RESIDENTIAL OVERHEATING RISK IN AN URBAN CLIMATE

KANCHANE R. GUNAWARDENA

The Martin Centre for Architectural and Urban Studies
Department of Architecture
University of Cambridge

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Kanchane R. Gunawardena

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Master of Philosophy, Declaration

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except as declared in the acknowledgments and specified in the text. I further state that no substantial part of my dissertation has already been submitted, or is being concurrently submitted for any such degree, diploma or other qualification at the University of Cambridge, or any other University or similar institution except as declared in the acknowledgments and specified in the text.

This dissertation does not exceed the prescribed word limit of the University of Cambridge, Architecture and History of Art Degree Committee. The word-count is 19,920; excluding title pages, orientation on pages i-xiv, appendices A to C, and the bibliography text.

Kanchane R. A. Gunawardena 27 July 2015

Abstract

A warming climate, increasing frequency and severity of extreme heat events, and the heat island effect are cumulatively expected to exacerbate environmental thermal loading on urban buildings. This in turn could lead to increased summertime overheating, with potential for causing adverse effects to the health and wellbeing of building occupants. The means for addressing such heat-related risks are likely to influence energy consumption and CO_2 emission trends, particularly in residential areas where active cooling has traditionally received less attention in the United Kingdom. If energy efficient approaches are not adopted, future patterns of urban living are likely to adversely influence the carbon reduction target prescribed by the Climate Change Act 2008.

This dissertation is concerned with identifying adaptations for addressing summertime overheating risk in temperate climate urban residential buildings, and ways in which both authorities and designers can facilitate such measures. The method for addressing this considered the simulation of a residential street canyon within the London heat island, with the findings discussed with reference to a multidisciplinary evidence base. The findings highlighted that accounting for the warmer urban microclimate had a beneficial 12.9% reduction in the energy consumption estimate, although at the expense of increased overheating risk. Improving the thermal performance of the envelope had a patent energy use benefit, although the mixed influence on overheating highlighted that threshold exceedance increased while 'severity' was reduced. Adding adaptive capabilities to this improved envelope demonstrated that 'comfort' could be achieved without the need for energy intensive active solutions. The argument against the widespread adoption of mechanical cooling as a principal adaptation was highlighted by an estimated 0.4 K increase in nocturnal canyon temperatures and 77 metric tons of CO_2 released to the climate. In addition to the said findings, the study verified a method pathway that included the use of an Urban Weather Generator to account for microclimatic variations in building energy simulations.

Dedicated to my loving parents,

Dr and Mrs Mahinda and Anoma Gunawardena;

&

paternal grandfather, the late Don Carlin Gunawardena,
Professor of Botany, and
maternal grandfather, the late M. A. A. Akmimana,
Surveyor

...for inspiring my research studies.

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Contents

Abbreviations

ANN	Artificial neural network
ARCC	Adaptation and Resilience in the Context of Change (umbrella network for EPSRC-funded research projects, UK)
ASC	Adaptation Sub-Committee (of the Committee on Climate Change, UK)
BEM	Building energy model
BES	Building energy simulation
BSI	British Standards Institution
CCC	Committee on Climate Change (independent body established under the Climate Change Act 2008 to advise the United Kingdom Government)
CIBSE	Chartered Institution of Building Services Engineers (UK)
CREW	Community Resilience to Extreme Weather - an EPSRC funded research project (UK)
DECC	Department for Energy and Climate Change (UK)
DHDC	District heating and district cooling
DSM	Dynamic simulation modelling
DSY	Design summer year
EPSRC	Engineering and Physical Sciences Research Council (UK)
EST	Energy Saving Trust (UK)
GIS	Geographic information system
HVAC	Heating, ventilation, and air-conditioning
IES-VE	Dynamic simulation modelling software (commercially available)
IPCC	Intergovernmental Panel on Climate Change (UN)
LGW	London Gatwick Airport (TMY weather station, UK)
LHR	London Heathrow Airport (TMY weather station, UK)
LSSAT	London Site Specific Air Temperature (ANN model from LUCID)
LUCID	Local Urban Climate Model and its Application to the Intelligent Design of Cities – an EPSRC funded research project (UK)
LWC	London Weather Centre (TMY weather station, UK)
NPPF	National Planning Policy Framework (England)
PBL	Planetary boundary layer
SAP	Standard assessment procedure
TEB	Town Energy Budget (an urban canopy layer model)
TMY	Typical meteorological year

UBL	Urban boundary layer
UCL	Urban canopy layer
UCM	Urban canopy layer model
UHI	Urban heat island
UWG	Urban Weather Generator (an urban climate simulation model)
WBGT	Wet-bulb globe temperature
WCC	Westminster City Council (a borough in inner London, England)
WMO	World Meteorological Organization (UN)
ZCH	Zero Carbon Hub (UK)

Study abbreviations

Base-LGW	Free-running base unit (as existing), simulated with rural London Gatwick Airport (LGW) weather data.
LGW+UHI	Free-running base unit simulated with the heat island morphed weather data from the UWG.
+INS	Simulated with insulation retrofit options considered for the study (refer to Appendix B.3, p. 103).
+AC	Simulated with domestic air-conditioning options considered for the study (refer to Appendix B.4, p. 104).
+AC0	Air-conditioning applied to unit simulated with rural LGW weather data.
+AC1	Air-conditioning applied to unit simulated with the heat island morphed weather data from the UWG.
+AC2	Air-conditioning applied to thermally upgraded (+*INS*) unit simulated with the heat island morphed weather data from the UWG.
+UAC	Simulated with widespread air-conditioning use in the urban canyon area (refer to Appendix B.4, p. 104).
FamOcu	Small family occupation profile (two working adults and a child) per flat (refer to Appendix B.2, p. 101).
EldOcu	Older couple occupation profile (two retired adults) per flat (refer to Appendix B.2, p. 101).
N	North-facing.
S	South-facing.

Nomenclature

Symbol	Description	Unit
Q_F	Anthropogenic heat flux	W·m^{-2}
DBT	Dry-bulb temperature	°C
ΔDBT	Dry-bulb temperature change for heat island	K
DBT_{mod}	Dry-bulb temperature modified	°C
$Q_{F,B}$	Energy flux from buildings (to outdoor climate)	W·m^{-2}
$Q_{F,M}$	Energy flux from human metabolism	W·m^{-2}
$Q_{F,T}$	Energy flux from transportation	W·m^{-2}
$UHI\ \Delta T_{max}$	Maximum urban heat island intensity	K
$UHI\ \Delta T_{min}$	Minimum urban heat island intensity	K
T_{op}	Operative temperature (indoor)	°C
$UHI\ \Delta T$	Urban heat island intensity	K

Key definitions

Comfort: Described as a state of physical ease and freedom from pain or constraint (Stevenson, 2010).

Degree-hrs: Defined by the Energy Saving Trust (2005) to describe overheating severity, as the hours weighted by how much the prevailing temperature exceeds the defined threshold, e.g., an hour measured at 31°C (dry-resultant temperature) would be 4 degree-hrs above the 27°C threshold.

Dry-bulb temperature (DBT): Refers to air temperature excluding radiation and moisture influence, measured by a thermometer (ZCH, 2015b).

Failure-day: Refers to a normalised measure used to compare between different overheating assessment methods. It essentially describes the failure of a room to meet an assessment criterion for a given day.

Free-running buildings: Refers to naturally ventilated buildings that do not use mechanical cooling (CIBSE, 2015).

Health: The World Health Organisation (WHO) definition describes it as 'a state of complete physical, mental, and social wellbeing and not merely the absence of disease or infirmity' (Park & Allaby, 2013).

Heatwave: The World Meteorological Organization (WMO) definition describes it as 'when the daily maximum temperature of more than five consecutive days exceeds the average maximum temperature by 5°C, the normal period being 1961-1990' (www.metoffice.gov.uk).

Operative temperature (T_{op}): Also referred to as **dry resultant temperature** (in IES-VE), combines air temperature (T_a) with radiant effects (T_r) to provide a more realistic representation of the temperature perceived by occupants within a space (CIBSE, 2015). As air velocity increases, (T_{op}) tends towards (T_a), at air speeds of 0.1 m·s^{-1} or less (typical in buildings) it approximates to the following (CIBSE, 2013):

$$T_{op} \approx \frac{(T_r + T_a)}{2}$$ *Equation 1*

PBL: The 'planetary boundary layer' is described as a part of the atmosphere that is influenced by its contact with the planetary surface (Oke, 1976).

RCP8.5: 'Representative Concentration Pathway 8.5' is a climate change scenario that assumes high population, slow income growth, and modest rates of technological change and energy efficiency leading in the long-term to high energy demand and greenhouse gas emissions in the absence of climate change mitigation policies. Compared to other RCPs, this pathway would lead to the highest emissions and resultant climate impact (Riahi, et al., 2011).

Running mean (T_{rm}): Refers to the exponentially weighted daily mean outdoor temperature, which factors the recent past as having greater significance to occupant comfort (CIBSE, 2015).

$$T_{rm} = (1-\alpha)\,(T_{od-1} + \alpha\,T_{od-2} + \alpha^2\,T_{od-2} + \ldots)$$ *Equation 2*

Where α is a constant (<1) and T_{od-1}, T_{od-2}, etc. are the daily mean temperatures for yesterday, the day before, ...etc. (CIBSE, 2013). BS EN 15251 (2007) presents an approximate method for calculating T_{rm} using mean temperatures for the previous seven days (α = 0.8 - investigated using data from European comfort surveys):

$$T_{rm} = \frac{(T_{od-1} + 0.8T_{od-2} + 0.6T_{od-3} + 0.5T_{od-4} + 0.4T_{od-5} + 0.3T_{od-6} + 0.2T_{od-7})}{3.8}$$

Equation 3

This approximate value can also be used to 'start off' a longer run of T_{rm}:

$$T_{rm} = (1-\alpha)\,T_{od-1} + \alpha\,T_{rm-1}$$ *Equation 4*

Where T_{od-1} and T_{rm-1} represents the mean outdoor temperature and running mean for the previous day.

Thermal comfort: Described as 'the condition of mind that expresses satisfaction with the thermal environment' (ASHRAE, 2013).

T_{max}: Refers to the maximum acceptable indoor temperature for assessing Adaptive Comfort Criterion 3 (CIBSE, 2013).

$$T_{max} = 0.33\,T_{rm} + 21.8$$ *Equation 5*

UBL: The 'urban boundary layer' is a mesoscale concept referring to the part of the atmosphere that is also a part of the planetary boundary layer and situated directly above the urban canopy layer (UCL), with its qualities influenced by the presence of an urban area at its lower boundary (Oke, 1976).

UCL: The 'urban canopy layer' is a microscale concept that describes the part of the atmosphere consisting of the urban roughness elements (between the surface and tops of buildings and trees), where the climate is dominated by the nature of immediate surroundings (materials and geometry) and human activity (Oke, 1976).

$\boldsymbol{UHI\ \Delta T}$**:** Oke (1973) defined the maximum difference in surface air temperature between the urban city centre (T_u) and the rural area (T_r) as the intensity of the heat island; a relative description that varies seasonally and daily.

$$UHI\ \Delta T = T_u - T_r \qquad \textit{Equation 6}$$

Unit: Refers to the representative mid-terraced townhouse unit of the case study Gloucester Terrace canyon (detailed description in Appendix B.2).

Wellbeing: The Oxford dictionary defines it as a state of mental and physical health, as well as social wellness, satisfaction with their lives, and experiencing a good quality of life (Castree, et al., 2013).

Wet-bulb globe temperature (WBGT): An index, calculated for in-shade areas that is a function of all four environmental factors affecting heat stress. It includes dry-bulb, naturally ventilated wet-bulb, and black globe temperature. Since the index is concerned with extremes of heat stress, CIBSE consider such conditions as beyond those required for thermal comfort, or acceptable levels of overheating (CIBSE, 2013).

Source: © Google Images.

Chapter 1

Introduction to urban heat risks

In scientific terms, 'heat' is described as a form of energy that is transferred from one body to another following a temperature gradient by the processes of conduction, convection, and radiation. 'Risk' is described as a measure of the probability that something of value such as life, health, property, or the environment, experiencing harm or damage from a particular hazard (Park & Allaby, 2013). 'Heat risk' therefore refers to the harm or damage that may be experienced to such things of value owing to their exposure to the defined hazard of excessive heat. The dissertation presented here further focusses heat risk to consider the geographical distinction of urban environments, as they have long been observed to experience an artificial warming effect (Howard, 1833). Described in climatology as the 'urban heat island' (UHI), this phenomenon results from the inadvertent modification of the earth's surface properties (Oke, 1987). Sundborg (1951) explained this unique phenomenon in terms of the 'urban energy balance', which accounts for the energy flows in and out of the urban climate system. The dynamics of this physical balance is said to define the nature of a given urban climate, which in turn influences how cities operate (i.e., energy is used), and ensures the wellbeing of their inhabitants (i.e., their health). Although in high latitude colder cities the phenomenon may be welcome for its winter warming effect, in most urban centres it is regarded as a concern particularly in the summer. Its adverse effects on health, increased energy consumption, and pollution, combined with expected climate change is emphasised as a significant risk to the habitability of many future urban environments. Given that global urbanisation is on an upward trend (UN, 2014), the imperative to mitigate the adverse impacts of this phenomenon has gained greater emphasis in recent times.

The increased attention given to urban heat risks exists within the larger context of a warming climate. The recently published Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report confirms that the earth's climate is warming and that an average temperature increase greater than 2 K (RCP8.5) above preindustrial levels can be expected by the 2050s (IPCC, 2013a). The evidence of this warming is emphasised by the fact that eight of the warmest years in the UK, and nine globally having occurred since the turn of the century (Slingo, et al., 2014). The principal reason for such record warming experienced in recent times is claimed by the IPCC (global consensus) and the Met Office (UK) as the direct result of human activity (IPCC, 2013a; Slingo, et al., 2014). In addition to such continued warming, they highlight that many nations including the UK, are likely to experience increases in the frequency and severity of extreme weather events such as heatwaves. The impacts from excess heat are therefore stressed as requiring greater attention and planned mitigation strategies to safeguard the health and wellbeing of citizens.

1.1 Excess heat and health

Although the cold remains the dominant climate risk to health (accounting for 7% of total mortality), higher summer temperatures have received increased public health attention with recent epidemiological studies establishing strong correlation to increased human morbidity and mortality (Gosling, et al., 2009). Further studies have demonstrated that exposure to heat is already a significant health issue (circa 2,000 annual premature UK deaths) with predicted climate warming likely to contribute to even higher rates of mortality (257% increase estimated by the 2050s, Hajat, et al. (2013)). Public health experts have suggested that although physiological, behavioural, generational, and cultural adaptation is anticipated, the rate at which climate warming is expected to increase both the magnitude and variability of future temperatures will be unparalleled since the agricultural age. Adapting to a warming climate is therefore likely to require a range of measures that can moderate human interactions with the environment, and thereby facilitate population adaptation to heat-related health risks (Hajat, et al., 2013; King, et al., 2015).

An individual's exposure and sensitivity to excess heat, and their ability to adapt to its presence is understood as their vulnerability to this hazard. Table 1 summarises key vulnerability groups derived mainly from epidemiological studies; the principal approach taken by public health researchers. Most epidemiological morbidity and mortality associations have been derived from health events measured against weather station temperatures. The key measurement parameter here is 'outdoor temperature' and its effect on health outcomes for an aggregated population, as opposed to temperatures within buildings. The results from such studies therefore are not directly transferable to indoor temperatures, with the debate still inconclusive on whether it is exposure to indoor or outdoor temperatures that carries the greatest health risk. This means that although the correlation between outdoor temperatures and morbidity and mortality data is understood for most UK populations (Armstrong, et al., 2011), it is contentious to conclude high-risk indoor temperatures purely based on epidemiological evidence (DCLG, 2012a). In any event, there is limited epidemiological evidence that associates building characteristics with heat-related morbidity or mortality save for air-conditioning, where it has been repeatedly demonstrated as a protective feature, particularly in American studies (O'Neill, et al., 2005; Reid, et al., 2009).

Table 1. Key building occupancy groups and their vulnerabilities.

Groups	Key risk factors
Medical conditions	▪ Pre-existing physical conditions; cardiovascular; neurological; endocrine disorders (diabetes, hyperthyroidism, hyperpituitarism); skin disorders impairing sweating; and infections (respiratory, gastrointestinal, septicaemia) (Kovats & Hajat, 2008). ▪ Drugs that compromise thermoregulatory processes (e.g., phenothiazines, antidepressants, diuretics, alcohol, and narcotics substances). ▪ Obesity (Koppe, et al., 2004). ▪ Serious physical disabilities (Benzie, et al., 2011).
Mental conditions	▪ Serious psychological disabilities (Benzie, et al., 2011). ▪ Depression, dementia, Parkinson's Disease, or other compromised cognitive states (Kovats, et al., 2006). ▪ Perception of vulnerability (Abrahamson, et al., 2008).

Groups	Key risk factors
Older people	▪ Ageing (senescence) resulting in reduced thermoregulatory capacity; begins from around 50 years of age (Grundy, 2006; Kovats & Hajat, 2008). ▪ Increased levels of dependency and isolated living arrangements (Klinenberg, 2002; UN, 2013).
Children	▪ Increased levels of dependency, limited ability to thermoregulate, and higher potential for dehydration (Hajat, et al., 2007). ▪ Children under four, who are obese, taking medication, with disabilities or complex health needs at increased risk. ▪ Vigorous physical activity during outdoor temperatures >30°C should be avoided (PHE, 2014).
Gender	▪ European studies suggest women to be more vulnerable than men, even after accounting for age (Kovats & Hajat, 2008). ▪ Women aged ≥65 at higher risk due to a negative effect of the menopause on thermoregulation and cardiovascular fitness (Kovats & Hajat, 2008). ▪ Men at greater risk of heatstroke due to higher physical activity and exposure to outdoor warmer weather (Kovats & Hajat, 2008).
Socio-economic status	▪ Not fully understood and varies with context (Brown & Walker, 2008); not commonly found in European studies (ZCH, 2015c). ▪ Poverty or lower socio-economic status (i.e., inability to purchase air-conditioning); and lower education levels in American studies (Klinenberg, 2002).
Regional	▪ Excess mortality with increasing temperature is apparent at higher thresholds in warmer climates compared with milder climates (Kovats & Hajat, 2008). ▪ Lower mortality thresholds observed in the north relative to south (UK), e.g., Northeast mortality threshold is 20.9°C, while for Southeast is 23.5°C (Armstrong, et al., 2011). ▪ The Heatwave Plan accounts for these variations by establishing region specific thresholds (PHE, 2014).
Urban	▪ Increased urban sensitivity is largely attributed to the UHI effect, although not easily quantifiable (Hajat, et al., 2007).
Occupancy patterns	▪ How building occupancy patterns relate to temperature peaks (ARUP, 2014). ▪ Isolated or communal occupation (Brown & Walker, 2008); social networks (Benzie, et al., 2011); and engagement with social capital (Pelling & High, 2005).

Table 2. Key physiological temperature thresholds.

Physiological conditions	Core body temp.
Death from heat stroke Cellular proteins are damaged, and cells die	>42 °C
Hyperthermia at upper limits Exercise and common fever at lower limits	37.8-to-40°C
Core body temperature (normal)	36.1-to-37.8°C
Hypothermia Impaired central nervous system function	30-to-35°C
Loss of consciousness	30°C
Death due to ventricular fibrillation	<28°C
	Skin temperatures
Human skin temperature	33°C (surface temp.)
Triggers pain receptors in the skin	46°C (surface temp.)
Tolerance from thermal insulation of the air layer around the skin (short duration, e.g., sauna)	85°C+ (dry-air temp.)

Sources: ASHRAE (2013) and Kuht & Farmery (2014).

Healthy young individuals not belonging to any epidemiological vulnerability category described in Table 1, may also be adversely affected by heat stress (Kovats & Hajat, 2008). Physiological studies, the principal approach taken by comfort scientists, provide a better understanding of how the excess of heat can alter the health of any individual. The focus of investigation in such studies is how higher temperatures affect physical functions, and at what thresholds adverse health effects are manifested or physical function impaired (Table 2). Advanced physiological studies have identified that adverse effects are facilitated by not only higher air temperatures, but also other environmental thermal factors such as radiant temperature, humidity, and air movement; along with the intrinsic factor of metabolic rate of the individual; and adaptive clothing. Overheating from this physiological perspective is defined by all such factors and has been explored by climate chamber experiments as in Fanger's (1970) studies. Testing the specific health effects resulting from exposure to extreme heat parameters is a contentious task as it is ethically impractical to carry out such climate chamber experiments with living subjects. Such controlled studies consequently are limited to the bounds of determining comfort criteria (DCLG, 2012a). This has translated to assessments of overheating in buildings being predominantly predicated on comfort science findings. The assessment of heat stress risk in buildings has therefore appropriated much from comfort science, with recent approaches considering ‘adaptive comfort theory’ as the leading framework for assessing overheating risk.

