1996), to 1590 W/m^2 in central Tokyo (Ichinose et al., 1999). This contributes between 1 and 3 °C to the heat island effect (Fan and Sailor, 2005). Data from energy consumption statistics suggest a more refined range for the mean annual anthropogenic heat flux of 20–160 W/m^2 for large cities (Oke, 1987), ranging between 20 and 40 W/m^2 in summer and between 70 and 210 W/m^2 in winter (Taha, 1997). The effect of this waste heat production is to create a 2–3 °C heat island in the central areas of such cities (Taha et al., 1992).

As discussed above, several studies have found urban morphology to be of fundamental importance to the timing and magnitude of the heat island effect (Arnfield, 1990; Oke et al., 1991; Swaid, 1993). In contrast, the thermal absorption and reflectance of urban and rural landscapes are not dissimilar (Oke, 1981). Nevertheless, Oke et al. (1991) suggest that the thermal admittance of the urban fabric and the canyon geometry are of approximate equal importance to UHI formation. Within a city, temperature patterns are dominated by an inverse relationship between temperature and distance from the city centre, but are also strongly related to land use, which is often a surrogate for urban morphology and geometry as well as to surface characteristics such as the availability of water (Eliasson and Svensson, 2003; Henry and Dicks, 1987; Landsberg, 1981; Wilby, 2003).

2.2. Applied climatology

As summer temperatures rise, planners and designers will seek to modify the urban climate to reduce inhabitants' vulnerability to heat stress. This is achievable by altering key terms in the energy balance, which governs the thermal contract between urban and rural areas. Measures to redress the balance include reducing solar radiation receipts, or increasing the latent heat flux away from the surface (see previous section). However, it should be borne in mind that high-risk areas in summer may benefit from winter temperature increases of 1–2 °C by the 2050s (Hulme et al., 2002). This will lead to substantial savings in winter energy consumption for space heating, reducing the incidence of fuel poverty. It is important that any adaptation of urban planning and building design to raise comfort levels in summer should not impinge on the potential for reducing winter heating demands.

Thermal discomfort can occur in both the internal and external environments. The greening of urban environments by planting more vegetation to encourage evapotranspiration, and the reduction of solar gains by using high reflectivity materials in urban structures, have frequently been cited as possible options for alleviating the thermal discomfort of the external urban environment (Akbari et al., 1997; Gill et al., 2007; Rosenfeld et al., 1995; Santamouris et al., 2007; Synnefa et al., 2007). Yet both methods have seen only limited integration into UK cityscapes (Mills, 2005), in spite of the wide range of associated benefits that they offer. More vegetation can mean improved drainage and greater potential for biodiversity, while the use of reflective materials reduces energy consumption in the summer (Rosenfeld et al., 1995). Under the Government's sustainable communities plan, the low uptake of these approaches is likely to change. Local authorities are being encouraged to look to continental Europe (e.g. Malmö, Aarhus, Copenhagen and Berlin) for best practice case studies (Beer and Jorgensen, 2004; CABE Space, 2004, 2005).

Microclimate modification through the use of vegetation can also be integrated into the building envelope in the form of green roofs or bio-shaders (Niachou et al., 2001). This form of passive cooling not only brings benefits to the internal occupants of the building but also provides significant external cooling, potentially offsetting future temperature increases (Gill et al., 2007). The use of water features in a city offers an alternative to vegetation as a method of alleviating high urban temperatures by increasing the latent heat flux from the surface, as exemplified in Arabic and Indian architecture.

The amount of solar energy that buildings receive can be reduced by considering the orientation of streets and streamlining their design. East–west oriented streets suffer from a prolonged period of solar exposure by comparison with north–south oriented streets during the summer. This is a critical factor affecting thermal comfort, as direct solar radiation is capable of elevating the radiant temperature by as much as 25 °C (Watkins et al., 2007). In Spain, which offers a useful analogue to the future UK climate in some respects (although in Spain the sun is higher in the sky and the solar irradiance generally greater), awnings are used to intercept solar radiation and to provide shade on the street level and in buildings. However, it is important that shading does not cut out visible light, which would cause the energy savings from cooling to be counteracted by its use for artificial lighting. As an alternative, the receipt of solar energy by the internal environment can be controlled by careful positioning of glazing in the building façade or by taking advantage of technical advances in glazing. New glazing materials are capable of reducing solar heat transmission by up to 75% while optimising light infiltration.