1.2 Introduction to a case study

As the focus of this dissertation is concerned with residential overheating risk and its energy consumption implications, a case study approach is presented to investigate and discuss the many aspects that relate heat-related risks to energy use and resulting CO_2 emissions in cities. The case study selection was influenced by acknowledged risks within the London context (a temperate climate with heightened geographical risk), resource and programme constraints of the project, and availability of data to facilitate a meaningful investigation. A review of literature highlighted mid-terraced housing of compact arrangements, and in particular multiple occupation as having notably increased vulnerability (Beizaee, et al., 2013; ARUP, 2014). As the project was constrained by limited availability of resources to carry out longitudinal monitoring (equipment and programme), a site located within proximity to existing datasets was preferred for ease of verification purposes. Finally, the ability to aggregate results was also considered as a reason for selecting a site within a relatively planned and uniform urban morphological context. In conclusion, the neighbourhood of Gloucester Terrace was selected for meeting the said criteria, and for the added reason that it includes a typology of residential accommodation that provides a significant contribution to housing needs of the area (policy S15 protected, WCC (2013)).

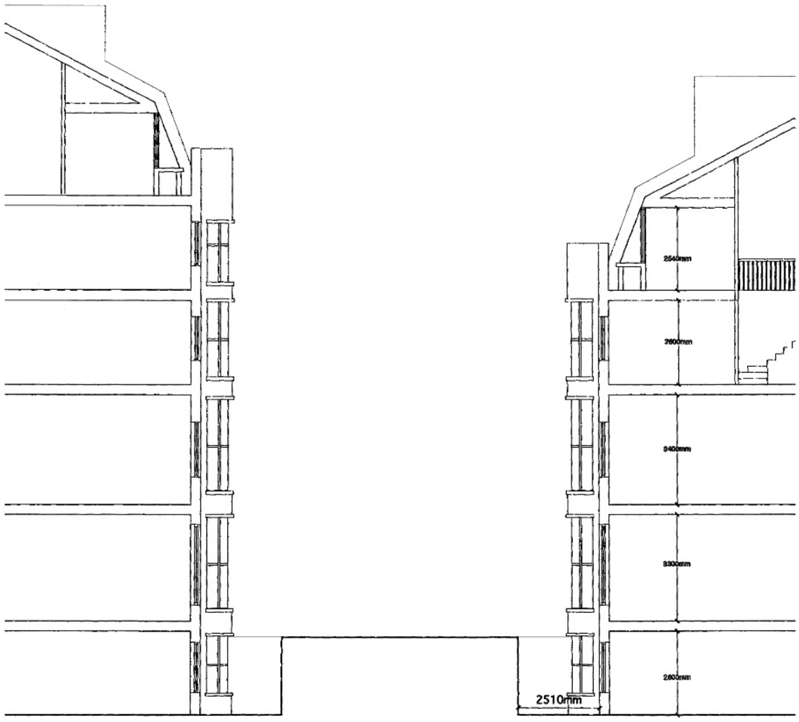
1.2.1 Gloucester Terrace

The urban canyon considered for simulation represents a 100 m length of Gloucester Terrace in the Bayswater Conservation Area of Westminster, London. The built form on either side of this canyon represents Grade II listed terraces of narrow 4-5 storey stuccoed townhouses that include attics and basements. Most of the terraces were built by William King and William Kingdom (1843-52) to a layout presumably by George Gutch (surveyor), with the long avenue and terraces to mask the railway line into Paddington

Station. The units are characterised by segmental bay or bow windows, shallow entrance porches, and pierced parapets fronting dormers, all with neoclassical detailing. The construction includes stuccoed uninsulated masonry facades typical of the area, with thick masonry uninsulated party-walls, timber joisted floors, and uninsulated slated and lead trimmed mansard roofs (WCC, 2000). Although extensive refurbishment work has been carried out over the years, the core construction is assumed to accord with the above following listing and conservation controls. Most units however have been internally converted to multi-occupancy arrangements, with some isolated energy performance enhancements (not considered for this simulation study). The morphology and materiality of the street is therefore relatively uniform, and ideally suited for the aggregated assessment as a street canyon condition.

Figure 1. Gloucester Terrace and context in plan.

Figure 2. Gloucester Terrace, typical canyon view.



Note: drawing not to scale. Sources: drafted using Ordinance Survey data from Digimap, and sectional information from Westminster City Council (2015).

Figure 3. Gloucester Terrace, typical canyon cross-section.

Source: Google Street View.

Figure 4. Grade II listed Gloucester Terrace, typical south elevation.

Chapter 2

Review of literature and methods

The broader topic of this dissertation draws from multiple bodies of knowledge with core material considered from public health, epidemiology, climatology, heat island and climate change science, urban planning, and architectural and engineering sources. For each of these core subject areas, key volumes were considered to clarify fundamental concepts and their interdisciplinary associations. Most of these however were dated in terms of their evidence base and field examples, which in turn made it necessary to include the consideration of recent papers addressing the current state of their subjects. Supporting evidence and points of discussion have thus been drawn from such published papers and acknowledged reports. For this study, this evidence base was also geographically limited to include European and North American sources principally, with examples from the broader global context drawn upon to highlight notable outlying conditions.

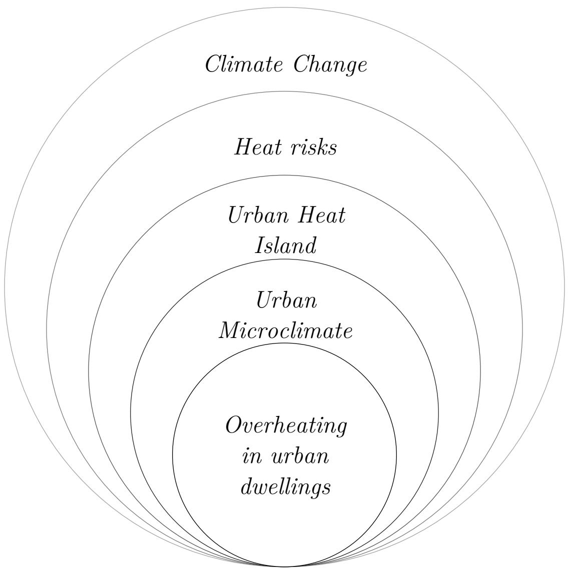


Figure 5. Venn diagram of dissertation topic context.

2.1 Literature review

A principal aim of this dissertation is to present an understanding of the current state of the mentioned core subjects, in order to guide architectural discourse and contribute to a sound evidence base for mitigating residential overheating risk in cities, while maintaining the UK carbon reduction commitment. This task was strongly influenced by an integrated (i.e., systematic) approach to considering the urban built environment, which brings together and reconciles the said knowledge bodies as an interdisciplinary exercise. The following presents a concise standard review of the essential interdisciplinary material considered for this dissertation, to be read in conjunction with the bibliography.

Table 3. Literature source types considered for the dissertation.

Key volumes	▪ Fundamental theory on topic. ▪ Most include Standard Reviews. ▪ Broader geographical scope (global, continental, or national).
Statutory and other guidance reports	▪ Concise theory on topic. ▪ Defined geographical limitations (national, regional, or local focus). ▪ Descriptive and/or prescriptive outcomes presented.
Published studies and papers	▪ Case specific studies (most with concise Standard Reviews), e.g., London. ▪ Standard Reviews for topic (assessing many studies). ▪ Systematic Reviews (meta-analyses of many studies).

2.1.1 Wider climatic context

The state of the global climate is addressed in IPCC Assessment Reports (Fifth Assessment Report published recently), which provides the current scientific understanding on climate change (IPCC, 2013; IPCC, 2014; IPCC, 2014a). In response to global consensus, the UK Government introduced the Climate Change Act (Great Britain, 2008), which established the legal framework for both mitigating and adapting to climate change, with legally binding carbon budgets that address an 80% reduction target in carbon emissions by 2050. The legislation also put in place an 'adaptation policy cycle', which is repeated every five years and is reviewed by the Committee on Climate Change (CCC) (ASC, 2014). In addition to the main legislative framework, many secondary legislative instruments, policy directives, and statutory reports are in force to address climate change related issues. Furthermore, independent bodies such as the Royal Society (2014) and the Energy Saving Trust (EST, 2005) publish scientific data and strategy options that inform government policymaking.

2.1.2 Reasons for concern

The principal risks from excess heat are highlighted as adverse effects on health and mortality from heat stress (Patz, et al., 2005), as well as from reduced air quality (Akbari, 2008); and increased energy consumption (carbon emissions) resulting from the approaches taken to mitigate excess heat (Taha, 1997). The risk to health and wellbeing from excess heat is recognised in public health and epidemiological research dating back to the 70s; although a vast majority of the available literature has been published since the turn of the century (Gosling, et al., 2009). This is particularly evident in the European context, where the adverse consequences of the 2003 pan-European heatwave emphasised the need for better understanding the association between higher temperatures and mortality (Johnson, et al., 2005; Patz, et al., 2005). This devastating heat event resulted in UK government attention and action, as exemplified by the introduction of the Heatwave Plan (PHE, 2014), and numerous subsequent reviews and assessments of overheating risk (DCLG, 2012a; ZCH, 2015a).

The epidemiological research considered for this dissertation refers to studies mainly from Europe and the United States, reviewed in detail in Gunawadena (2015). The studies highlight that in addition to intrinsic factors such as age, gender, and health conditions (Hajat, et al., 2007; Kovats & Hajat, 2008), socioeconomic factors as significant in assessing heat vulnerability (Chestnut, et al., 1998; Pelling & High, 2005; Simister & Cooper, 2005; Klinenberg, 2002; Lindley, et al., 2011; Preston, et al., 2014). Geographical exposure is assessed predominantly from a regional perspective, with most studies highlighting urban areas as having significant vulnerability (Hajat, et al., 2007; Kovats & Hajat, 2008); which consequently represents the focus of this dissertation.

2.1.3 Urban climate and the built environment

Urban form and its reciprocal association to its climate was first suggested by Luke Howard (1833), with many subsequent studies identifying specific aspects including urban density, surface-to-volume, height-to-width (i.e., aspect ratio), and buildings-to-space (i.e., sky-view factor) ratios (Steemers, et al., 2004). The correlation between the heat island intensity and street geometry was first examined by Oke (1981; 1988a), and has since been advanced by simulation and observation studies (Marciotto, et al., 2010; Theeuwes, et al., 2014). Urban grain or texture and its influence on radiation flows in cities have been considered by Oke (1988a) and Steemers et al. (1998), while the materiality of such arrangements have been addressed by several studies, mainly focusing on albedo and heat storage influence on the energy balance (Taha, 1997; Taha, et al., 1988; Akbari, et al., 2009). Urban features such as green (Oke, 1989; Bowler, et al., 2010; Doick, et al., 2014) and blue-spaces (Theeuwes, et al., 2013; Volker, et al., 2013) have been identified as having a significant heat mitigating influence, and have been extensively reviewed in Gunawardena (2015a).

2.1.4 Overheating and energy

While progress has been made in adapting to cold climate loads (ASC, 2011; 2014; DECC, 2011; ZCH, 2015a), the space-heating dominated UK building stock is generally considered to be poorly adapted to heat-related climate loads as until recently overheating had not been a major concern (Smith & Levermore, 2008; DCLG, 2012a). In research, the general effects of warmer climate loading are addressed to some extent, although only a few studies have considered how the urban microclimate specifically affects building performance (Crawley, 2008). The majority of studies presented thus far mainly target commercial building cooling concerns (Kolokotroni, et al., 2007; 2012; Crawley, 2008), with some earlier studies having identified beneficial savings in heating loads (Chandler, 1965). In addition to commercial buildings, recent typology based overheating studies have also been presented for healthcare infrastructure and dwellings (2014; Beizaee, et al., 2013; ARUP, 2014; CIBSE, 2005; BRE, 2012). There is however limited availability of monitoring data on dwellings, with studies presented dominated by simulation assessments. The significance of such modelling studies is dependent on the input data, with uncertainty associated with occupant behaviour and detailed thermal properties (ZCH, 2015a). Overheating in other typologies is addressed by design guidance from CIBSE (2005a; 2015) and building use-specific sources. Recent guidance however departs from fixed criteria to consider 'adaptive comfort theory' (Nicol, et al., 2012; ASHRAE, 2013; CIBSE, 2013; 2015). As far as planning policy is concerned, the National Planning Policy Framework (NPPF) makes no overt reference to addressing overheating (DCLG, 2012). 'Lifetime Homes' (required by the London Plan), and now incorporated into the 'Code for Sustainable Homes' (DCLG, 2010), also does not presently include overheating as a design issue. Statutory obligations concerning indoor environments is specified in Building Regulations Part F (DCLG, 2010a) and Part L (DCLG, 2013). The Regulations however do not specify requirements to control overheating on grounds of either health or thermal comfort (ASC, 2014). The only association to addressing overheating is through the 'standard assessment procedure' (SAP rating, BRE (2012)), discussed further in Appendix A, p. 94.

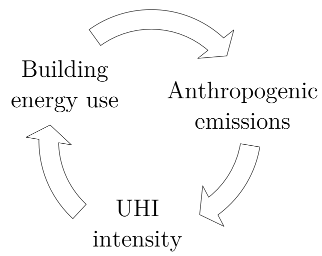


Figure 6. Energy use, anthropogenic emissions, and heat island feedback loop.

The consumption of building energy affects its surrounding climate (Figure 6), which in the urban energy balance is represented as anthropogenic heat emissions (Taha, 1997; Oke, 1982). Building heat rejection to the outdoor climate by air-conditioning is considered as a growing source of urban anthropogenic heat, particularly in the United States (Ackermann, 2002; Akbari, 2002), with growth in the United Kingdom anticipated (Boardman, et al., 2005; Pathan, et al., 2008). Energy use and climate interactions are considered by a number of studies, which highlight increased use of air-conditioning as adversely affecting the urban climate (Sailor, 2010; Iamarino, et al., 2012; de Munck, et al., 2013), as well as the UK national carbon reduction target (He, et al., 2005; Pathan, et al., 2008). Strategies for addressing climate warming risks have advocated the introduction of detailed legislation (ASC, 2014), and as an alternative, 'nudge theory' to assist behavioural adaptation (Thaler & Sunstein, 2008).

2.2 Methods for application

To assess the relationship between overheating risk and energy usage in residential buildings, this dissertation utilises a case study approach. The following is a review of methodologies considered for this case study assessment (extended in Appendix A, p. 94).

2.2.1 Dynamic simulation modelling

Dynamic simulation modelling (DSM), or building energy simulation (BES), refers to the use of validated models that simulate the changing energy interactions of buildings against their outdoor climate (CIBSE, 2006). These physically-based models (e.g., EnergyPlus, or IES-VE), utilise heat balance principles to resolve energy exchanges between different boundary conditions. A typical process of using dynamic simulation for estimating overheating risk involves a model of the building simulated and assessed against a given overheating standard. The key inputs are location and orientation, climate data, building geometry, construction assemblies, internal zoning, internal heat gains for each zone, and implemented ventilation strategies. The assessor has the discretion to allocate appropriate inputs, including the weather data used, and modify the design to gain compliance with the criteria considered.

2.2.2 Climate data

The accuracy of a DSM's output is dependent on the relevance and validity of the weather data used. For compliance assessments, buildings in the UK are typically assessed using CIBSE Test Reference Year (TRY) files for energy analysis, and Design Summer Year (DSY) files for summer overheating (Eames, et al., 2011). Although hourly temperature observations are becoming more accessible, solar radiation and wind variables are not commonly measured at all sites. This disparity in available Met Office information reflects the limited number of DSY, TRY (#14 UK sites) and TMY location files offered. Thus, for a project that is sited beyond these locations, it is the technician's responsibility to make assumptions and select the most approximate weather file. EnergyPlus for example recommends a TMY file within 30-50 km and a few hundred feet (100 m) in elevation of the site in question. Single-year TRY weather data is also recommended to be avoided, as no single year can represent long-term weather patterns useful for dynamic simulation (Crawley, 1998). CIBSE's TRY data addresses this by providing a composite and continuous one-year sequence of data selected from a twenty-year dataset, while their DSY consists of a one-year sequence of hourly data selected (April-to-September DBT) from the twenty-year dataset to represent a year with a hot summer. Recent research output from CIBSE has also made available *Design Summer Years (TM49)* that include the heat island effect in London with reference to three sites: LWC (urban), LHR (semi-urban), and LGW (rural), for three years (1989, 2003, and 1976) of varying severity of extreme events (CIBSE, 2014). Although such files provide better representation of the phenomenon, microclimatic variations resulting from urban morphological features cannot be explicitly addressed by standard weather files, except through models that simulate their interactions (discussed below). It is also worth noting that the 'weighted cooling degree-hour' measure used for the selection of these new DSYs is based only on temperature, and excludes the significance of direct solar radiation penetration, localised wind dynamics, and humidity in determining overheating risk (ZCH, 2015a).

2.2.3 Climate models

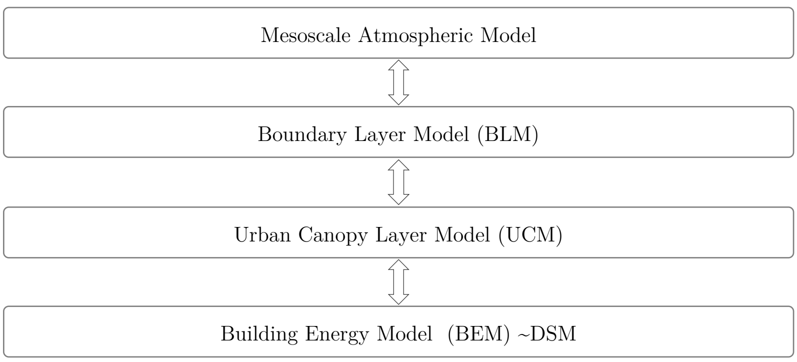
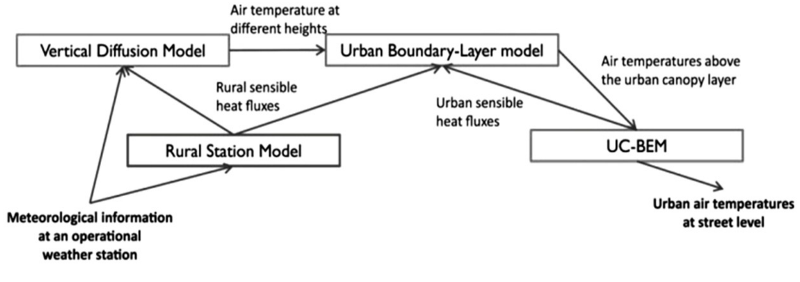


Figure 7. A generic climate model coupling framework.

Urban climate model domains vary from street canyon, neighbourhood, to citywide scales. Most are structured as coupled frameworks (e.g., Figure 7) with multiple heat balance models utilised to capture the complexity of urban climate and energy interactions at the different atmospheric scales. The approach of coupling an urban canopy model (UCM) with a building energy model (BEM) provides the benefit of including reasonably realistic representations of buildings and their heating, ventilation, and air conditioning (HVAC) systems to resolve climate-loading interactions. Recent studies have achieved this by either coupling a UCM with an established and verified building energy model such as EnergyPlus, or by developing bespoke UCM-BEM integration.

As a progressive refinement of the Town Energy Balance (TEB)-BEM model (Bueno, et al., 2012; Pigeon, et al., 2014), the Urban Weather Generator (UWG) has been developed to account for the heat island effect for specific urban sites (Bueno, et al., 2013). This generator is composed of four coupled modules (Figure 8), which interrelate with one another to output a modified weather file (EnergyPlus *epw* format) that can be used for dynamic simulation. It has been verified against field data from Basel, Switzerland and Toulouse, France, with simulations demonstrating the significance of including both canopy and boundary layer effects to account for the aggregated influence of the heat island over the entire city. From the heat island effect observed inside urban canyons, more than half is attributed to this mesoscale influence. The resolution of such boundary layer influences requires mesoscale effects to be reconciled by atmospheric simulations, which is a key feature of the UWG framework (Bueno, et al., 2013).



Source: Bueno et al. (2013).

Figure 8. Schematic of data exchanges between the modules of the UWG.

2.2.4 Methods and their limitations

The most accurate means of accounting for microclimatic environmental loading on buildings is to acquire measured site data. In order for such data to be representative, the measurements would require longitudinal study to account for long-term weather patterns (Crawley, 1998), as well as the spatial and temporal diversity of unique urban climate features such as the heat island effect (Oke, 1987). The resource cost required to achieve such a data collection framework however is likely to make this approach impractical for most building simulation tasks.

Dynamic simulation tools such as EnergyPlus or IES-VE are primed with weather data files that are representative of the nearest weather station (i.e., TMY), often located at airports beyond the urban periphery (e.g., LGW). The data from these files may not always correspond to the urban microclimate under study, which in turn can lead to inaccurate estimates that neglect the influence of the heat island (Sailor, 2010; Bueno, et al., 2013). The use of intermediary translating tools such as the UWG can generate area-specific climate loads to increase the accuracy of both overheating and energy consumption estimation without the need for onerous data collection frameworks. In the interest of making such tools acceptable for general use, their reliability must be further verified against diverse case study conditions, which represents a significant aim of this dissertation project.

Many of the existing tools and methodologies have been developed with commercial building use in mind. Dynamic simulation modelling is thus regarded to be rarely used for the analysis of domestic buildings (ZCH, 2015a). This commercial building use focus has meant that certain aspects of such methodologies presenting inconsistencies in the simulation of other building typologies. The consideration of occupant densities between commercial and domestic sectors serves as an example, with the floor area per occupant parameter in commercial buildings unlikely to present an accurate representation of the diversity experienced in domestic occupancy.

Most simulation approaches for estimating overheating risk and energy performance depend on the modeller's discretion to input appropriate parameters. Currently, there is no standard for how parameters such as weather data or occupancy profiles are to be used in the simulation of dwellings, which in turn makes it difficult to conduct meta-analyses of the results and formulate generalisable conclusions. This is particularly significant in the case of free-running buildings such as most UK dwellings, as the many assumptions made regarding aspects including occupancy profile (affects gains), window-opening patterns, ventilation, shading, and thermal mass are all likely to vary the results obtained (ZCH, 2015a). Although standardising profiles is advocated as a solution, the degree of variability encountered in living arrangements makes it a restrictive approach that is less likely to be adaptable to future occupation patterns or changes in building use. The application of algorithms to define occupant behaviour in relation to the use of windows and other adaptive behaviours may be encouraged to improve accuracy (Rijal, et al., 2007), although most such algorithms are currently available only to researchers and are yet to be introduced to mainstream simulation practices, particularly in relation to domestic circumstances (ZCH, 2015a).

2.3 Assessment thresholds

The results obtained from the methods defined above may be assessed against different measures or thresholds to determine whether a dwelling overheats. These thresholds are expressed by various sources as climate (e.g., temperature, humidity, and air velocity), temporal (e.g., annual, monthly, or daily significance) and/or spatial (e.g., regional, urban) terms (Table 4 and Table 5, p. 34). The following details current understanding.

2.3.1 CIBSE and BSI guidance

Although there is no statutory obligation to satisfy CIBSE overheating guidance, client requirements often attach contractual significance to the thresholds and specifications principally expressed in *Guide A* (2006a; 2015). This guide recognises the determination of the occupancy descriptions and internal gains as the most challenging aspects when assessing residential buildings. It also acknowledges that individuals in such domestic circumstances are at greater liberty to adapt, and that bedroom temperature is likely to be more critical than living room temperature, particularly at night to avoid sleep deprivation (CIBSE, 2006a; 2015). The limiting threshold criterion of the 2006 edition however has recently been superseded (Table 5, p. 34). It had been argued that this limit exceedance assessment fails to identify the severity of overheating present, and that the definition of 'occupied hours' used as being susceptible to inappropriate modification (CIBSE, 2013). The advancement of research by de Dear & Brager (1998) has also gained increased acceptance to suggest that a single indoor temperature limit that is disassociated from the outdoor climate as no longer sufficient for the assessment of free-running buildings (CIBSE, 2013). TM52 (CIBSE, 2013), which follows the methodology and recommendations in BS EN 15251 (BSI, 2007), accordingly forwarded an approach for considering 'adaptive comfort theory' in assessing comfort and overheating risk, which has now been integrated into the 2015 edition of the CIBSE *Guide A*.

The overheating assessment described in BS EN 15251 (BSI, 2007) is similar to ASHRAE *Standard 55* (2013a), and is based on the principles of adaptive comfort. The assessment is differentiated according to whether buildings are mechanically ventilated or free-running, with four categories of 'expectations'. Category II applies for new-builds and III for existing buildings, while Category I is designated for spaces with occupants with high expectations of comfort, such as older people or very young children. Adaptive theory argues that in addition to indoor comfort temperatures in free-running buildings being closely associated to outdoor temperatures, occupant comfort responses are strongly reliant on their thermal experience, with greater significance assigned to the recent past (ASHRAE, 2013a; CIBSE, 2013). TM52 consequently introduces a 'running mean' for outdoor temperatures that is weighted according to temporal proximity. This translates to an overheating threshold that is dynamic and dependent on the outdoor climate, i.e., the weather file used (CIBSE, 2013). The assessment compares between the maximum acceptable indoor temperature (T_{max}) calculated from the running mean (T_{rm}) of the outdoor temperature and either the simulated or measured room operative temperatures (T_{op}) of the building zone in question. The comparison is assessed against three criteria, all defined in terms of ΔT, where $\Delta T = T_{op} - T_{max}$. At least two criteria must be satisfied for a building zone to avoid the risk of being classified as overheating. The first criterion (H_e - *Hours of Exceedance*), considers a permitted seasonal (non-heating months from May-to-September) deviation of up to 3% (suggested in BS EN 15251, 2007), for the number of occupied hours that the T_{op} can exceed T_{max}. The second criterion (W_e - *Daily Weighted Exceedance*), addresses the severity of overheating, and sets acceptable daily limits represented by a function of both temperature increase and duration. The third criterion (T_{upp} - *Upper Limit Temperature*), sets an absolute maximum acceptable temperature for the given zone. For a Category II or III building, ΔT should not exceed 4.0 K to be within bounds of achieving comfort with the use of typical adaptive measures (CIBSE, 2013; 2015). As with BS EN 15251 (BSI, 2007), the CIBSE approach gives the opportunity to make allowance for air movement (i.e., forced convective cooling), with the comfort temperature reduced with increased air velocity (e.g., use of a fan).

Table 4. Key outdoor temperature thresholds for health and comfort.

Source	**Variable**	**Threshold**	**Outcome when exceeded**
Heatwave Plan for England (2014)	Night-time maximum outdoor air temperature (°C)	18.0°C	Heat-Health Warning Level 3 trigger for the London region.
	Daytime maximum outdoor air temperature (°C)	32.0°C	Heat-Health Warning Level 3 trigger for the London region.
Armstrong et al., (2011)	Daily maximum outdoor air temperature (°C)	24.7°C	Excess heat-related mortality for the London region.
King et al. (2015)	WBGT index (°C) (in shade)	>28°C	Outdoor sports activities should cease.

Table 5. Key indoor temperature thresholds for health and comfort.

Source	**Typology**	**Variable**	**Threshold or range**	**Outcome when threshold exceeded**
WHO Guidance	Dwellings	Indoor air temp. (°C)	24.0°C	Heat-related health effects evident
DoH TM03-01 (2007)	Healthcare buildings	Indoor dry-bulb temp. (°C)	28.0°C	Should not exceed 50 annual occupied hours

Source	**Typology**	**Variable**	**Threshold or range**	**Outcome when threshold exceeded**
DfES BB101 (2006) Referenced in Part L2 (DCLG, 2013)	Schools	Indoor air temp. (°C)	23.5°C	Overheats if 120 occupied hours is exceeded
			≤ 5 K	Indoor/outdoor air temp. difference
			32.0°C	Max. permitted temp.
Housing Health & Safety Rating (DCLG, 2006)	Dwellings	Indoor air temp. (°C)	>25.0°C	Mortality risk increases
Standard assessment procedure (SAP): *Appendix P* (BRE, 2012)	Dwellings	Monthly mean summer indoor temp. (°C)	20.5-22.0°C	Slight likelihood of high indoor temperatures during hot weather
			22.0-23.5°C	Medium likelihood of high indoor temperatures
			>23.5°C	High likelihood of high indoor temperatures
Heatwave Plan England (2014)	Care facilities	Indoor air temp. (°C)	>26.0°C	Room would not function as a ‘cool space’
HSE Guidance	Workplaces	Indoor air temp. (°C)	30.0°C	Heat-related health effects increase
EST (2005)	Dwellings	Indoor air temp. (°C)	27.0°C	Overheating is measured by degree-hrs by which the threshold is exceeded
BS EN 7243 (BSI, 1994)	Workplaces	Wet-bulb globe temp. (WBGT) reference value (°C)	33.0°C 32.0°C	If acclimatised to heat Not acclimatised to heat Resting @Met<65 W·m^{-2}
			30.0°C 29.0°C	If acclimatised to heat Not acclimatised to heat Met 65<M<130 W·m^{-2}
BS EN 15251 (BSI, 2007)	Dwellings	Temp. range for cooling, (°C)	23.5-25.5°C 23.0-26.0°C 22.0-27.0°C	Category I (sensitive) Category II (new build) Category III (existing) Clothing ~0.5 clo Sedentary ~1.2 met
	Offices Auditorium, Cafeteria, Restaurants, Classrooms		23.5-25.5°C 23.0-26.0°C 22.0-27.0°C	Category I Category II Category III Clothing ~0.5 clo Sedentary ~1.2 met
	Pre-school		22.5-24.5°C 21.5-25.5°C 21.0-26.0°C	Category I Category II Category III Standing-walking ~1.4 met
CIBSE *Guide A* (2006a)	Dwellings	Indoor T_{op} (°C)	*23.0°C**	*Summertime thermal discomfort in free-running bedrooms**
			*25.0°C**	*Summertime thermal discomfort in free-running living rooms**

Source	Typology	Variable	Threshold or range	Outcome when threshold exceeded
			*26.0°C**	*Overheating if free-running bedrooms exceed 1% annual occupied hours**
			*28.0°C**	*Overheating if free-running living rooms exceed 1% annual occupied hours**
	Schools & Offices		*25.0°C** *28.0°C**	*Summer comfort temp.** *1% annual occupied hours**
	Offices		30.0°C	'Rarely acceptable to occupants of office buildings in the UK'
	All Buildings		28.0°C	Threshold above which the majority will start feeling uncomfortable
CIBSE *Guide A* (2015)	Dwellings	Maximum Summer temp. (°C)	26.0°C	Nocturnal bedroom temp. should not exceed this, unless air movement is created in space, e.g., fan
		Indoor T_{op} (°C)	24.0°C	Sleep impairment in free-running bedrooms. From Humphreys (1979)
			23.0-25.0°C	Summertime thermal comfort in living rooms and bedrooms in air-conditioned dwellings
	Offices		22.0-25.0°C	Summertime thermal comfort (air-conditioned)
	Schools		21.0-25.0°C	Summertime thermal comfort (air-conditioned)
	Schools & Offices		26.0°C	Max. temp. for free-running Category II Clothing ~0.5 clo Sedentary ~1.2 met
CIBSE TM40 (2006b)	Institutional buildings	Surface temp. (°C)	43.0°C	Safety limit, including heating radiators for institutional buildings
		Indoor air temp. (°C)	50.0°C	Medical supervision needed for workplaces (extreme environments)
			35.0°C	Fans should be avoided
British Council of Offices (2009)	Offices	Indoor air temp. (°C)	24.0°C ±2 K	UK office space should not exceed this criterion
Passivhaus	Dwellings	Indoor air temp. (°C)	25.0°C	Percentage of annual hours; 10% required for Passivhaus Certification

Source	Typology	Variable	Threshold or range	Outcome when threshold exceeded
King et al. (2015)	Indoor (shaded) environment	Wet-bulb globe temp. (WBGT) index	≥40.0°C ≥36.0°C ≥30.0°C ≥36.0°C	Survival daytime Survival Night-time Sleep deprivation Work (‘too hot to work’)
Pathan, et al. (2008)	Dwellings	Indoor air temp. (°C)	24.0-25.0°C	Switching-on of air-conditioning (if installed)

* CIBSE *Guide A* (2006a) thresholds superseded by the adaptive overheating criteria in CIBSE (2013; 2015).

2.3.2 Thresholds and their limitations

The definitions used in current assessment practices have moved beyond heat stress to focus on thermal comfort. Most part from fixed thresholds, as they are increasingly viewed as ineffective attempts to define a phenomenon that is inherently imprecise (CIBSE, 2013). Measures such as the ‘percentage of hours of exceedance’ above a fixed threshold and ‘average temperatures’ are now being superseded to consider relative thresholds offered by adaptive comfort practices. These now account for seasonal durations of overheating, as well as short-term daily intensities and relative maximum thresholds. The remaining criticism however is that the significance of prolonged exposure to moderately high temperatures (>25°C, acknowledged as detrimental to health and sleep), is not explicitly addressed by the criteria. Furthermore, the criterion thresholds offered are still mostly based on studies of office buildings. There is therefore limited evidence considered on occupant health and comfort in dwellings, with even less examined for their nocturnal conditions when adaptive practices are inherently limited (ZCH, 2015a).

2.4 Methods and thresholds for study

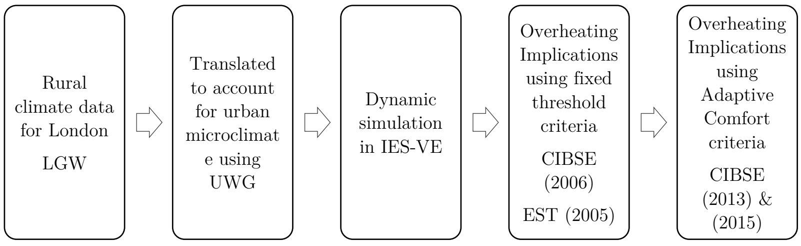
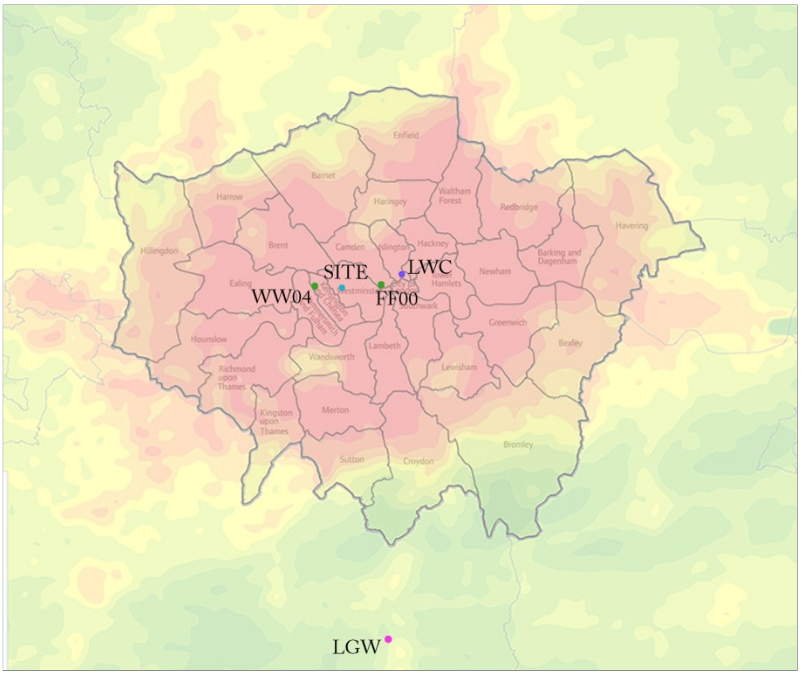


Figure 9. Method pathway for overheating analysis.

The resource and programme constraints of the dissertation project (no available summer period) excluded the opportunity to carryout fieldwork at the proposed case study in London. The simulation study presented here consequently utilises the UWG for the principal reason that it provides the opportunity to generate a microclimate weather file (remotely) for the aggregated analysis of urban canyon conditions, which is then inputted to a dynamic simulation modeller (e.g., IES-VE) to assess overheating risk, energy use, and CO_2 emissions implications. The overheating assessments presented considers the recently superseded CIBSE (2006a) and EST (2005) fixed criteria, as well as the recently published adaptive comfort method (CIBSE, 2013; 2015). The following chapters present these assessments to be read as a 'series of appraisals' that addresses the logical steps of discerning appropriate urban climate parameters; assessing overheating risk at the representative sample unit; and adaptive tests to conclude energy use and carbon emissions implications for this unit and the aggregated street canyon.



Note: FF00 includes two monitoring sites near the British Museum - FE00 and FW00. Source: modelled London atmospheric heat island underlay from ARUP (2014) and University College London.

Figure 10. Weather stations in relation to the Gloucester Terrace site.

Chapter 3

Urban warming and dwellings

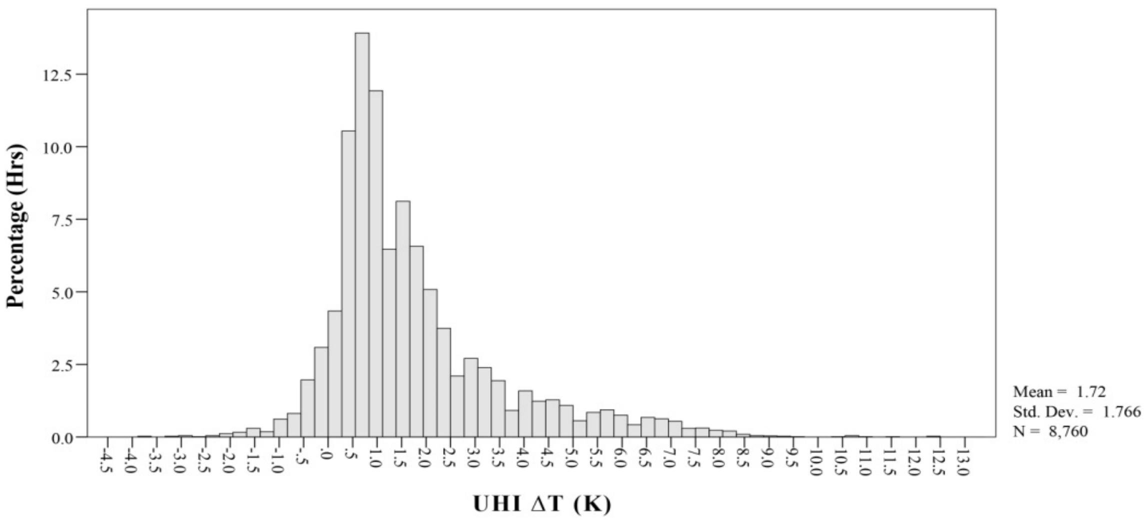
$$\textit{Net radiation} + \textit{Anthropogenic heat} = \textit{Convection} + \textit{Evaporation} + \textit{Heat storage}$$

Equation 7

Climatology explains the uniqueness of the urban climate in terms of the 'urban energy balance' (Equation 7), which accounts for the physical base for land-use and climate interactions (Sundborg, 1951). As the First Law of Thermodynamics states that 'energy is never lost', the energy absorbed by the urban surface from radiation and generated by anthropogenic activity is physically balanced by warming the air above the surface, evaporated as moisture, and stored as heat in surface materials (Oke, 1988). Although naturogenic phenomena can affect this balance, anthropogenic modifications and activities are identified as the predominant influence in urban areas. By constructing the features that constitutes the built environment, and conducting the activities that occur within it, the transformations of energy and its distribution across the components of the balance are modified (Oke, 1982). In an ideal setting (minimal weather interference), increased net radiation and anthropogenic heat (addition of thermal energy to the climate), combined with reduced evaporation and convection, and increased heat storage (increased retention of thermal energy), facilitate the suitable balance for the formation of a heat island (Oke, 1987). This in turn presents a pronounced environmental thermal load that urban buildings must address, or the failure of which may lead to overheating. The methodology section (2.2.2) earlier highlighted how traditional simulation approaches using TMY data can miscalculate climate loading for a given site, as they fail to account for such unique urban climate features. To address this shortcoming, the following details how the UWG described in Chapter 2 was applied to simulate the Gloucester Terrace site.

3.1 Generating an urban microclimate profile

TMY data from the London Gatwick Airport station (LGW), Figure 10was used for translation by the UWG as it is defined as a 'rural' station (CIBSE, 2014), which satisfies a principal assumption. The resulting translation produced a microclimate profile for the Gloucester Terrace canyon with an annual $UHI\ \Delta T$ M = 1.7 K, $UHI\ \Delta T_{max}$ = 12.5 K and $UHI\ \Delta T_{min}$ = -3.8 K as single datapoints. The mean $UHI\ \Delta T$ is slightly higher than the recorded 1.4 K for central London (1.6 K in the summer and 1.2 K in winter), reported by Chandler (1965) examining temperature data for the period from 1931-60; although it is lower than the Watkins et al. (2002) mean of ~2.8 K measured during 1999. The $UHI\ \Delta T_{max}$ = 12.5 K is considerably higher than the Watkins et al. (2002) observed summer peak value of 8 K, 9.5 K derived from modelled data in Bohnenstengel et al. (2011), and Doick et al. (2014) recorded values of 10 K for the nocturnal heat island on certain nights. Reviews of $UHI\ \Delta T$ frequency distributions highlight these extreme peak values to be a rare occurrence (CIBSE, 2015). The singular (hourly) high datapoint of the UWG translation could therefore be regarded as an anomalous value in a frequency distribution that presented intensities >9 K as representing <0.2% of the simulated annual hours (Figure 11).



Note: refer to Figure 35, p. 93, for UWG morphed $UHI\ \Delta T$ annual hourly profile.

Figure 11. $UHI\ \Delta T$ frequencies for the Gloucester Terrace canyon (K).