Street orientation is also an important factor for urban ventilation. An angle of 45° to the prevailing wind direction is considered optimal (Sandberg et al., 2003) and advection across parks can accentuate the cooling effect of the wind (Eliasson and Upmanis, 2000). Appropriate alignment of street canyons can be used for external cooling but also has implications for passive cooling in buildings. A critical appraisal of natural ventilation options for UK buildings (Hacker and Holmes, 2007) suggested that passive design of buildings (i.e. without reliance on mechanical cooling systems) is a viable option, at least for the next 50 years. With natural ventilation, the ability of the mass of the building to absorb summer heat during the day and release it at night is an important consideration (Levermore, 2000). Because it involves openings in the façade, implementation is dependent upon the mitigation of air and noise pollution and on risk of crime. All three are often a consideration in urban areas. However, given the increasing enforcement of air quality and noise standards within city environments it is likely that there will be a reduction in these adverse effects in the future.

While it is often simpler to integrate adaptive building design into new developments, existing buildings should not be neglected. These dominate energy usage owing to the low turnover rate of buildings by comparison with most other assets. Existing buildings will become increasingly vulnerable to overheating. Retrofitting them to reduce energy consumption provides an opportunity for tackling their internal thermal environments.

Human behaviour is also vital in determining the energy use of buildings. Substantial energy savings can be made within buildings by educating the consumer and influencing occupant behaviour (IPCC, 2007a, b).

A gradual warming of the climate creates an opportunity for people to adapt to the external climate and increase their tolerance of high temperatures. The current UK guidelines for thermal comfort in office buildings recommend that internal temperatures should exceed 28 °C for less than 1% of the occupied time (CIBSE, 2006). In hotter climates these comfort levels would be scaled up to reflect the local monthly mean outdoor temperature, which has been shown to display an approximate linear relationship with the perceived comfortable temperature in naturally ventilated buildings with openable windows (Humphreys, 1976; Nicol and Humphreys, 2002). Comfort can also be determined by the social and cultural environment (Cooper, 1998), so greater flexibility here offers an alternative mechanism for adaptation. For example, the relaxing of the office dress code in the Japanese Cool Biz campaign aimed to change the attitude of city workers to formal dress, as a means of combating thermal discomfort and reducing air-conditioning loads (Moffett, 2007).

However, in addition to hotter summers generally, the UK climate is also set to experience extreme events (e.g. heatwaves) of increasing magnitude and frequency (Hulme et al., 2002). These will hinder human adaptive capacity and have implications for the comfort of the built environment (Levermore et al., 2004).

3. Future developments

Successful adaptation to reduce future vulnerability to heat stress is dependent upon a range of social, environmental and technical factors. Policies, regulations and guidelines can be used to shape adaptation (e.g. Building Regulations Part L, 2006; Defra, 2006; IPCC, 2007b). The adaptation policy framework is likely to encourage a more integrated approach to adaptation and can be used to identify conflicts, feedbacks and linkages across sectors

(Lindley et al., 2007). For example, by reducing energy consumption in buildings and transport, urban heat emissions are reduced, which will help to alleviate the heat island effect. In addition, the lower greenhouse gas emissions associated with increasing energy efficiency measures will help to mitigate further climate warming.

On a more local scale, the long-term implications of decisions concerning the built environment mean that any action taken needs to be based on detailed information across a range of disciplines. A crucial first step towards adaptation in urban areas is the identification of vulnerable parties. The IPCC defines vulnerability as a function of hazard, exposure and sensitivity. This emphasises the need for a holistic approach to decision-making. It must incorporate knowledge of the risk of occurrence of high temperatures and of the socio-economic characteristics which limit adaptive capacity, such as being elderly or infirm (e.g. Lindley et al., 2006). The activity associated with a particular building or space will also relate to the likelihood of its occupants experiencing thermal discomfort and its timing, as with disrupted sleep, and is an important consideration for risk assessment. This type of integrated appraisal offers a mechanism through which risk can be readily quantified, in addition to highlighting areas in most need of immediate adaptive action.