For verification purposes, the generated UWG summer profile (between 29 March and 25 October) was compared against existing data from the nearby urban monitoring station at the London Weather Centre (LWC), and LUCID [i] project monitoring sites to the east (*FF00* = *FE00* and *FW00*) and west (*WW04*) of Gloucester Terrace (see Figure 10, p. 38, for locations, and Table 6, p. 42, for results comparison). Visual inspection of the profiles for warmest and coldest months highlighted LUCID data related best to the LWC (DSY) to a certain extent, while the UWG profile was related to LGW (Figure 12, p. 42). These proximities are expected since the morphed files have been generated from the respective base data. The mean temperature comparison however highlighted LUCID *WW04* station data to be statistically proximate [ii] to UWG data. This suggested that the generated UWG summer profile on average was neither colder nor warmer than this proximate site (circa 4 km away, Figure 10). The difference in the distribution of temperatures between the two profiles may be explained by the different base data utilised for translation, and the UWG accounting for the microclimate differences of the neighbourhood resulting from its built environment morphology, which is its central purpose. Based on this premise, the UWG profile was considered for the simulation of the representative unit at Gloucester Terrace.

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[i] LUCID site data was generated by LSSAT, an ANN model trained with measured data. The site-specific outdoor air temperatures generated from the model have been assembled with monitored data from the nearest weather stations at LHR (relative humidity, wind speed, atmospheric pressure, and cloud cover) and LWC (global and diffuse solar radiation) for the same period to create site-specific '*epw*' (EnergyPlus) weather files (Demanuele, et al., 2012).

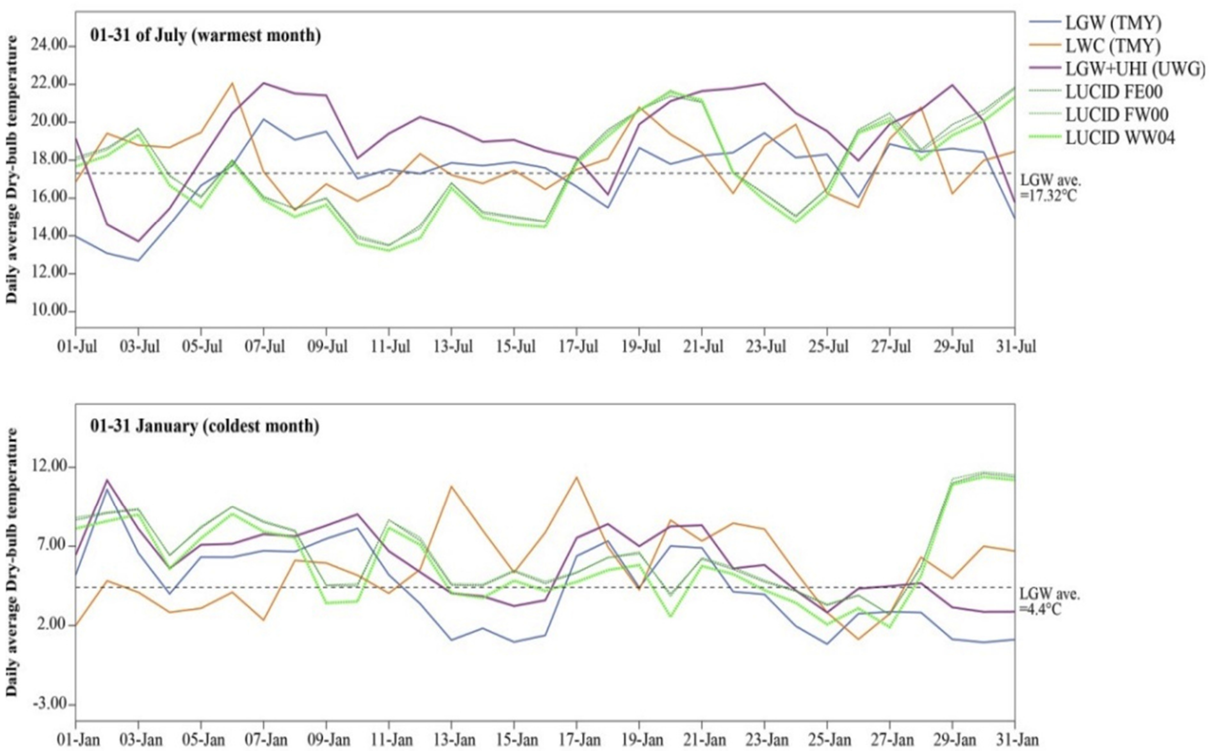
[ii] Kolmogorov-Smirnov Normality Test for LUCID *WW04* and *LGW+UHI*: D(5064) = 0.034, p <0.00 and D(5064) = 0.27, p <0.00, respectively. Visual inspection of histograms, Q-Q plots, and box plots showed both datasets to be not normally distributed, with skewness values of 0.097 (SE = 0.034) and 0.153 (SE = 0.034); and kurtosis values of 0.097 (SE = 0.069) and -0.094 (SE = 0.069), respectively. A non-parametric Wilcoxon Signed Ranks Test performed with Z(5064) = -0.78, p = 0.435; i.e., not statistically dissimilar with positive ranks ≈ negative ranks. Same test for LUCID *FW00* and *FE00* and LWC (DSY) demonstrated statistically significant differences with Z(5064) = -5.98, -5.37, and -6.56, p <0.000, respectively.

Table 6. Summer DBT comparison between weather stations.

Monitoring station	Approx. distance to site (km)	Hourly Min. temp. (°C)	Hourly Max. temp. (°C)	Annual hourly mean temp. (°C)
Base-LGW (TMY)*	40 km (South)	-3.4	31.3	13.5
*LWC-DSY***	6 km (East)	-0.7	28.8	14.8
LUCID *FW00*	4 km (East)	0.4	30.1	15.5
LUCID *FE00*	4 km (East)	2.5	29.3	15.5
LUCID *WW04*	4 km (West)	1.1	32.5	15.1
LGW+UHI	0 km	3.3	31.0	15.1

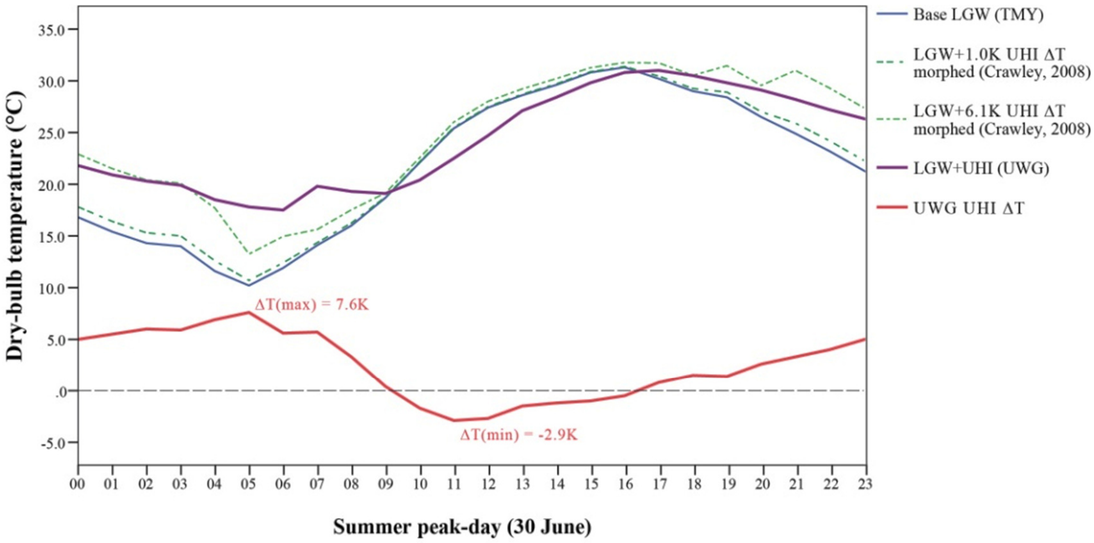
Note: N = 5064 hours (summer 29 March to 25 October); *FW00* and *FE00* are two sites at the British Museum.

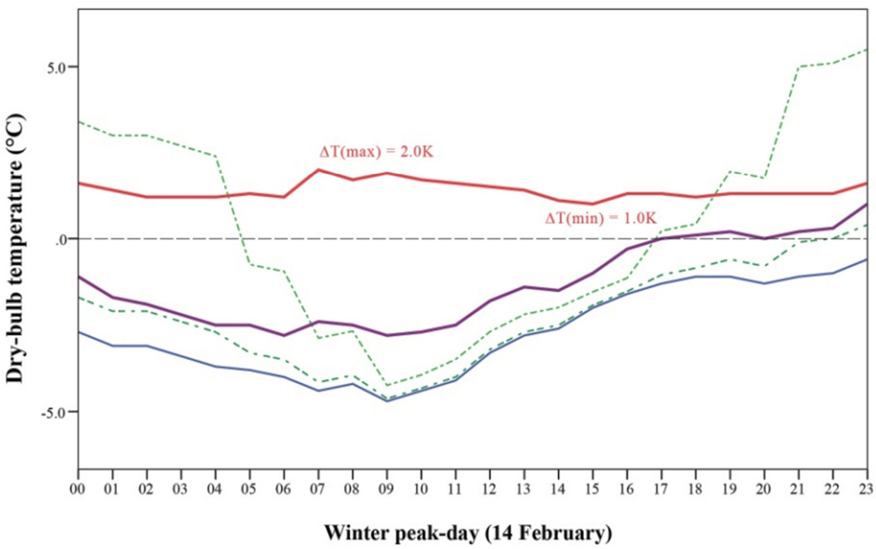
Sources: *EnergyPlus; **PROMETHEUS (Eames, et al., 2011); LUCID (Demanuele, et al., 2012); and UWG.



Sources: as above.

Figure 12. Daily average DBT comparison for warmest and coldest months.





Sources: LGW (TMY) from EnergyPlus; refer to Appendix B.5, p. 105, for Crawley algorithm (Crawley, 2008); and UWG simulations.

Figure 13. Peak-day hourly DBT profiles for summer and winter.

Figure 13 represents a comparison for the summer and winter peak-day profiles between rural LGW (TMY) data (in blue); and two morphed approaches accounting for the heat island effect. As expected, the application of the Crawley (2008) lower and upper limit algorithm (Appendix B.5, p. 105) presented higher nocturnal temperatures (in green) than the TMY profile for LGW. The UWG profile (in purple) similarly showed higher nocturnal values; although the midday values were noticeably lower than what the LGW (TMY) data suggested. The lowest heat island intensity ($UHI\ \Delta T$ in red) for the summer peak-day occurring at midday corresponds with Watkins et al. (2002) diurnal profile observations. The heat island intensity for the winter peak-day noticeably showed little variation, although a marginal increase in intensity was noted during the morning to midday period.

3.1.1 Discussion on microclimate profile

The daytime drop in the summertime heat island intensity noted above (Figure 13, p. 43), is explained here by the radiation balance, which is influenced by both the canyon geometry and its material finishes. An arrangement that achieves a high aspect ratio can modify radiation transfer in opposing terms, with the net result determining the canopy layer temperatures experienced. In street canyons as at Gloucester Terrace, buildings on either side shade the lower levels and street surface during the day to limit direct solar (shortwave) radiation penetration and absorption. This canyon ‘shading effect’ decreases shortwave radiation incidence, which in turn leads to lower daytime temperatures and less heat absorbed by the urban fabric. The relatively higher thermal inertia of urban materials means that lower daytime heat absorption translates to lower levels of longwave energy reradiated back into the atmosphere, thereby leading to a potential reduction in the nocturnal heat island experienced (Theeuwes, et al., 2014). Oke (1988a) highlighted that the significance of the shading effect increases with latitude and is pronounced greater in winter when sun angles are lower. Furthermore, it is also observed to increase with canyon aspect ratio and when oriented on the east-to-west rather than north-to-south axis; all of which are factors that determine the degree of solar radiation penetration permitted (Oke, 1988a).

Net radiation = *Incoming solar radiation (shortwave) -*
Reflected solar radiation (shortwave) +
Atmospheric radiation (longwave) -
Surface radiation (longwave)

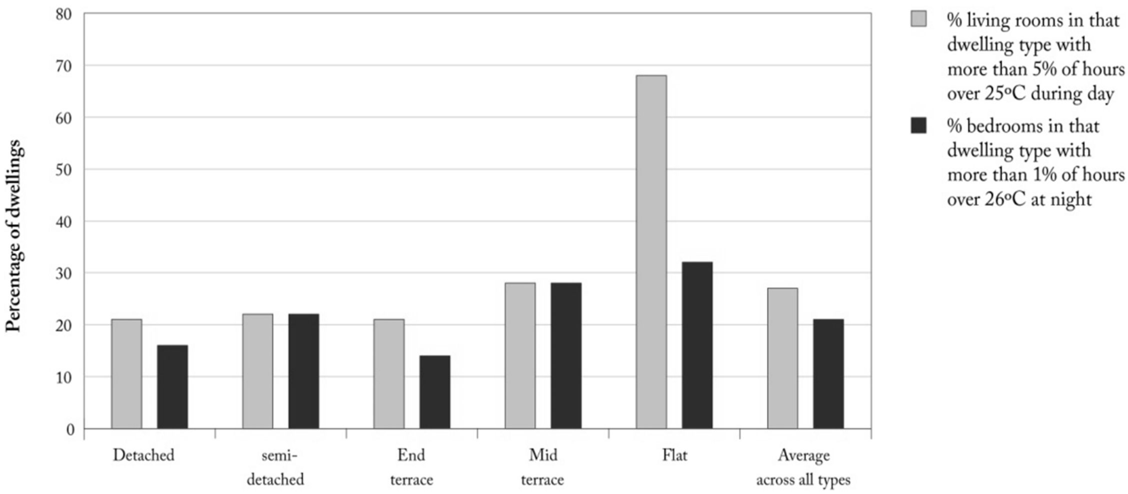
Equation 8

Canyons and areas with tall building clusters tend to trap radiation by reflecting shortwave radiation from surface to surface leading to higher proportions of absorption (Steemers, et al., 1998). In the broader context of the city, its built environment grain or texture has a similar influence. Complex arrangements with cavities such as courtyards tend to trap greater radiation than an open city with large blocks. A modelling study revealed that accounting for surface reflectance, urban form could absorb up to 40% more solar energy than a comparative reference plane (Steemers, et al., 1998). The complexity of urban grain also affects the degree of the radiation absorbed (Oke, 1988a). The same study considered sample urban fabrics from Toulouse and Berlin to find that the reduction in reflectance between the models varied from 40% for Toulouse with its narrow streets and buildings, as opposed to 15% for Berlin with its wider open spaces (Steemers, et al., 1998). This ‘trapping effect’ of urban geometry can also obstruct the release of longwave infrared radiation back into the atmosphere (reradiated by urban form at night), thereby leading to an increase in net radiation. Urban areas with building clusters and deep canyons have as a result been shown to cool considerably slower, thereby contributing to an increase in the nocturnal heat island experienced (Oke, 1981).

Whether the shading or trapping effect becomes dominant depends on both the availability of shortwave radiation (season, latitude, cloud cover), and the timing of the nocturnal heat island formation. A modelling study had found the shading effect to be significant at the beginning of the night, while the trapping of longwave radiation later in the night to moderate the effect on the heat island (Theeuwes, et al., 2014). In addition to geometry considerations of the built environment, its materiality is highlighted as a key factor in determining the net effect of radiation flows. The canyon effect can be further enhanced by increasing the albedo of surfaces, with a recent study measuring potential reductions in air temperatures of up to 3-4 K with the use of lighter coloured surfaces (Watkins, et al., 2007). The simulation for Gloucester Terrace in agreement highlighted a summer peak-day canyon effect with a temperature reduction of ~3 K, aided by the white-painted stucco facades on either side of its canyon.

3.2 Overheating in urban dwellings

The characteristics of a dwelling factors considerably in determining its overheating risk. Main features to be concerned with include envelope insulation, thermal capacity, solar gain, and ventilation rates; all of which describe how dwellings modify their outdoor climate interactions (BRE, 2014). In contrast to larger detached dwellings, apartment flats and mid-terraced dwellings tend to have increased vulnerability due to their compact arrangements (Figure 14, Beizaee, et al. (2013)). Reviews of the UK dwelling stock have revealed those built before 1920 (uninsulated loft conversions in particular), in the 1960s, and post-1990s to be at heightened risk (BRE, 2014). The number of flats, a typology with greater vulnerability to overheating, is worryingly increasing as a percentage of the total stock to constitute >40% of new dwellings (ASC, 2014).



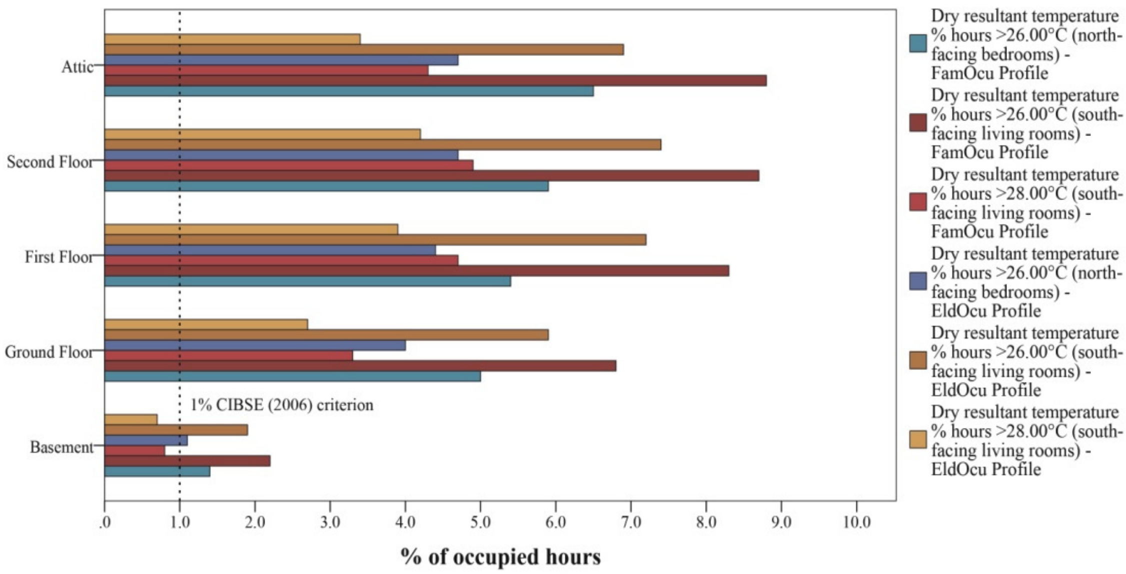
Note: survey year 2007 was a relatively cool summer. Source: Beizaee et al. (2013).

Figure 14. Survey of dwellings found to overheat in the summer.

In terms of arrangement, top-floor flats and terraced house attic spaces have been found to demonstrate higher risk of overheating. Single-aspect arrangements (particularly south-facing) are highlighted to exacerbate the issue by preventing cross ventilation and being adversely affected by heat flows from adjoining properties (ARUP, 2014). The management of flats also places such arrangements at risk as inadequately ventilated communal areas and reduced capacity to have openable windows (due to security and pollution concerns) causing such spaces and circulation routes to overheat and transfer gains to adjoining dwelling units. Space standards of new dwellings contribute to the issue as rising demand for housing enables market forces to condense arrangements to the minimum floor areas permitted. This is particularly evident in the UK as the spatial standards are currently the lowest in western Europe. Most such high-density arrangements also tend to be in urban areas (e.g., 95% of high-rise flats), where the risk of overheating is heightened by high occupancy and the additional climate load presented by the heat island effect (ASC, 2014).

3.2.1 Overheating estimation with fixed thresholds

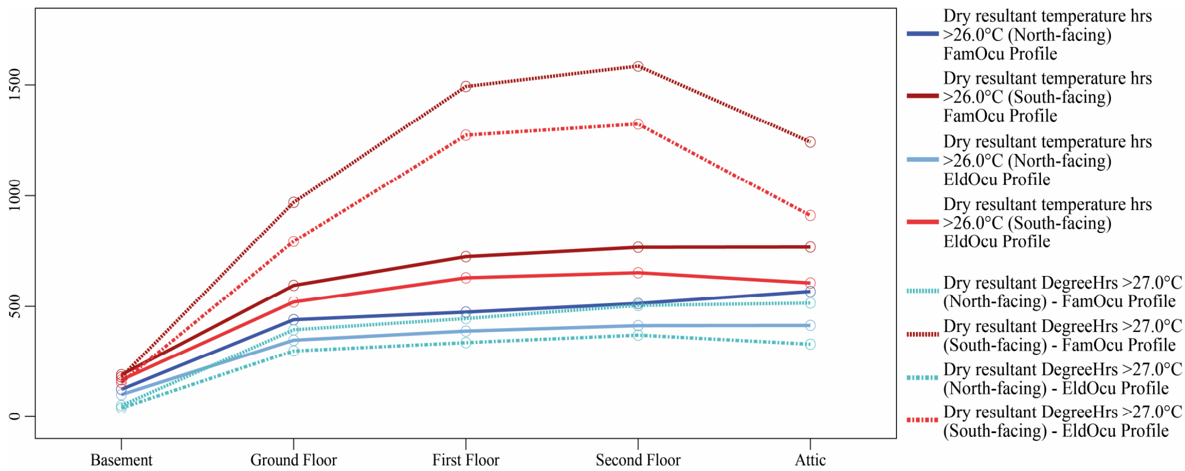
As emphasised in Chapter 2, fixed thresholds for defining overheating vary between sources. The simulation of the case study Gloucester Terrace unit was considered for both small family (*FamOcu*) and older couple (*EldOcu*) profiles (defined in Appendix B.2, p. 101), in relation to the fixed thresholds and criteria defined by CIBSE (2006a) and the Energy Saving Trust (EST, 2005).



Source: IES-VE simulations.

Figure 15. Overheating hours of exceedance by profile, level, and room.

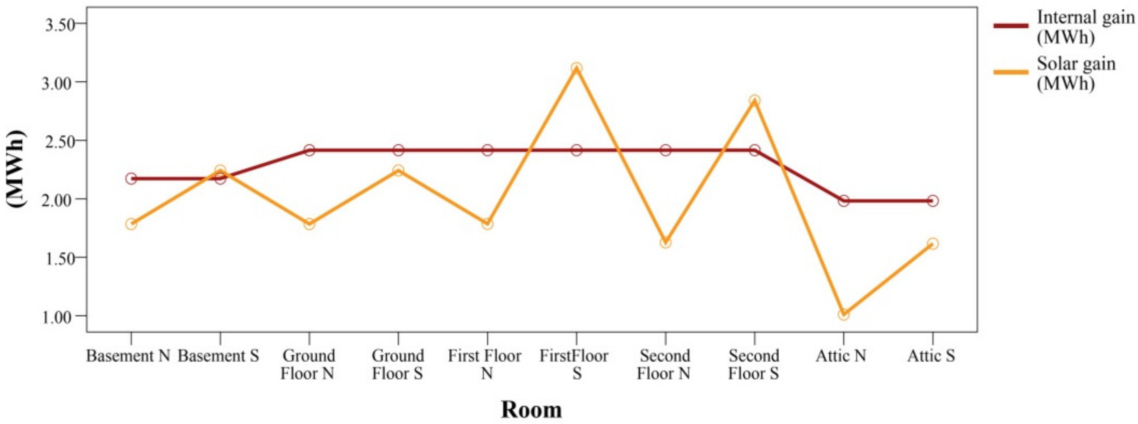
Under single-aspect and free-running conditions with minimal adaptive measures employed, the simulation results for both occupancy profiles demonstrated nearly all rooms to exceed the CIBSE (2006a) overheating criterion (Figure 15, p. 47). Both north and south-facing rooms demonstrated strong positive correlations[iii] with building level, suggesting overheating hours of exceedance to increase with level, e.g., highest risk was at south-facing attic room, which overheated (hrs >26°C) for 8.8% of its occupation (for *FamOcu* profile). However, with the higher threshold of >28°C, and >26°C for the *EldOcu* profile considered, overheating hours of exceedance at the attic level was slightly lower than the penultimate level. This anomaly is explained by the unique characteristics of the dwelling concerned. Since the attic storey is offset to facilitate the mansard-parapet junction detail (Figure 3, p. 22), the rooms at this level have a reduced floor area (~7 m^2 less) in relation to the ones below (in addition to head height). This resulted in the area-based internal gains profile calculating lesser gains relative to lower rooms. The effect was also amplified by considerably lower solar gains (Figure 17, p. 49), principally attributed to smaller windows at the attic level (35-45% less glazed area than floors below).



Source: IES-VE simulations and calculations.

Figure 16. CIBSE hrs >26°C & EST degree-hrs >27°C by level, room, and profile.

[iii] Datasets limited (N = 5), and most not normally distributed (Shapiro-Wilk Normality Test). Spearman's rho correlations significant (p <0.05) for all except: >26°C (south-facing) - *EldOcu* profile; and degree-hrs >27°C (north-facing) - *FamOcu;* (south-facing)- *FamOcu*; (north-facing) - *EldOcu*; (south-facing) - *EldOcu* profiles.



Source: IES-VE simulation.

Figure 17. Summertime gains by level and room for FamOcu profile.

The results for the *FamOcu* profile highlighted a statistically significant[iv] higher overheating risk for rooms facing south (M = 562, SD = 216) than north (M = 378, SD = 154), when the CIBSE (2006a) hrs >26°C criterion was considered. A similar relationship was demonstrated with the EST (2005) degree-hrs >27°C assessment[v] for south (MR = 13.9) and north-facing (MR = 7.1) rooms[vi]. The EST (2005) assessment, which gives a better account of overheating severity (Figure 16, p. 48), highlighted first and second floor rooms as experiencing considerably greater severity than attic rooms. This again is explained by the abovementioned features of the unit modifying internal and external gains for these levels (Figure 17). The peak-day gains profiles (Figure 25, p. 56), highlighted south-facing living rooms to peak in the morning hours, while north-facing rooms peaked (greater in relative magnitude) in the afternoon; which is not ideal for the higher daytime occupancy of the *EldOcu* profile. Gains analysis also demonstrated that the cooler temperatures achieved in basement rooms to be explained by a beneficial summer (disadvantage in winter) heat flux to the

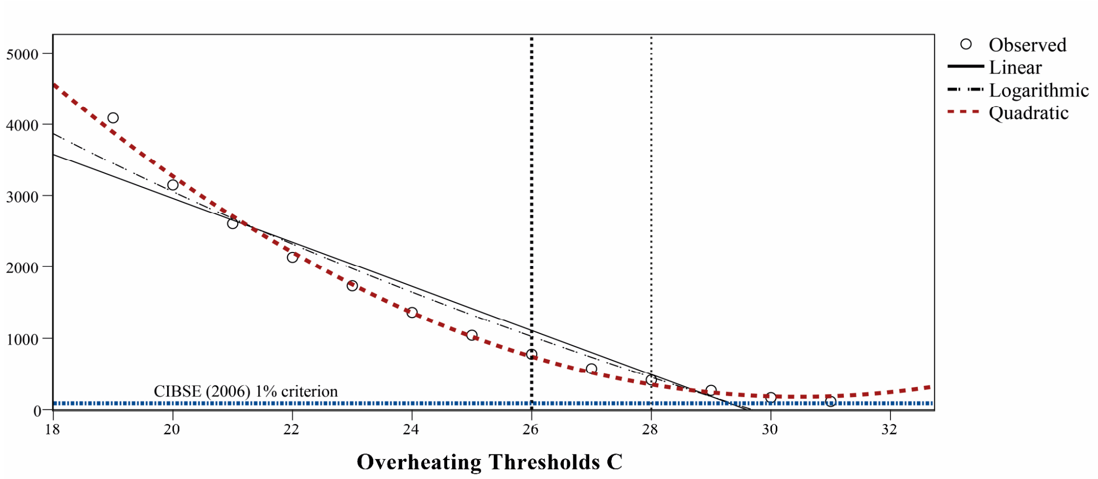
[iv] Data normally distributed, Shapiro-Wilk, W(20) = 0.945, p = 0.297. Independent-samples T-Test implemented with t(18) = 2.19, p = 0.04.

[v] EST (2005) threshold of 27°C is presented as an air temperature measurement. However, for the purposes of consistency and comparative assessment, the value is assessed in this study in relation to dry-resultant temperature measurements.

[vi] Data not normally distributed, Shapiro-Wilk, W(20) = 0.901, p <0.05. Non-parametric Mann-Whitney Test implemented with U(20) = 16, Z = -2.57, p = 0.01.

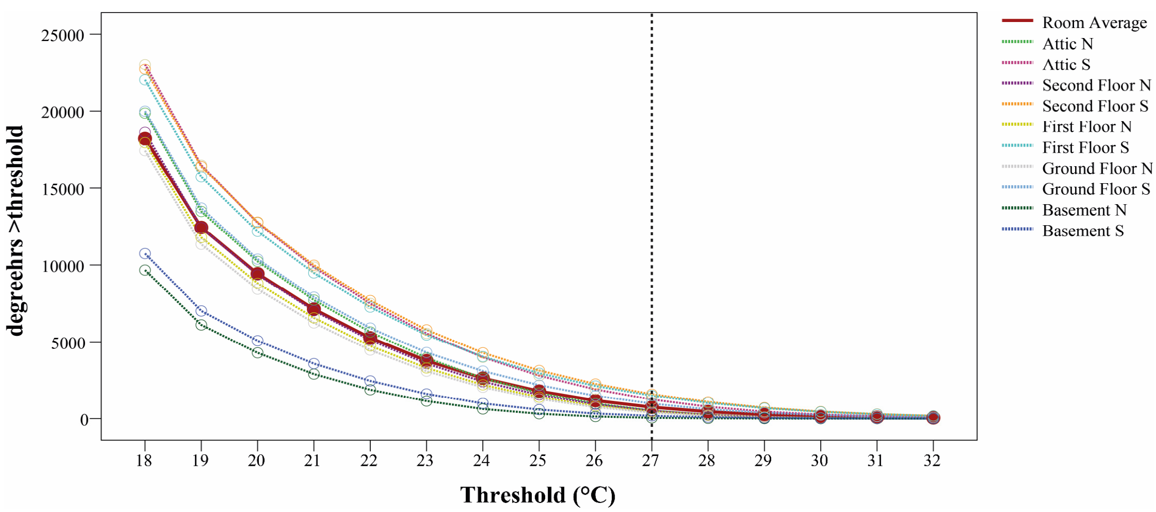
subsurface (through the uninsulated floor construction). For the *FamOcu* profile, ~3 MWh of thermal energy representing ~70% of summer gains for the rooms were conducted through to the ground. This form of building heat flux (typically higher in winter) is highlighted as a significant contributor to the subsurface heat island (Menberg, et al., 2013a); discussed further in Appendix C.2, p. 112.

3.2.2 Discussion on fixed thresholds



Source: IES-VE simulations.

Figure 18. CIBSE (2006a) fixed threshold variation (FamOcu profile).



Source: IES-VE simulations and calculations.

Figure 19. Overheating degree-hrs threshold variation (FamOcu profile).

Simulations against multiple fixed thresholds CIBSE (2006a) presented a negative correlation with a quadratic regression[vii] for hours of exceedance (Figure 18, p. 50). Analysis of the EST (2005) degree-hrs assessment against multiple thresholds highlighted similar negative correlations and regression[viii] that reached neutrality between 30-32°C (Figure 19, p. 50). The fixed threshold value considered for assessment therefore has direct effect on the expected overheating hours of exceedance and severity. In recent times, such thresholds have been criticised for their insensitivity towards adaptive capacities, particularly in free-running buildings. Updates to CIBSE guidance have consequently revised their assessment practices to utilise adaptive comfort theory (section 2.3.1, p. 32), which suggests a 'dynamic' threshold that is sensitive to climate variations, as oppose to a fixed one that is either arbitrary or based on limited evidence. The Gloucester Terrace case study is assessed later against such criteria in Chapter 4.

In the context of previous studies on domestic overheating, top-floor rooms have been repeatedly identified as at risk (DCLG, 2012a). This vulnerability is generally attributed to higher exposure to solar thermal loading, which transfers to indoor rooms, particularly in poorly insulated constructions. Ground floor and basement conditions in contrast have been commonly found to be relatively cooler (Capon & Hacker, 2009). These findings generally accord with Gloucester Terrace results as noted above, save for minor deviations explained by the unique features of the unit. It is worth noting that in comparison to nineteenth century terraced housing such as Gloucester Terrace, these findings have been found to be pronounced in dwellings built around the 1960s, post-1990, and compact purpose-built top-floor flats built in recent times (DCLG, 2012a; ARUP, 2014; ASC, 2014; Firth & Wright, 2008).

[vii] Data normally distributed, Shapiro-Wilk, W(13) = 0.901, p = 0.136, Pearson r = -0.955, N = 13, p <0.01. Best-fit, quadratic regression: F(2,10) = 1,097.6, p <0.00, with hours exceeding overheating threshold = 26,336 - 1,717 × threshold - 28 × threshold^2, $R^2 = 0.995$.

[viii] For 'room average' quadratic regression: F(2,12) = 211.6, p <0.000, with degree-hrs exceeding a threshold = 117,529 – 8,216 × threshold + 143 × threshold^2, $R^2 = 0.972$.

Table 7. Monitored study and simulation comparison for a summer period.

Measure	**Room**	**Monitored values from Firth & Wright (2008)**	**Glo. Terrace Simulation *FamOcu* profile**	**Glo. Terrace Simulation *EldOcu* profile**
Average daily maximum temperatures*	Living room	25.9°C	*24°C*	*23.5°C*
	Bedrooms	26.6°C	*23.3°C*	*22.8°C*
Range of temperatures*	Living room	18.5-25.9°C	*16.9-35.8°C*	*16.5-35.6°C*
	Bedrooms	18.1-26.6°C	*16.8-31.2°C*	*16.4-30.9°C*
Average percentage of hours with temp. >25°C	Living room	3.2%	*35%***	*30%***
	Bedrooms	4.6%	*28%***	*22%***

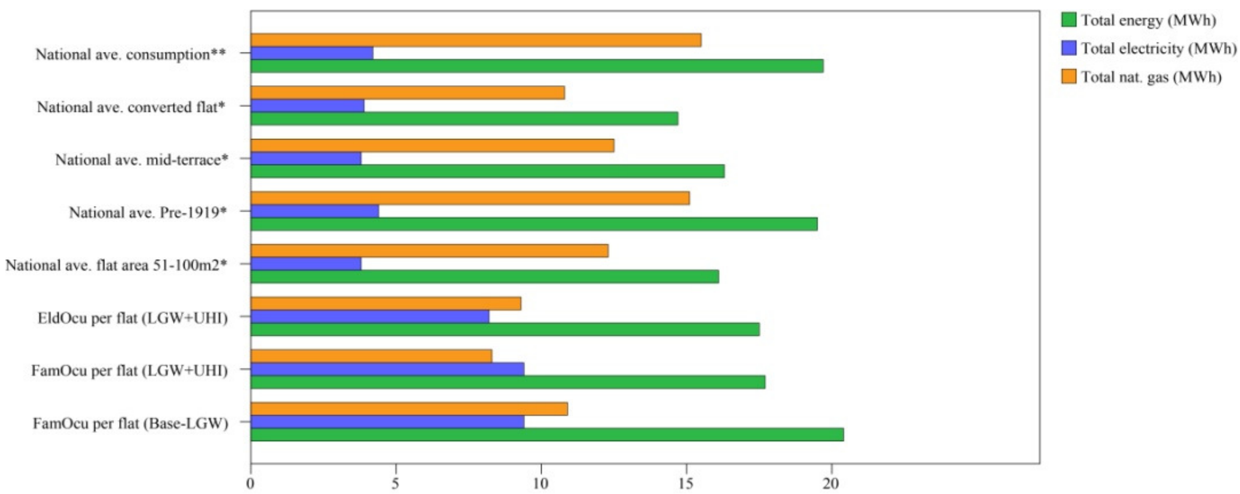
* Air temperature considered. ** High values may be explained by the simulation only considering single-aspect conditions with minimal adaptive measures employed.

Sources: Firth & Wright (2008) for monitoring duration of 984 hrs between 22 July-to-31 August (2007); and parallel IES-VE simulations.

A monitoring study of English dwellings (n = 224) had found their indoor temperatures to be at their highest during the evening and lowest during early morning hours (Firth & Wright, 2008). The Gloucester Terrace simulation for the *FamOcu* profile agreed, although the *EldOcu* profile demonstrated the daytime average T_{op} for all bedrooms to be marginally higher than the evening; possibly explained by higher daytime occupancy resulting in marginally increased gains. Summertime monitoring data from a study of London dwellings (n = 36) had highlighted >40% to exceed the recommended CIBSE (2006a) night-time overheating threshold (Mavrogianni, et al., 2010). For north-facing bedrooms at Gloucester Terrace, the nocturnal hours (ten hours between 8:00 PM to 6:00 AM) that exceeded this 24°C sleep deprivation threshold was estimated at 38% and 27% for the *FamOcu* and *EldOcu* profiles, respectively. These high failure percentages suggest that summertime nocturnal sleep deprivation may already be an issue for the current occupants of this dwelling unit.

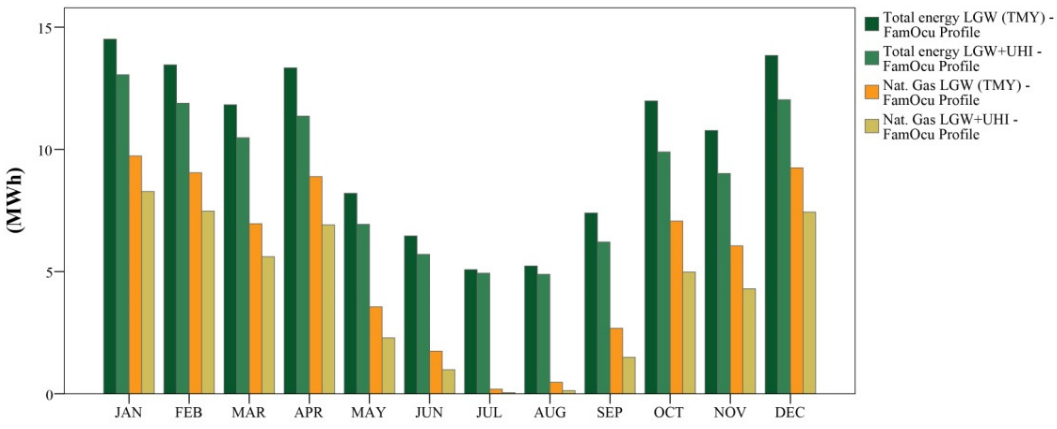
The net effect of building characteristics contributes significantly to the assessment of residential overheating risk (Mavrogianni, et al., 2010). It must be noted that studies that consider dwelling type-based assessments are unlikely to identify the same order of overheating risk, as the findings are dependent on the way such building characteristics have been considered. As no standardised categorising of dwelling types and their features are presently in use, any meta-analysis and generalised conclusions should be considered with caution (DCLG, 2012a). The assessment presented here is therefore dependent on the characteristics considered for Gloucester Terrace as described in Appendix B.2, p. 101, and is only aggregated to the canyon area as its uniform morphological features lends itself suitable (within reason) for such analysis.

3.3 Energy and CO_2 implications



Note: *for the period 2005-11; ** 2008-13. Sources: DECC (2014) and IES-VE simulations per flat.

Figure 20. Simulated energy usage comparison with national averages (MWh).



Source: IES-VE simulation.

Figure 21. Total annual energy and natural gas usage for FamOcu profile.

The comparison between simulations and national average figures highlighted that the total energy use values per flat were within reasonable agreement (Figure 20, p. 53). The notable difference however was in the split between fuel types, with the simulation profiles having consumed more electricity than national averages, while the converse was true for natural gas usage.

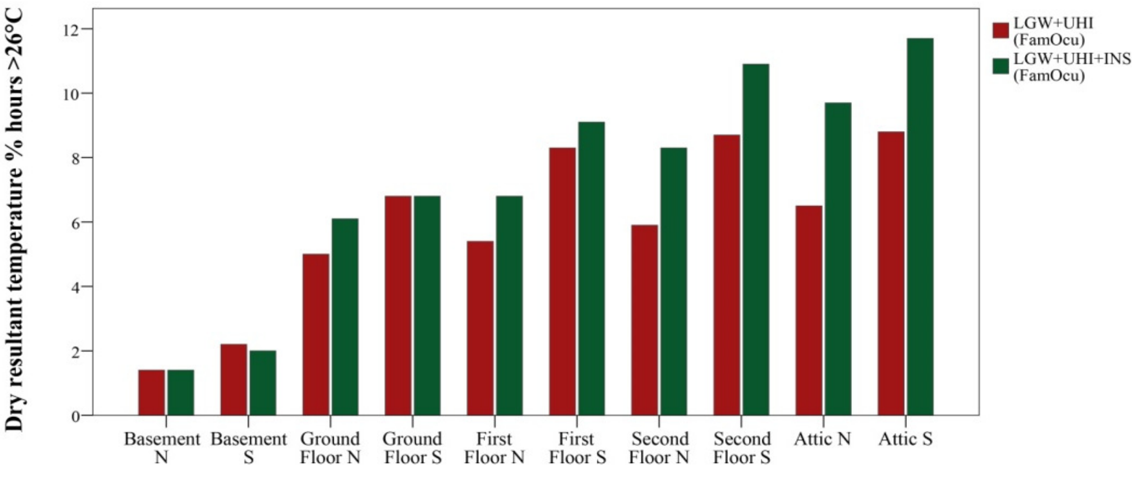
Simulation of the representative unit for the *FamOcu* profile with the UWG weather file (Table 16B, p. 101), demonstrated that accounting for urban microclimate conditions resulted in a 12.9% fall in predicted annual energy use, which equated to a 7.0% reduction in the energy cost (£) estimate. Carbon emissions as a result were also estimated to be reduced by 8%. The reduction in energy usage was attributed to a 23.9% fall in annual central heating energy use (i.e., boiler load), emphasised during winter months (Figure 21, p. 53). The results confirmed that when a building operates within a warmer than expected climate, the need to heat the building to achieve both safe and comfortable temperatures during the winter months is significantly reduced. In urban climate research, this is described as the 'winter warming effect' of the heat island and is considered as a favourable consequence of the phenomenon (Oke, 1988a). As energy demand in the UK housing sector is dominated by space-heating requirements (Steemers, 2003), the aggregated winter reduction in urban heating loads is significant for residential districts in dense urban areas, and particularly when assessing capacity for district heating networks.