Future requirements for reducing the UHI will stem from changes in the Building Regulations. These will be increasingly tightened in the future to reduce carbon and consequently heat emissions, as required by the EC Directive on the Energy Performance of Buildings (EC, 2002). Designed to meet the Kyoto commitment and to address issues of energy supply security, the Directive is set to promote improved energy performance in buildings. It will involve energy certification, inspection and assessment of heating and cooling installations, a methodology for calculating the integrated performance of buildings, and the setting of minimum standards for new and existing buildings (Bowie and Jahn, 2003). The technical factors mentioned above will be used to establish low-energy buildings without air conditioning.

However, the greater problem is the existing building stock, which will be around for many years to come. Article 6 of the Directive requires the upgrading of existing buildings with over 1000 m^2 of useful floor area, but only when they are refurbished. The refurbishment of smaller buildings and domestic dwellings is also crucial and will have to be addressed. Insulation, more efficient boilers and appliances, and better glazing and shading systems will all be needed, much as they will for new buildings. A more contentious idea is the demolition of some existing buildings (Lowe, 2007).

The success of this new performance-based regulation depends on the effectiveness of compliance, inspection and enforcement, and the Directive requires metering and displaying of energy consumption in many buildings to aid compliance and enforcement.

Future planning and development can help to reduce the UHI considerably, by adding to the evapotranspiration of built up areas with green spaces as outlined in the ASCCUE project (ASCCUE, 2006 and its successor under way at present, SCORCHIO, 2007). Green roofs will also contribute to the openness of the urban area, to allow cooling winds to take away the heat.

This means that the design of spaces and buildings can deliver improved comfort and more sustainable energy solutions. The technology is largely there but policy and planning commitments are required to make sure it is used. This is of crucial importance, as urban areas are set to grow in the future at the expense of rural ones.

References

Akbari, H., Kurn, D.M., Bretz, S.E., Hanford, J.W., 1997. Peak power and cooling energy savings of shade trees. Energy and Buildings 25, 139–148.

Arnfield, A.J., 1990. Canyon geometry, the urban fabric and nocturnal cooling: a simulation approach. Physical Geography 11, 220–239.

Arnfield, A.J., 2003. Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. International Journal of Climatology 23, 1–26.

ASCCUE, 2006. Adaptation strategies for climate change in the urban environment 〈http://www.k4cc.org/bkcc/asccue〉.

Beer, A.R., Jorgensen, A., 2004. New Approaches in Europe. Decent Homes, Decent Places, Improving the Green Spaces for Social Housing. Peabody Trust, London, pp. 14–16.

Bowie, R., Jahn, A., 2003. European union—the new directive on the energy performance of buildings—moving closer to Kyoto. European Commission, Directorate General for Energy & Transport, Unit D1—regulatory policy & promotion of new energies and of demand management 〈http://www.managenergy.net/download/r210.pdf〉.

Britter, R.E., Hanna, S.R., 2003. Flow and dispersion in urban areas. Annual Review of Fluid Mechanics 35, 469–496.

Building Regulations, Approved Document Part L, 2006. Department of Communities and Local Government, London.

CABE Space, 2004. Is the Grass Greener…? Learning from International Innovations in Urban Green Space Management. Commission for Architecture and the Built Environment, London.

CABE Space, 2005. Start with the Park: Creating Sustainable Urban Green Spaces in Areas of Housing Growth and Renewal. Commission for Architecture and the Built Environment, London.

Chapman, L., Thornes, J.E., Bradley, A.V., 2001. Rapid determination of canyon geometry parameters for use in surface radiation budgets. Theoretical and Applied Climatology 69, 81–89.

CIBSE, 2006. Environmental Design, CIBSE Guide A, seventh ed. Chartered Institution of Building Services Engineers, London.

Cooper, G., 1998. Air-Conditioning America: Engineers and the Controlled Environment 1900–1960. Johns Hopkins University Press, Baltimore.

Defra, 2006. Climate Change: The UK Program. Defra, London.

DTI, 2003. Our energy future—creating a low carbon economy.

EC, 2002. Directive 2002/91/EC of the European parliament and of the council of 16 December 2002 on the energy performance of buildings 〈http://ec.europa.eu/energy/demand/legislation/buildings_en.htm〉.

Eliasson, I., 1996. Urban nocturnal temperatures, street geometry and land use. Atmospheric Environment 30, 379–392.