3.3.1 Thermal performance retrofit

The energy efficiency and resilience to cold temperatures of UK dwellings have significantly improved over the years, with the average SAP rating bettered from <41 (out of 100) in 1990 to >57 in 2012 (DECC, 2014). All such measures of increasing insulation and airtightness however have also been suggested by modelling studies to have increased the risk of summertime overheating (DCLG, 2012a). To investigate this further, the case study unit was simulated for the *FamOcu* profile with thermal performance enhancements to ascertain their impact on overheating risk, as well as energy efficiency. It is worth noting that the energy efficiency requirements of Part L1B (DCLG, 2013) are not applicable to

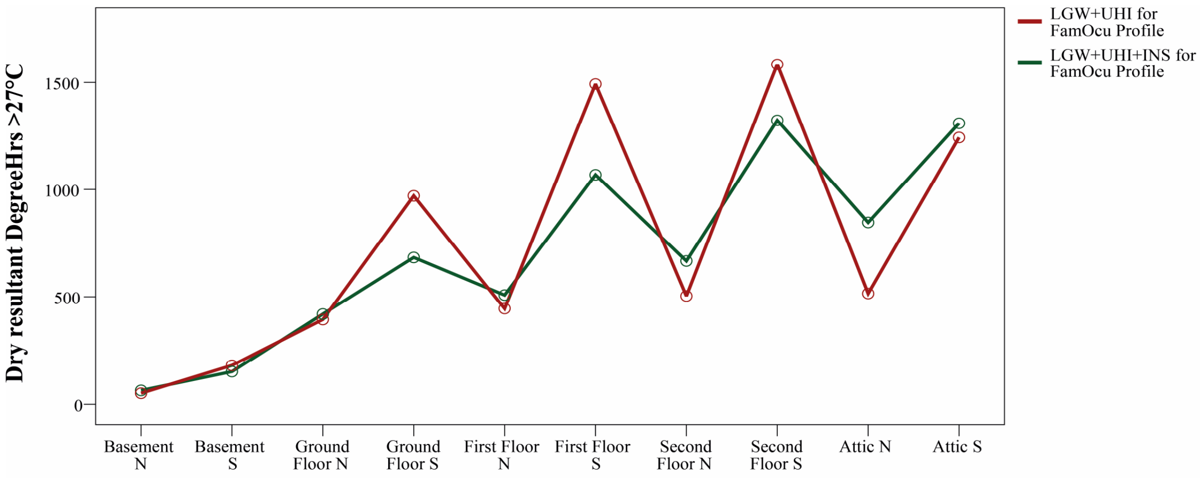
Gloucester Terrace due to its Grade II listing and Conservation Area designation. Energy enhancements are only advocated in such circumstances when they do not alter the appearance and character of the listed features and are reasonably practicable to achieve. All proposed improvements are also subject to consultation with the Westminster City Council Conservation Officer and English Heritage. Following generic guidance from English Heritage (EH, 2011), the *INS* (i.e., insulated) option considered potential performance upgrades entirely for the purpose of theoretical analysis (detailed in Appendix B.3, Table 17B, p. 103).

The simulation results demonstrated that the *INS* upgrade reduced annual energy consumption by 31.6%, which equated to an 18.1% reduction in the energy cost (£) estimate relative to *LGW+UHI*. This in turn translated to a 20% reduction in the annual CO_2 emissions estimate. Improving thermal performance of the building envelope however had a mixed effect on overheating risk, with the occupied hours >26°C criterion (CIBSE, 2006a) having demonstrated an increase of 27%, while the degree-hrs >27°C assessment (EST, 2005) estimated a 5% reduction. This suggested that even though the occurrences increased, overheating 'severity' was reduced by the improvement in fabric thermal performance. Notably, the increase in the number of hours >26°C was pronounced at higher levels of the unit (Figure 22), while severity was reduced for all levels (mid) except basement and attic (Figure 23, p. 56).



Source: IES-VE simulations.

Figure 22. INS (i.e., insulation) upgrade influence on hours of exceedance by level.



Source: IES-VE simulations and calculations.

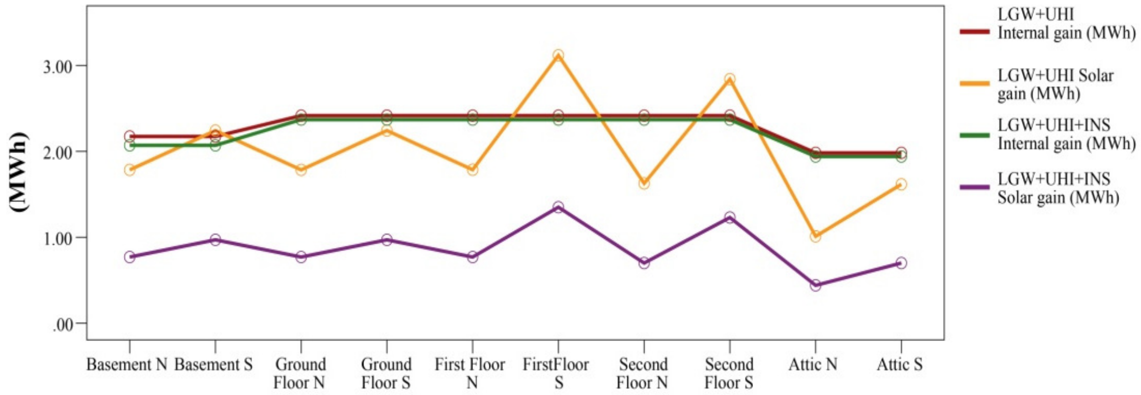
Figure 23. INS (i.e., insulation) upgrade influence on overheating severity by level.

3.3.2 Discussion on thermal retrofit

The proposed retrofit thermal enhancements applied insulation as an internal lining, as an external solution will not be accepted under the listing for the terrace in any instance. Recent studies however have found external rather than internal insulation application to present the most effective means of mitigating overheating risk. The Community Resilience to Extreme Weather (CREW) project for example, assessed a dwelling occupied by a working adult couple with children, and found external, followed by internal wall insulation, as the effective approaches for both living rooms and bedrooms (Hallett, 2013; DCLG, 2012a). A similar study considering retrofit solutions had advocated that such insulation measures should evaluate annual thermal performance (including summer) and modify solutions to address specific occupancy patterns (Mavrogianni, et al., 2012). Care however must be taken with such specific adaptations, as future adaptability to changes in building use and occupancy may be compromised.

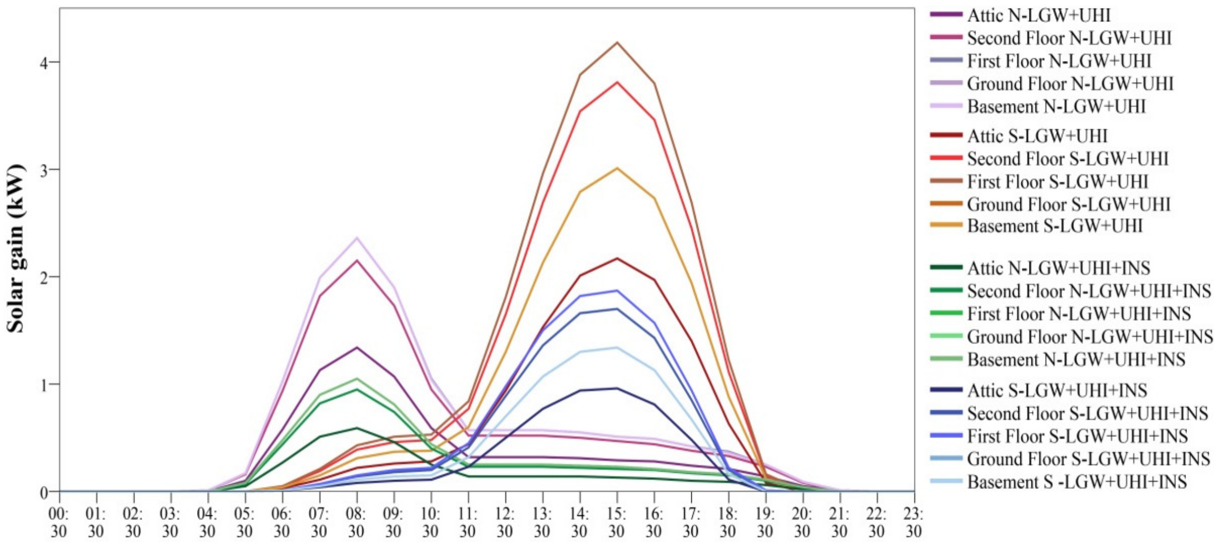
Significant to limiting climate load penetration is the degree of thermal inertia offered by the building fabric in question. In heavyweight dwellings as at Gloucester Terrace, the outdoor daytime climate heat load is absorbed by the mass of the structure and slowly released (reradiated) during the night. This means that the heat release has a time lag that aids in maintaining lower daily peak indoor temperatures (Coley & Kershaw, 2010). Although this inertia is beneficial for keeping the daytime indoor environments relatively cooler (particularly beneficial for an *EldOcu* profile), at Night-time the delayed heat release can have a detrimental effect (for both profiles) if adequate purging is not achieved. In dwellings such as at Gloucester Terrace, this purging will require occupant engagement to leave windows open at night. Such adaptive behaviour is therefore significant for taking advantage of the inherent benefit offered by the building's heavyweight construction.

Adding insulation to the correct building fabric surface can moderate climate loads in favour of achieving cooler indoor spaces. As the simulation for the *INS* upgrade demonstrated, the addition of insulation served to moderate climate gains, which was manifested by a significant drop in solar gain (Figure 24, p. 58). This in turn explains the moderation in overheating severity observed, despite the increase in hours of exceedance or occurrences (explained by the increased trapping of internal gains). Adding the correct insulation level at the appropriate surface is critical, as the reduction in thermal transmittance may also work in opposing terms to trap internal and penetrated climate gains. A comparative study of dwellings had demonstrated that increasing insulation had greater benefit in mitigating overheating in Edinburgh where solar gains are lower, than in a super-insulated dwelling in London exposed to higher levels of solar gain (Peacock, et al., 2010). The CREW project advocated that while improving thermal insulation is significant for enhancing energy efficiency, both solar and internal heat gains also need to be assessed and limited to minimise overheating risk (Hallett, 2013). Orientation in this calculation is a critical factor, as south-facing surfaces will receive direct radiation, typically leading to higher gains as highlighted by Figure 24, p. 58. For the arrangement at Gloucester Terrace, these gains currently transfer into living rooms, although if the arrangements were to be reversed as bedrooms, sleep deprivation amongst other heat-related health risks would be considerably amplified.



Note: internal gains for *FamOcu* profile; Source: IES-VE simulations.

Figure 24. Summertime gains comparison, INS (i.e., insulation) upgrade influence.



Note: peak-days, *LGW+UHI*, N: 30 June and S: 10 April; *LGW+UHI+INS*, N: 30 June and S: 15 September. Source: IES-VE simulations.

Figure 25. INS (i.e., insulation) upgrade influence on peak-day solar gains for unit.

The need for a strategic approach to introducing retrofit solutions is highlighted by the profile of the UK domestic stock. Demolition and replacement rates of dwellings in the UK are considerably lower than Europe, with the building stock considered to be one of the oldest in the world (DEFRA, 2012a). Modification and adaptation are therefore essential for addressing climate change challenges, including overheating risk. The Committee on Climate

Change estimates that at the current replacement rate, 80% of the dwelling stock that will be in use in 2050 as already built (ASC, 2014). This represents a considerable adaptation challenge that is likely to require a strategic approach to funding and implementation. Initiatives such as the ‘green deal’, which removes upfront capital of improving energy efficiency with costs recovered through energy-bill savings (DECC, 2011), should be extended to undertake strategic stock assessments that would eventually support modifications addressing both overheating and energy efficiency targets as an integrated exercise.

3.3.3 Adding a cooling load

The Chartered Institution of Building Services Engineers (CIBSE) have stressed that it is unlikely that comfort targets in free-running London buildings will be satisfied without some form of mechanical cooling being used by the 2050s (CIBSE, 2005). Accepting this outlook and planning for the use of mechanical cooling will modify energy consumption patterns, particularly in the domestic sector as at present the space-conditioning profile remains dominated by heating energy expenditure. To investigate the influence of this active adaptation, the following considered hypothetical scenarios in which domestic air-conditioning was utilised to address prevailing overheating risk for the *FamOcu* profile (detailed in Appendix B.4, Table 18B, p. 104), with the resultant modifications in energy usage and CO_2 emissions discussed.

The first scenario (referred to as *AC1*) considered domestic air-conditioning applied to *LGW+UHI*. The second scenario (*AC2*) considered the earlier mentioned thermally upgraded unit (i.e., *LGW+UHI+INS*), with cooling applied to resolve residual overheating risk. With scenario *AC1*, the use of the cooling system purged overheating with 3.5% additional energy usage. The usage split of this configuration was dominated by higher-tariff electricity, which led to a net cost (£) increase of 4.9%. The impact of accounting for the heat island effect on cooling (i.e., comparison between *AC0* and *AC1*), was highlighted by a 24.6% increase in the chiller load estimate. Applying *AC2* with the *INS* unit highlighted that the combined mitigation approach offered energy and cost (£) savings of 27.9% and 12.5%, respectively (Table 15, p. 92).

3.3.4 Cooling load assessment for the canyon

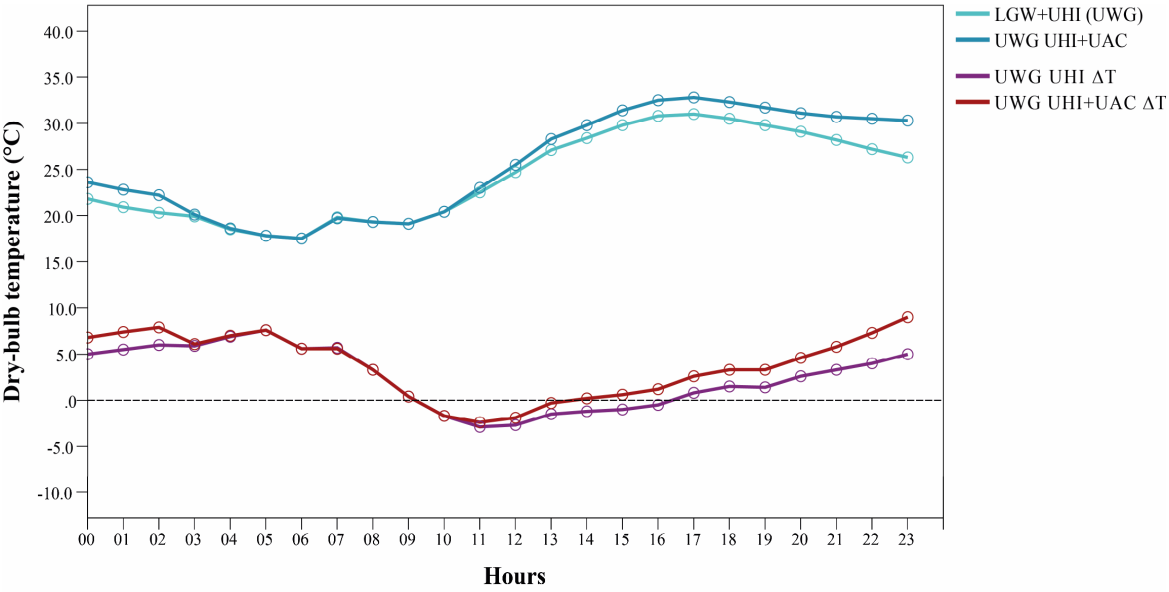


Figure 26. Summer peak-day (30 June) DBT profile comparison.

The UWG provides the opportunity to include aggregated energy consumption patterns in the analysis of urban canyon microclimates. The Gloucester Terrace neighbourhood was accordingly simulated to estimate the impact of widespread use of air-conditioning on canyon microclimate temperatures. Visual inspection of the simulated peak-day $UHI\ \Delta T$ profiles for both $LGW+UHI$ and $LGW+UHI+UAC$ scenarios highlighted that the influence was minimal during the morning-to-midday period, while in the evening and at night a pronounced increase in canyon temperatures was estimated (Figure 26). The summertime hourly $UHI\ \Delta T$ comparison for both scenarios indicated a statistically significant difference in estimated canyon temperatures[ix]. The $UHI\ \Delta T$ mean for the space-heating dominated canyon ($LGW+UHI$) was therefore

[ix] Kolmogorov-Smirnov Normality Test, D(5,064) = 0.181, p <0.00 and D(5,064) = 0.157, p <0.00 respectively; and visual inspection of histograms, Q-Q plots, and box plots showed both datasets as not normally distributed, with skewness values of 1.80 (SE = 0.034) and 1.73 (SE = 0.034); and kurtosis values of 3.851 (SE = 0.069) and 4.336 (SE = 0.069) respectively. A non-parametric Wilcoxon Signed Ranks Test was performed with: Z(5064) = -16, p <0.000.

elevated from M = 1.65 (SD = 1.7, N = 5,064) to M = 1.81 (SD = 2.02, N = 5,064) with the widespread use of domestic air-conditioning (i.e., *LGW+UHI+UAC*). This equated to an hourly average temperature increase of 0.1 K during the day and 0.4 K at night (8:00 PM to 6:00 AM) for the summer (29 Mar to 25 Oct).

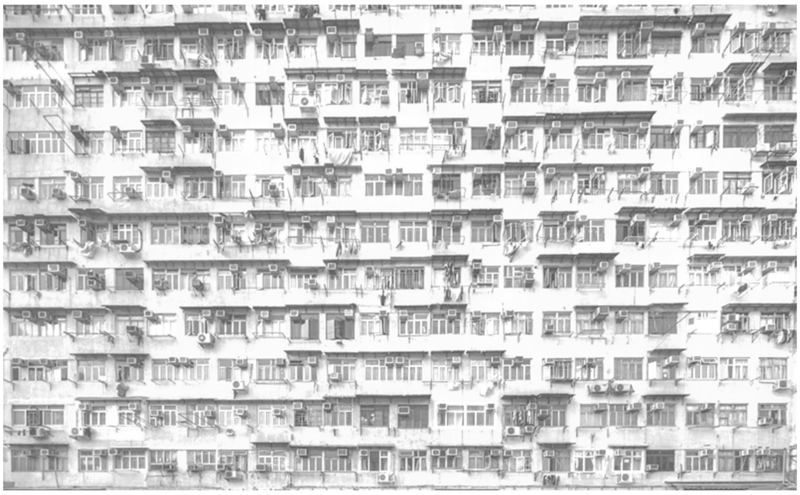
As rejected heat from widespread air-conditioning use adds to environmental thermal loading, a modest 1.5% energy and 0.8% cost (£) reduction was estimated relative to the free-running *LGW+UHI* unit; attributed to a marginally reduced heating load. With mechanical cooling also employed at the representative unit (i.e., *LGW+UHI+AC1+UAC* scenario), a modest 0.3% increase in energy use, and a notable 6.6% increase in cost (£) was estimated; resulting from an increase in higher-tariff electricity expenditure. In terms of aggregated assessments, a future scenario in which the entire canyon (100 m length including ×40 mid-terraced units) adopts mechanical cooling (excluding thermal performance upgrades), an additional 70 metric tons of CO_2 was estimated to be released to the climate. If on the other hand thermal upgrades are applied to all units with summer air-conditioning used to address residual overheating risk (i.e., *LGW+UHI+INS+AC2+UAC* scenario), CO_2 release to the climate may be reduced by 244 metric tons, relative to the free-running *LGW+UHI* canyon.

3.3.5 Discussion on mechanical cooling

For a city such as London where high-density occupation is increasing, there is growing concern that increased cooling demand will soon lead to unsustainable residential energy consumption patterns. Currently, there is little use of domestic air-conditioning in the UK (circa 3%, DECC, 2013) and in Europe in general. This however is expected to change as ever-increasing health risks may eventually compel its widespread introduction to address heat vulnerability (Palmer, et al., 2014). A projection study had estimated that climate change could result in 29-42% of households in the south of England acquiring air-conditioning by 2050 (Boardman, et al., 2005). The Committee on Climate Change meanwhile has stressed that domestic air-conditioning unit sales as steadily rising, with 5% of extensions and conservatories in London already identified to be air-conditioned (ASC, 2011).

Studies from the United States have established both room and central air-conditioning to demonstrate negative correlation with heat-related mortality (Chestnut, et al., 1998), with centralised systems potentially having a stronger effect (Chestnut, et al., 1998; O'Neill, et al., 2003). Modelling studies in the UK have mainly assumed domestic air-conditioning to be deployed in bedrooms to counter sleep deprivation and nocturnal discomfort. A recent study had estimated that cooling loads required for maintaining bedrooms at ~22°C to be double that for a living room (He, et al., 2005). A monitoring study from London also recorded longer average operation periods for bedrooms (9 hrs, switch-on at 23.9°C) than living rooms (5 hrs, switch-on at 25.0°C, Pathan, et al., (2008)). The use of domestic air-conditioning is also observed to create a behavioural change in users, with the technology used for longer periods to create indoor climates that are cooler than necessary to protect health and ensuring comfort. Unless usage is managed remotely through smart meters or centralised control, the net effect of widespread domestic air-conditioning is likely to increase energy usage and CO_2 emissions of dwellings (DCLG, 2012a).

In urban environments where the heat island effect presents an added climate load, energy use in mechanically cooled buildings can be significantly modified. A simulation study that located a prototypical air-conditioned office building within multiple locations of the London heat island had found annual cooling loads to be 25% higher than rural loads (Kolokotroni, et al., 2007). A study from Athens (subtropical Mediterranean) had demonstrated a 10 K $UHI\,\Delta T$ to double the required cooling load (Santamouris, 2001). A recent study from Toulouse (temperate) had suggested that residential energy demand modifications by up to 20% may be evident for a typical daily $UHI\,\Delta T_{max}$ of 4 K (Bueno, et al., 2012). For the Gloucester Terrace simulation, a similar 4 K daily heat island intensity modified the energy demand estimate between 12-14%. The significance of these modifications is determined by the dominant usage pattern relevant to the building in question. Buildings with predominant cooling requirements consequently are adversely affected by the heat island, while the contrary is true for those with heating only (Kolokotroni, et al., 2007). For the current urban energy profile, the London heat island is estimated to provide a 13% energy (space-heating) benefit to its households (ACN, 2011). Although the impact of the heat island had a similar (12.9%) benefit to Gloucester Terrace's consumption estimate, the risk of overheating and the resulting necessity for cooling was evident (in the interest of health and comfort). The way such cooling requirements are to be addressed will considerably influence future energy consumption, particularly if air-conditioning is utilised as the principal adaptation. The Committee on Climate Change have calculated that if the UK adopts widespread domestic air-conditioning, this will mean an additional financial burden (over fifteen years) of around £2 billion to retrofit existing homes, and £400 million for new build homes (ASC, 2011).



Source: © Google Images.

Figure 27. Widespread air-conditioning use in Hong Kong.

The use of excess energy in abeyance, air-conditioning is also identified for having an adverse effect on the urban climate from the heat rejected from such systems (Sailor, 2010). A simulation study of semiarid Phoenix (USA) established waste heat released from air-conditioning to have negligible effect near the surface during the day (despite maximum released), while during the night, increased air temperature >1 K had been observed (Salamanca, et al., 2014). A simulation study of central Paris (temperate) had found a similar 1 K nocturnal increase (sensible heat), while the day effect was deemed minimal. A similar study considering Toulouse also concluded that under a future scenario with air-conditioning widely used, rejected heat would elevate outdoor summer air temperatures by 0.8 K for residential and 2.8 K for commercial quarters (Bueno, et al., 2011). In comparison, the simulation of the Gloucester Terrace canyon resulted in a moderate nocturnal increase of 0.4 K. The nocturnal significance of such anthropogenic heat emissions is attributed by climatologists to the contracted urban canopy layer, which concentrates emissions nearer to the surface, while during the day the greater depth of the urban boundary layer encourages rejected heat to rise further up into the atmosphere to minimise the effect at the surface (de Munck, et al., 2013). Another complicating factor is that some air-conditioning systems use evaporative cooling to exchange heat (as latent heat) with the outdoor environment (Sailor, 2010). This means that rejected moisture can modify canopy layer humidity levels, thereby affecting nocturnal urban comfort and heightening vulnerability to heat-related health risks (Kalkstein & Davis, 1989).

The rejection of waste heat from air-conditioning increases outdoor temperatures and discomfort, from which urban inhabitants must then seek to protect themselves further by increasing energy consumption needed for further cooling. This spiralling feedback loop (Figure 6, p. 27), eventually leads to unhealthy and unsafe urban surroundings that discourage inhabitants from engaging with the outdoor environment (Steemers, et al., 1998). The dominant and convenient use of the technology therefore adds to environmental, economic, and social burdens, while diverting attention away from alternative low-impact adaptive measures. Avoiding, or in the very least managing the use of air-conditioning is therefore a primary objective in reducing energy use and anthropogenic emissions.

Chapter 4

Adaptation and occupant behaviour

A recent study had demonstrated that heat-related mortality could be reduced by 30-70% if adaptation measures managed to reduce indoor temperatures by 1-2 K by the 2050s (Jenkins, et al., 2014). To achieve such a reduction, adaptation may be approached as both environmental (indoor surroundings) and behavioural (occupant) modifications. Adapting buildings to be more resilient to heat represents an environmental adaptation that seeks to alter the way they are designed, constructed, and operated. As most buildings are built with the intention of providing decades of continued service, the changing climate has burdened them with the requirement to be adaptable to not only expected warming, but also other climate risks. Consequently, there is a requirement for buildings to be 'future-proofed', in design, construction, and operational processes, all with flexibility to adapt to future changes with the minimum expenditure of resources. A recent survey however had highlighted that most building designers are encountered with resistance from development stakeholders when proposing the introduction of overheating adaptation measures, as such solutions (e.g., facade shading devices) tend to have high capital costs with non-tangible returns to their commercial interests (ZCH, 2015a). Designers are often compelled to justify their inclusion in terms of the return offered in energy savings, which in any case is now required by code and growing demand (ASC, 2014). The argument for bettering the health of future building occupants is often considered as a difficult claim for economic interests to quantify, and in turn justify capital investment.

Economic accountability, particularly in a market economy such as the UK, is significant for improving energy efficiency and adapting buildings to future climate risks. While energy savings can be calculated and estimated, betterment in intangible gains such as health and wellbeing are complicated claims to value. Although some guidelines exist in the UK (HM Treasury, 2011), the key barrier to introducing adaptive design measures in new buildings is this inability to accurately account and profit from offered betterment in wellbeing. This in turn is a significant disincentive for proactive market engagement. The Committee on Climate Change argues that to address such shortfalls in industry and market enthusiasm, the introduction of regulatory direction to be necessary (ASC, 2014). Direct and binding instructions to market interests are therefore advocated for catalysing the creation of resilient and adaptable residential built environments.

Table 8. Summary of adaptation possibilities.

Measure	Strategy	Considerations
Urban planning	*Minimising urban environmental thermal load on built form*	
Heat island mitigation	Reduce heat storage within the urban system	▪ Morphological planning ▪ Materiality of built environment ▪ Green and blue space distribution ▪ Anthropogenic emission controls
Location factors	Avoid high heat rejection areas	▪ Reduce anthropogenic emissions ▪ Avoid local hot spots for residential purposes
Strategic cooling	Low impact communal cooling	▪ Access to green and blue spaces ▪ District cooling network (with heat from CHP), e.g., Copenhagen, and London Olympic Park (GLA, 2013)
Building envelope	*Preventing environmental thermal load from migrating into occupied indoor spaces*	
Albedo	Lighter colours to reflect solar radiation	▪ Aesthetics ▪ Planning and listing restrictions ▪ Glare risk ▪ Maintenance
Shading	Limit solar gain	▪ Dependent on orientation and location ▪ External found to be most effective (capital cost); internal blinds and curtains less effective (Hallett, 2013)
Insulation	Managing the temperature gradient	▪ Dependent on location/surface of envelope

Measure	Strategy	Considerations
	between indoor and outdoor environments	▪ External found to be more effective ▪ Subject to condensation analysis ▪ Loss of internal floor area (GIA) ▪ External may not be achievable, e.g., listing, or spatial-fit
Thermal mass	Increase thermal inertia of the building fabric	▪ Not practical for retrofitting ▪ Structural and spatial-fit issues ▪ Loss of internal floor area (GIA) ▪ Not effective on its own
Ventilated facades	Double skin to minimise penetration and conduction of solar gain	▪ Not practical for retrofitting ▪ Construction and spatial-fit issues ▪ Loss of internal floor area (GIA)
Building operation	*Dissipation of penetrated environmental and internal thermal gains*	
Passive strategies	Increase window opening; buoyancy assisted stack effect etc.	▪ Dependent on occupant behaviour ▪ Dependent on indoor/outdoor temperature gradient; and wind loading and flow dynamics ▪ Needs to be simulated and studied
Active strategies	Most efficient solution	▪ Dependent on occupant behaviour ▪ Centralised control/smart meter ▪ Minimise heat gain ▪ Needs to be simulated and studied
	Hybrid solutions	▪ Heat recovery ▪ Heat pumps circulating cold fluid during the summer
Management practices	*Avoiding risk*	
Occupancy management	Mitigating risk to principal occupants	▪ Occupancy profile - assessing vulnerability (e.g., older occupants) ▪ Activity/rest - metabolic rates ▪ Avoid overcrowding ▪ Monitoring - social capital
Personal climate	Mitigating risk to occupant	▪ Clothing choice ▪ Localised cooling e.g., fan etc.

4.1 Environmental adaptation

Adaptation of the built environment may be approached from macroscale urban planning to microscale detailing of buildings. The adaptation of urban parameters is principally associated with measures that mitigate the heat island effect. The fundamental principle here is to quantify and target the parameters that trap thermal energy within the urban system, i.e., to minimise the heat storage factors of the urban energy balance (Equation 7, p. 39). Urban morphology, materiality, and greenspace and blue-space distribution are key contributing components that urban planning processes can influence and modify to mitigate heat island intensities. In addition to targeting these root causes, urban adaptations serve to provide immediate relief to communities. Opportunities to access cool features during warm weather for example, requires long-term planning to address community specific vulnerabilities.

It must be acknowledged that extensive citywide adaptation is not always a viable approach when adaptive resources are limited, and other constraints such as historical value and sociocultural complexities need to be resolved through inclusive and democratic processes. Urban scale adaptations are thus unlikely to offer rapid relief and remedy, but are long-term measures offering progressive contribution. It is therefore critical to establish and incorporate such adaptation principles into urban development policy as early as possible, which in turn will drive the necessary building specific adaptations and determine their eventual efficacy.

At the building scale, the available adaptation measures are numerous with varying different efficiencies for each context and set of circumstances (summarised earlier in Table 8, p. 66). Good ventilation for example, is considered as a fundamental necessity for moderating a free-running dwelling's indoor climate, with higher rates associated with the efficient dissipation of heat absorbed from climate loads and generated from internal gains from various heat sources. The CREW project notably stressed such 'minimal cost' behavioural solutions to add considerable value to domestic adaptation strategies (Hallett, 2013).

4.1.1 Window opening

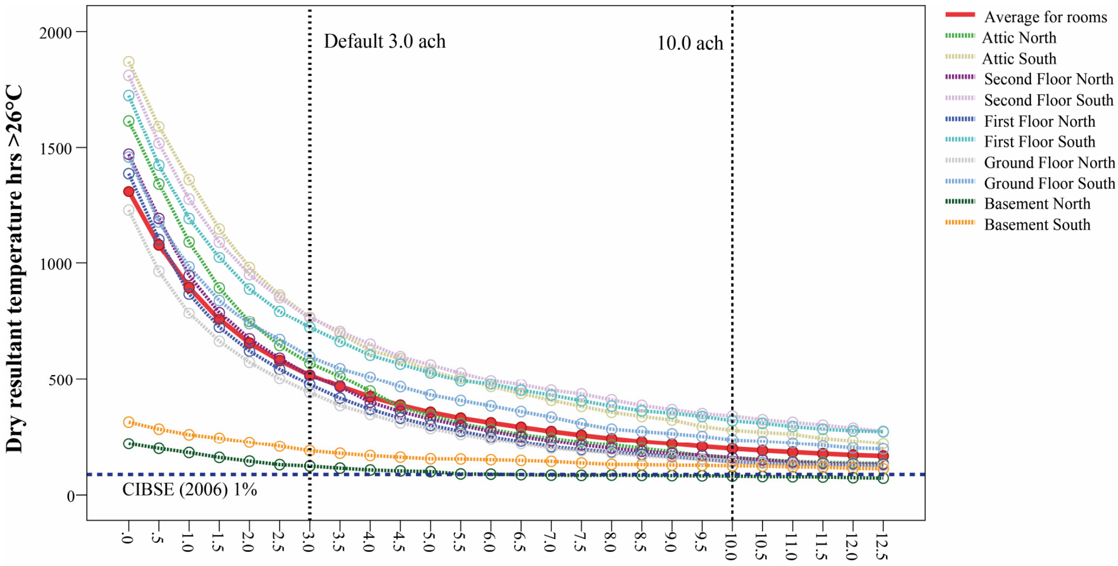


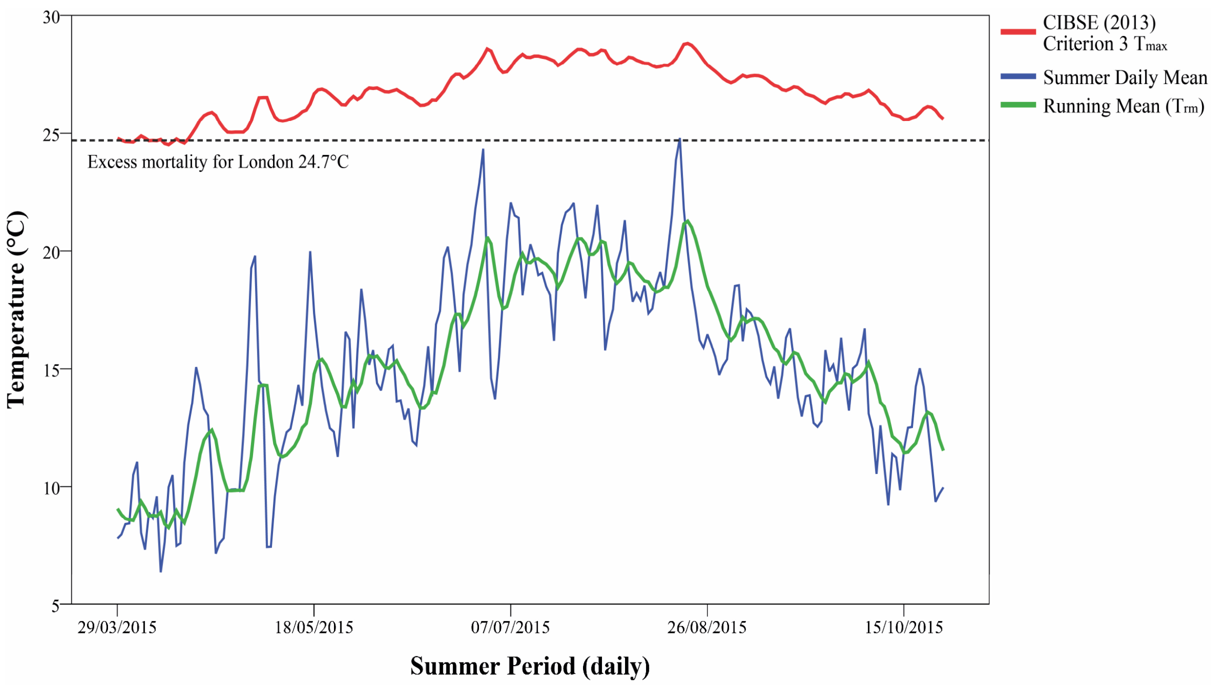
Figure 28. Overheating hours of exceedance (>26°C) variation with air-change rate.

The simulation of the Gloucester Terrace representative unit considered standard ventilation rates recommended by CIBSE (2015), for a profile that considered windows left open only during the day and following the applied summer occupancy profile. Night-time window operation was excluded from this base simulation, as it was assumed a security and noise concern given the central and exposed locality of the street (Grey & Raw, 1990).

CIBSE (2015) guidance states that if 24-hour operation of windows is utilised, air-change rates may be increased by up to 10 ach. To assess the influence of ventilation rates on expected overheating hours of exceedance (>26°C), the Gloucester Terrace unit for the *FamOcu* profile was simulated for the summer with incremental increases in air-change rate. Under single-aspect free-running conditions (*LGW+UHI*), the results demonstrated overheating hours decreasing following a polynomial regression [x] with increased air-

[x] Best-fit, cubic regression for 'average for rooms': $F(3,22) = 704$, $p < 0.000$; with hours exceeding overheating threshold = 1,230 – 335 × ach + 38 × ach^2 - 1.5 × ach^3, $R^2 = 0.990$.

change rate. Beyond 10 ach, the reduction in overheating hours was minimal as both indoor and outdoor environments approached equilibrium. Meeting the 1% CIBSE (2006a) criterion solely from air-change increases would require very high rates to be achieved; e.g., for the 'average for rooms' this is likely to be circa 13 ach [xi] (Figure 28, p. 69). Achieving such high rates however is a difficult task, as in free-running buildings air exchanges will be dictated by the indoor-to-outdoor pressure differential, which may not be adequate to facilitate such high airflow rates.



Source: calculated for *LGW+UHI* profile, using CIBSE (2013) methodology.

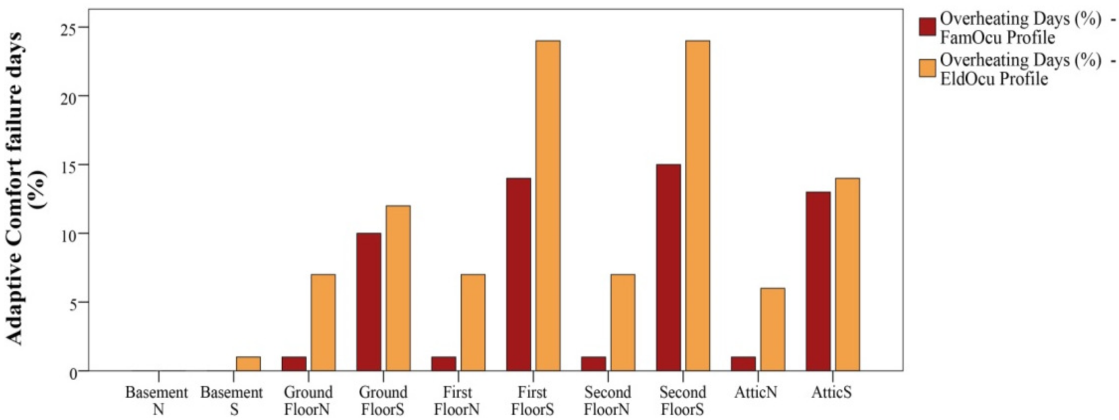
Figure 29. Running mean translation to obtain ΔT_{max} *for indoor rooms.*

As means of addressing the adaptive capacities of occupants to indoor and outdoor climate variations, recent developments in adaptive comfort theory have directed guidance towards dynamic thresholds for assessing overheating risk (see section 2.3.1, p. 32).

[xi] Applying the above regression equation.

The methodology presented by CIBSE (2013; 2015) restricts the assessment to the core non-heating months from May to September (N = 153 days), with rooms requiring compliance with a minimum two out of the three criteria defined. For Gloucester Terrace, the *FamOcu* profile was considered under the Category II ΔT_{max} threshold (Figure 29, p. 70), while the *EldOcu* profile was considered under Category I, which defines an onerous ΔT_{max} (-1 K) for assessment (CIBSE, 2013).

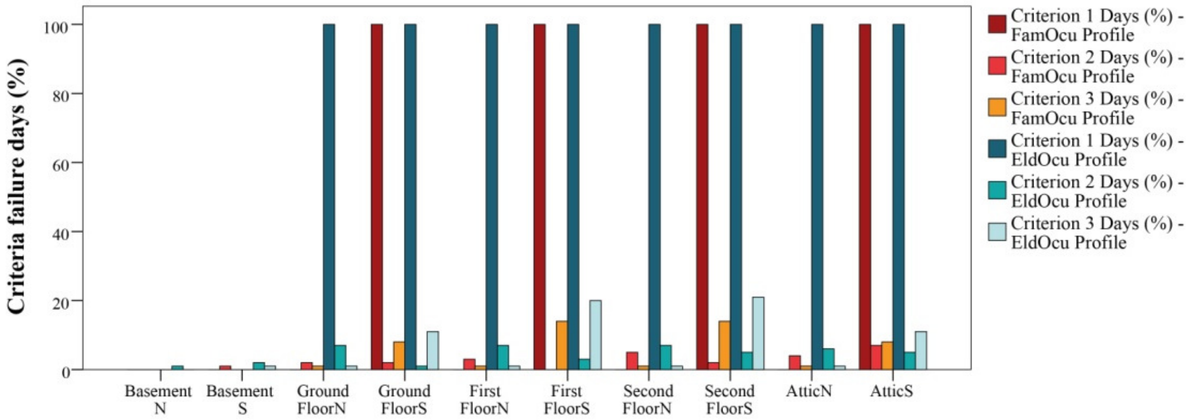
The analysis results showed 'failure-days' (days where two out of the three criteria are not satisfied) for both profiles to gradually increase with floor level, with the notable exception of the attic level. This finding and its explanation is in common with the previously considered fixed threshold assessments in section 3.2.1, p. 47. Comparing both occupant profiles highlighted the *EldOcu* profile (i.e., higher expectation) to report notably higher failure-days due to the onerous ΔT_{max} considered. In terms of orientation, both profiles demonstrated maintaining comfort with adaptive strategies to be challenging for south-facing rooms than north-facing (Figure 30). For most days and in the most frequented spaces of the *FamOcu* profile (i.e., bedrooms), comfort temperatures were achieved with adaptive practices.