Eliasson, I., Svensson, M.K., 2003. Spatial air temperature variations and urban land use—a statistical approach. Meteorological Applications 10, 135–149.

Eliasson, I., Upmanis, H., 2000. Nocturnal outflow from urban parks—implications for the city ventilation. Theoretical and Applied Climatology 66, 95–107.

Fan, H.L., Sailor, D.J., 2005. Modeling the impacts of anthropogenic heating on the urban climate of Philadelphia: a comparison of implementations in two PBL schemes. Atmospheric Environment 39, 73–84.

Fouillet, A., Rey, G., Laurent, F., et al., 2006. Excess mortality related to the August 2003 heatwave in France. International Archives of Occupational and Environmental Health 80, 16–24.

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, 115–133.

GLA, 2005. Adapting to Climate Change: A Checklist for Development. Greater London Authority, November 2005.

Goudie, A., 2005. The Human Impact on the Natural Environment: Past, Present and Future. Blackwell Publishing, Oxford.

Graves, H., Watkins, R., Westbury, P., Littlefair, P., 2001. Cooling Buildings in London: Overcoming the Heat Island. BRE and DETR, London.

Grimmond, C.S.B., 1992. The suburban energy balance: methodological considerations and results for a mid-latitude west coast city under winter and spring conditions. International Journal of Climatology 12, 481–497.

Grimmond, C.S.B., Oke, T.R., 1999. Heat storage in urban areas: local-scale observations and evaluation of a simple model. Journal of Applied Meteorology 38, 922–940.

Grimmond, C.S.B., Oke, T.R., 2002. Turbulent heat fluxes in urban areas: observations and local-scale urban meteorological parameterization scheme LUMPS. Journal of Applied Meteorology 41, 792–810.

Grimmond, C.S.B., Potter, S.K., Zutter, H.N., Souch, C., 2001. Rapid methods to estimate sky view factors applied to urban areas. International Journal of Climatology 21, 903–913.

Grimmond, C.S.B., Salmond, J.A., Oke, T.R., Offerle, B., Lemonsu, A., 2004. Flux and turbulence measurements at a dense urban site in Marseille: heat, mass (water, carbon dioxide) and momentum. Journal of Geophysical Research—Atmospheres 109.

Hacker, J.N., Holmes, M.J., 2007. Thermal comfort: climate change and the environmental design of buildings in the United Kingdom. Built Environment 33, 97–114.

Henry, J.A., Dicks, S.E., 1987. Association of urban temperature with land use and surface materials. Landscape and Urban Planning 14, 21–29.

Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M., Hassell, D., Boorman, P., McDonald, R., Hill, S., 2002. Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report, Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich.

Humphreys, M.A., 1976. Field studies of thermal comfort compared and applied. Building Services Engineering 44, 5–27.

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

IPCC, 2007a. Climate change 2007: impacts, adaptation and vulnerability. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 541–580.

IPCC, 2007b. Climate change 2007: mitigation. In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Mayer, L.A. (Eds.), Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge (Chapter 6).

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

Landsberg, H.E., 1981. The Urban Climate. Academic Press, New York.

Larsen, J., 2003. Record heatwave in Europe takes 35000 lives. Earth Policy Institute.

Levermore, G., 2000. Building Energy Management Systems; Application to Low-Energy HVAC and Natural Ventilation Control, second ed. E & FN Spon, Taylor & Francis Group, London.

Levermore, G., Chow, D., Jones, P., Lister, D., 2004. Accuracy of modelled extremes of temperature and climate change and its implications for the built environment in the UK. Tyndall Centre Technical Report 14.

Lindley, S.J., Handley, J.F., Theuray, N., Peet, E., McEvoy, D., 2006. Adaptation strategies for climate change in the urban environment—assessing climate change related risk in UK urban areas. Journal of Risk Research 9, 543–556.

Lindley, S.J., Handley, J.F., McEvoy, D., Peet, E., Theuray, N., 2007. The role of spatial risk assessment in the context of planning for adaptation in UK urban areas. Journal of Built Environment 33, 46–69.

Lowe, R., 2007. Addressing the challenges of climate change for the built environment. Building Research and Information 35 (4), 343–350.

McEvoy, D., Lindley, S., Handley, J., 2006. Adaptation and mitigation in urban areas: synergies and conflicts. In: Proceedings of the Institution of Civil Engineers, Municipal Engineer, vol. 159, pp. 185–191.

Mills, L., 2005. Sources of EU funding for urban environment activities in the UK. Royal Commission on Environmental Pollution 〈http://www.rcep.org.uk/urban-environment-evidence/lizmills-uk-gateway-additional.pdf〉.

Moffett, S., 2007. Japan sweats it out as it wages war on air-conditioning. Wall Street Journal 18th September 〈http://yaleglobal.yale.edu/display.article?id=9680〉.

Niachou, A., Papakonstantinou, K., Sanatamouris, M., Tsangrassoulis, A., Mihalakakou, G., 2001. Analysis of the green roof thermal properties and investigation of its energy performance. Energy and Buildings 33, 719–729.

Nicol, J.F., Humphreys, M.A., 2002. Adaptive thermal comfort and sustainable thermal standards for buildings. Energy and Buildings 34, 563–572.

Oke, T.R., 1981. Canyon geometry and the nocturnal heat island. Comparison of scale model and field observations. Journal of Climatology 1, 237–254.

Oke, T.R., 1987. Boundary Layer Climates. Routledge, London.

Oke, T.R., Johnson, G.T., Steyn, D.G., Watson, I.D., 1991. Simulation of nocturnal surface urban heat islands under 'ideal' conditions: part 2. Diagnosis of causation. Boundary-Layer Meteorology 56, 339–358.

Rosenfeld, A.H., Akbari, H., Bretz, S., Fishman, B.L., Kurn, D.M., Sailor, D., Taha, H., 1995. Mitigation of urban heat islands: materials, utility programs, updates. Energy and Buildings 22, 255–265.

Sailor, D.J., Lu, L., 2004. A top-down methodology for developing diurnal and seasonal anthropogenic heating profiles for urban areas. Atmospheric Environment 38, 2737–2748.

Sandberg, M., Westerberg, U., Claesson, L., 2003. Catchment area—a new approach to urban windiness. In: Proceedings of the Fifth International Conference on Urban Climate, 1–5 September, Lodz, Poland.

Santamouris, M., Pavlou, K., Synnefa, A., Niachou, K., Kolokotsa, D., 2007. Recent progress on passive cooling techniques—advanced technological developments to improve survivability levels in low income households. Energy and Buildings 39, 859–866.

SCORCHIO, 2007. Sustainable cities: options for responding to climate change impacts and outcomes 〈http://gow.epsrc.ac.uk/ViewGrant.aspx?GrantRef=EP/E017398/1〉.

Skote, M., Sandberg, M., Westerberg, U., Claesson, L., Johansson, A.V., 2005. Numerical and experimental studies of wind environment in an urban morphology. Atmospheric Environment 39, 6147–6158.

Souch, C., Grimmond, C.S.B., 2006. Applied climatology: urban climatology. Progress in Physical Geography 30, 270–279.

Spronken-Smith, R.A., Oke, T.R., 1999. Scale modelling of nocturnal cooling in urban parks. Boundary-Layer Meteorology 93, 287–312.

Swaid, H., 1993. Urban climate effects of artificial heat sources and ground shadowing by buildings. International Journal of Climatology 13, 792–812.

Synnefa, A., Santamouris, M., Apostolakis, K., 2007. On the development, optical properties and thermal performance of cool colored coatings for the urban environment. Solar Energy 81, 488–497.

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

Taha, H., Akbari, H., et al., 1992. Causes and effects of heat islands: sensitivity to surface parameters and anthropogenic heating. Lawrence Berkeley Laboratory Report 29864, Berkeley, CA.

UKCIP, 2004. Costing the impacts of climate change in the UK. Technical Report, UKCIP, Oxford.

United Nations, 2005. Department of Economic and Social Affairs, Population Division. World urbanisation prospects: the 2005 revision. Working Paper No. ESA/P/WP/200.

Watkins, R., Palmer, J., Kolokotroni, M., 2007. Increased temperature and intensification of the urban heat island: implications for human comfort and urban design. Built Environment 33, 85–96.

Wilby, R.L., 2003. Past and projected trends in London's urban heat island. Weather 58, 251–260.

Willows, R.I., Connell, R.K. (Eds.), 2003. Climate Adaptation: Risk, Uncertainty and Decision-Making. UKCIP Technical Report, UKCIP, Oxford.