Notes: N = 153 days (May-to-September); abbreviation 'N': north-facing, and 'S': south-facing.
Sources: IES-VE and adaptive comfort calculations.

Figure 30. CIBSE (2013; 2015) adaptive comfort assessment failure-days (%).

Failure-days for both profiles presented strong positive correlations with Criterion 3, moderate correlations with Criterion 1, and weak correlations with Criterion 2 [xii]. This suggested the variance [xiii] in overheating failure-days to be influenced by the failure of Criterion 3, followed by Criterion 1, and the least by Criterion 2 (considers daily severity of overheating). If the room remains within the seasonal duration criterion (H_e); and does not exceed the T_{upp} threshold (safeguard against heat stress); a warm day that exceeds the daily criterion (W_e), may fall within the permitted 'comfort range'. This relaxation is significant for anomalous extreme heat events, when for short durations warmer temperatures may be endured provided the T_{upp} limit is not exceeded. The sensitivity of the CIBSE (2013; 2015) adaptive comfort assessment in relation to the CIBSE (2006a) 1% hours of exceedance (>26°C) criterion for the same period between May-to-September highlighted that save for basement rooms, all other floors demonstrated significant reductions in reporting overheating failure-days; notably pronounced for north-facing than south-facing rooms (Table 9, p. 73).



Note: N = 153 days (May-to-September). Sources: IES-VE and adaptive calculations.

Figure 31. Criterion 1-3 CIBSE (2013; 2015) failure-days (%).

[xii] Most datasets not normally distributed (Shapiro-Wilk Normality Test). Spearman's rho correlations: $r_s = 0.993$, p <0.000; $r_s = 0.883$, p <0.001; $r_s = 0.169$, p = 0.641 (n.s.), N = 10 respectively (as above) for *FamOcu*, and $r_s = 0.914$, p <0.000; $r_s = 0.698$, p = 0.025; $r_s = 0.086$, p = 0.814 (n.s.), N = 10, respectively (as above) for *EldOcu* profile.

[xiii] Criterion 1: Cubic regression F(3,6) = 422.2, p <0.000, $R^2 = 0.995$; Criterion 2: Cubic regression F(3,6) = 0.169, p = 0.914 (n.s), $R^2 = 0.078$; Criterion 3: Cubic regression F(3,6) = 44.4, p <0.000, $R^2 = 0.957$.

Table 9. Sensitivity of adaptive comfort against fixed threshold assessment.

Reporting overheating failure-days	Basement N	Basement S	Ground floor N	Ground floor S	First floor N	First floor S	Second floor N	Second floor S	Attic N	Attic S
	%	%	%	%	%	%	%	%	%	%
Reduction *FamOcu*	0	0	**98**	78	**98**	73	**98**	71	**98**	73
Reduction *EldOcu*	0	0	74	73	74	51	74	50	77	68

Note: N = 153 days (May-to-September).

The adaptive comfort assessment is also influenced by the ambient air velocity in a room. The operative temperature (T_{op}) may be revised down from its default value (i.e., relatively still) to address the cooling effect provided by fan usage controlled by room occupants. If such fan usage raised room airflow velocity from 0.1 to 0.6 m·s^{-1} for example, the T_{op} may be adjusted down by up to 2 K (CIBSE, 2015) [xiv]. Applying this adaptation to the summer peak-day of 30 June (for *FamOcu* profile with default 3.0 ach natural ventilation), resulted in rooms deemed to overheat being reduced from eight to three. The overall effect was greatest for south-facing rooms from first floor and above. As far as the criteria were concerned, greatest effect was noted for Criteria 3 and 2, although Criterion 2 suggested a marginal (1%) increase in reporting failure at higher floor level south-facing rooms (Table 10).

Table 10. Impact of fan usage on overheating for FamOcu profile.

Fan usage on CIBSE (2013; 2015)	Basement N	Basement S	Ground floor N	Ground floor S	First floor N	First floor S	Second floor N	Second floor S	Attic N	Attic S
Reductions in:	%	%	%	%	%	%	%	%	%	%
Criterion 1	-	-	-	0	-	0	-	0	-	0
Criterion 2	-	0	67	0	80	0/**1***	86	0/**1***	83	82/**1***
Criterion 3	-	-	0	75	0	48	0	48	0	75
Overall overheating	-	-	0	0	0	**47**	0	**48**	0	**95**

Note: N = 153 days (May-to-September); * Failure of Criterion 2 increased by 1%.

[xiv] For sedentary person (1 met), page 5-62, Fig. 5.38.

4.1.2 Discussion on opening windows

The principle of opening a window is to increase airflow from one space to another to facilitate the dissipation of heat by convection. The existence of a temperature gradient (higher indoor temperature relative to outdoor) will make use of natural buoyancy forces to facilitate natural convection, and thereby cool the space. Convection can also be forced by the movement of air by artificially induced currents. Wind loading (velocity) and turbulent flow on and around a building envelope can force convectional heat loss to a much greater degree of efficiency than natural convection. With forced convection, the temperature gradient is also less significant. On calm days with low wind flow around buildings (conditions typical of heatwaves and when heat island intensity is high), forced convection processes are less available for efficient heat dissipation. This means that the cooling effect of leaving windows open is less relative to a much windier day. Furthermore, if the temperature gradient is minimal, the effectiveness of natural convection will be minimised. This is particularly critical for night purge ventilation, as with a warming climate the diurnal/nocturnal temperature variation may not be significant enough to purge the heat stored in the dwelling (CIBSE, 2005). Dwellings such as those at Gloucester Terrace are at particular risk, as their high thermal mass constructions tend to store heat that ideally must be purged efficiently to keep the nocturnal indoor temperatures at safe and comfortable ranges (Coley & Kershaw, 2010).

The effectiveness of a ventilation approach in a free-running building also requires a significant degree of user interaction, i.e., behavioural adaptation that requires the user to physically engage, open vents, and leave them open to facilitate the necessary cooler indoor conditions. Even if a building has adequate vents to facilitate necessary conditions, this will not be achieved if occupants are either unable or willing to engage. The ability to engage could therefore be influenced by the vulnerabilities of the occupants concerned. There is considerable guidance and legislation that addresses such physical accessibility concerns in the adaptive task of opening windows. Designers are dutybound to consider these regulations to ensure that vulnerable occupants have adequate means to engage. Cognitive impairments in contrast are less straightforward to address, with certain disabilities leaving such occupants unable to engage without either a carer's presence or automated mechanical assistance. The most difficult aspect to address however is when occupants avoid engagement despite having the ability and means to do so (i.e., lack of willingness). It is argued that in domestic arrangements in particular, there is significant necessity for behavioural change that encourages greater interaction with building elements to deliver better indoor climate conditions (Chappells & Shove, 2005).

4.2 Behavioural adaptations

There are many reasons for why dwelling occupants engage with the tasks of either opening or closing vents of all forms. These could be related to ventilation, thermal relief, noise, spatial layout, security and safety, privacy, and habitual concerns. A survey of window opening practices in temperate climates stressed that the principal reasons for opening windows were to do with improving air quality and maintaining the desire to relate to the outdoor environment, rather than seeking thermal relief. It was in fact demonstrated that windows were closed by occupants to control temperature, i.e., to keep warm rather than cool. The survey also found that windows were less likely to be opened in flats, older dwellings with sliding sash windows or with open fireplaces, with central heating, high airtightness, side-hung windows, and non-south-facing rooms (Dubrul, 1987); while another survey of new English and Scottish dwellings had demonstrated socioeconomic and demographic variables to have little to no bearing on window opening practices (Grey & Raw, 1990). The use of mechanical ventilation also made little significance, possibly explained by the dominance of habitual practices (Dubrul, 1987). Habitual behaviour is significant and often related to other rituals of dwelling. It could be said that some occupants may prefer to sleep with a window open to facilitate the exchange of 'fresh air', while inner-city dwellers will be discouraged by barriers such as noise, security, and urban pollution concerns. Such barriers may prove to be particularly disadvantages during extreme heat events. For example, a sample study of dwellings during the 2003 heatwave in London ($n = 5$) and

Manchester (n = 4) had found indoor spaces monitored to be ~5 K warmer, mainly explained by occupant behaviour (or lack thereof) leading to poor night-time ventilation rates (Wright, et al., 2005).

Table 11. Survey results of window opening practices by dwelling room.

Room	Window opening practices
Living rooms	▪ Minimal use at all times of day. ▪ Highest percentage of windows that are never opened.
Kitchens and bathrooms	▪ Frequent use for short-term ventilation. ▪ Used when required (e.g., cooking, showering).
Bedrooms	▪ Significant variation between households. ▪ Opened 3-4 times more than other rooms. ▪ In the UK and other temperate climates, increasing overnight with the peak in the morning. ▪ In England and Scotland, more likely to be opened during the day than at night (security concerns) (Grey & Raw, 1990).

Sources: Dubrul (1987) and Grey & Raw (1990).

4.2.1 Individual adaptations

In addition to behavioural tasks that seek to modify the environment, heat stress and thermal comfort is concerned with how individuals modify their own physiological state. The adjustment of activity levels (i.e., metabolic rate) and/or the application of clothing are two key physiological adaptation parameters requiring attention. The modification of activity levels is typically initiated in response to physiological signals that encourage an individual to reduce their metabolic rate by seeking rest, and/or the consumption of cold beverages to reduce core temperature and encourage evaporative cooling from perspiration. The use of clothing can be similarly modified as a response to physiological signals such as exhaustion and perspiration. The use of clothing however may be influenced by other factors such as availability, knowledge of clothing, and physical and mental ability to change. Furthermore, concerns relating to cultural traditions, social acceptability, and fashion can sometimes compel individuals to disregard physiological signals to endure heat stress and discomfort. In domestic environments however, warmth is often seen as a benefit to a more relaxed and comfortable state of habitation, not typically burdened with the necessity to maintain appearances. Such sociocultural dimensions to clothing and other adaptive measures have been recognised as having potential to be reconfigured towards more sustainable practices in the future (Chappells & Shove, 2005). Education and awareness are thus recognised by public health authorities to be critical for ensuring appropriate adaptation to warming conditions, with due primacy given to safeguarding health (PHE, 2014).

Individual occupant control has significant bearing on how occupants are likely to respond to warmer conditions. Greater control of the indoor climate is believed to increase the perception of comfort and encourage adaptive actions such as window opening (ASHRAE, 2013). In domestic circumstances, occupants often have considerable ability to control their environment unlike in communal settings such as offices. This control however is dependent on the physical and mental capacity of occupants to operate controls. If occupants are faced with some form of vulnerability, as with older people and those with disabilities, the lack of control over their surroundings may render adaptive approaches redundant. This is further exacerbated by overheating itself causing cognitive impairment, which in turn can lead to counter-adaptive behaviour. In such instances, intentions of averting risk may amplify it by inappropriately engaging with adaptive measures (DCLG, 2012a). The nature of controls and the complexity of their operation are therefore significant aspects to consider in the design of habitable spaces, particularly in dwellings where occupants may be isolated to the extent that their safety (from heat stress) may be dependent on such measures.

As highlighted by the Dubrul (1987) survey, effective engagement with adaptive strategies is strongly influenced by occupant rituals of dwelling, i.e., routines and habits. Some habits are governed by occupant automatic thinking and decision-making processes, while others will be rational and reflective. Opening a window when it has become unbearably hot, may be regarded as a reflex action triggered by the automatic thinking processes of the occupant. Anticipatory actions such as opening windows in the evening or drawing curtains before leaving the dwelling, may require rational planning. Such rational actions with repetition may eventually become 'automatic' habitual practices. The efficiency of engagement of adaptive measures consequently requires a deeper understanding of how dwelling occupants and their rituals favour or inhibit the use of adaptive measures. Building design must therefore seek to take account of occupant practices, rather than attempting to impose behaviours that the designers believe they ought to adopt.

4.2.2 Adaptive limitations

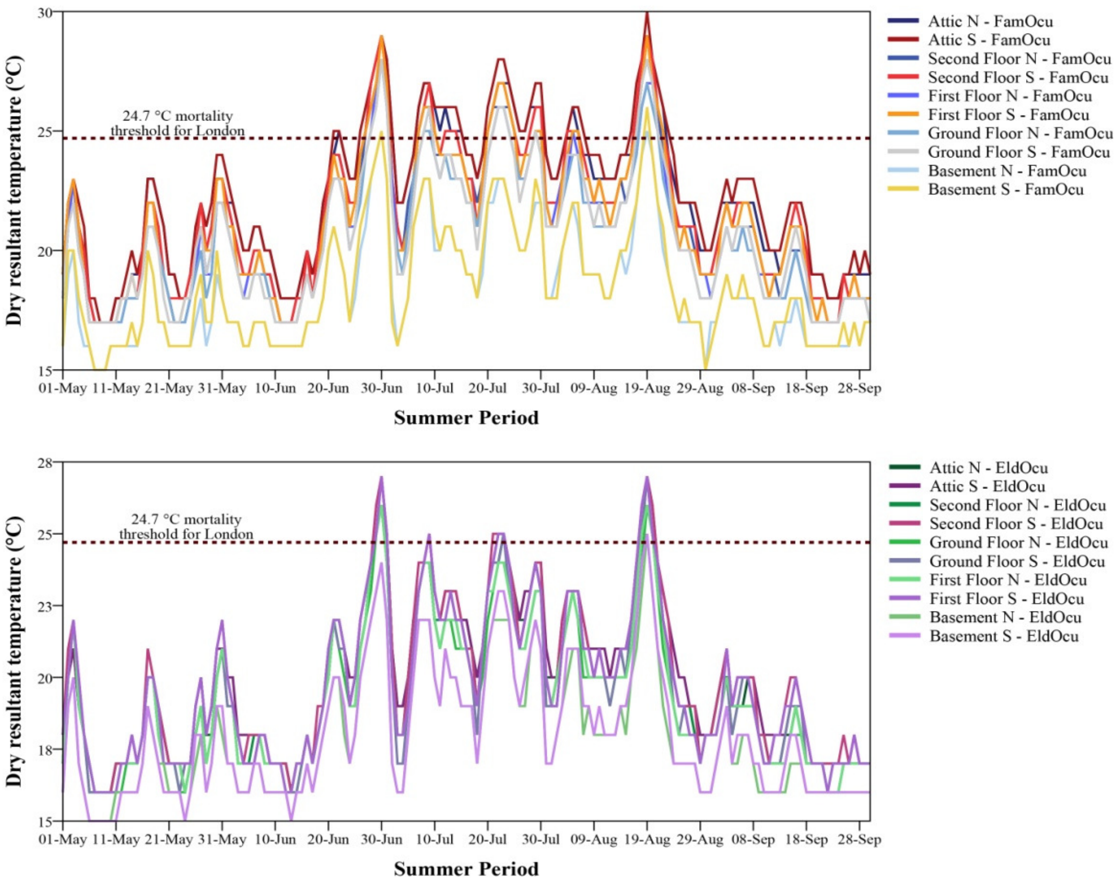
Table 12. Full adaptive influence for unit (residual overheating risk).

Residual overheating failure-days	Basement N	Basement S	Ground floor N	Ground floor S	First floor N	First floor S	Second floor N	Second floor S	Attic N	Attic S
FamOcu Profile										
LGW+UHI+INS+Fan	**0%**	**0%**	**0%**	1%	**0%**	**0%**	**0%**	1%	**0%**	1%
Mortality exceedance*	1%	1%	10%	10%	10%	**14%**	**12%**	**18%**	**22%**	**25%**
EldOcu Profile										
LGW+UHI+INS+Fan	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**
Mortality exceedance*	0%	1%	1%	3%	3%	5%	3%	6%	3%	5%

Notes: adaptive comfort assessment (CIBSE, 2013; 2015) for N = 153 days (May-to-September); full adaptive measures include *INS* upgrades and fan usage.

* Average daily T_{op} that exceeds the London mortality threshold of 24.7°C (Armstrong, et al., 2011).

Considering the Gloucester Terrace unit with the full range of adaptations assessed in this study, highlighted conditions that facilitate 'comfort' could be achieved in most indoor spaces for both profiles (Table 12). The assessment however considered overheating risk primarily in terms of comfort expectations, with vulnerabilities of certain occupants addressed with more onerous modifications to the criteria used (as with the *EldOcu* profile). This dynamic comfort approach is therefore not explicitly linked to morbidity or mortality concerns. The adaptive comfort principle of associating outdoor temperatures to indoor adaptability however suggests that such outdoor mortality thresholds should in turn be associated to the assessment of health risks in indoor spaces. As Table 12 (p. 78) and Figure 32 demonstrates, even though 'comfort' was achieved with adaptations, significant percentages of daily averages still exceeded the London mortality (24.7°C) threshold (Armstrong, et al., 2011); particularly emphasised at higher floor levels, and for the *FamOcu* profile. If such regional mortality thresholds are adopted as the limit (region specific and dynamically associated to its mortality regression) beyond which indoor temperatures may be considered unsafe, the representative unit may still be regarded to overheat despite achieving comfort. For the time being, the relationship between such outdoor mortality thresholds and indoor health are not explicitly associated in any available overheating assessment.



Note: N=153 days (May-to-September); source: IES-VE simulations and calculations.

Figure 32. Post-adaptation average daily room T_{op} for both profiles.

A climate projection study considering London dwellings had found that although window opening reduces indoor temperatures and overheating risk at present, its impact waned considerably towards the 2030s. The study consequently suggested that the future requirement for alternative active cooling solutions as increasingly likely, particularly in urban areas of southern England (Peacock, et al., 2010). If cooling is an inevitable future requirement for such specific domestic conditions and urban localities, alternative means should aim to achieve this with the minimum expenditure of energy resources. As demonstrated by the '40% House' project and its 60% carbon emissions reduction target by the 2050s, 'hard-to-cool dwellings' may be addressed by investing in strategic absorption cooling from district chilling networks using heat from combined heat and power (CHP) plants (Boardman, et al., 2005). Such centralised service provision however does require significant infrastructural investment, which is likely to necessitate considerable government engagement to realise.

4.3 Carbon target: to regulate or nudge

Political interests have historically favoured punitive regulatory measures for addressing environmental problems under the principle that state intervention should be limited to seeking remedy for damage caused. The only means by which the state has exercised direct influence on population behaviour has been through public health advice, justified by the long history of evidence highlighting the value of preventative healthcare. In recent times, governments have also recognised the significance of restorative behavioural modification in addressing climate change, particularly given the necessity to affect individual practices. Direct regulation of such modification however is regarded as unenforceable, resulting in the need for identifying alternative mechanisms for implementing behavioural adaptation (DCLG, 2012a; ZCH, 2015a). In the current political climate, which views additional regulatory obligations to be a public burden, the need for non-regulatory adaptation aligned with the objective of fostering local empowerment has gained significant preference. In the context of this deregulatory agenda, the present Government has devoted considerable attention to 'nudge theory' (Thaler & Sunstein, 2008), as means of addressing climate adaptation, amongst other issues of collective concern.

Table 13. Examples of 'nudges' for behavioural adaptation.

Purpose	Nudge type	Approach
Design-out risk	Defaults	Provide the safest solution to begin with (design-out overheating); prioritise low-impact solutions as defaults (e.g., user-controlled fans).
Provide information	Rules of thumb	Make aware the overheating thresholds as easily identifiable indicators.
	Anchoring heuristic	Comparative threshold significances: what they mean for health, comfort, and energy use; for their local climate and circumstances.
	Availability heuristic	Increase frequency of awareness measures to ingrain heat mitigation practices into population psyche, e.g., awareness campaigning.
	Loss aversion and inertia	Quantify the cost of losing health and wellbeing; highlight economic cost of inertia.
Improve design use	Representativeness heuristic	Design/adaptation legibility, e.g., a window's operation must be intuitive.
Situational awareness	Prompts	Tangible reminders of risk and cost, e.g., traffic-light, or audible indicators, Smart Meters (Smart Energy GB), portable device apps, etc.
	Confidence	Highlighting frequency, forecasts, and increasing trend. Worst scenario (e.g., RCP8.5) should be the basis for planning (King, et al., 2015).
Incentives	Social norms	Community rewards, e.g., recognition.
	Involvement	The significance of social capital.
	Betterment	Quantify wellbeing, health, and economic savings.

Source: based on Thaler & Sunstein (2008).

Drawing from the context of behavioural economics and social psychology, nudge theory is presented as a conjoined framework under the banner of 'libertarian paternalism', which seeks to guide individual choices in their best interests while still preserving their liberty to oppose (Thaler & Sunstein, 2008). The premise here is to employ low-cost measures to design environments that aim to address climate risks (including heat stress), and other public concerns, to eventually result in improvements in wellbeing. Such measures aim to take advantage of the automatic decision-making processes of individuals, so that a 'choice architect' can design environments that direct individual behaviours to deliver paternalistic aims such as facilitating their lives to be healthier, safer, and comfortable. Since these measures are not mandates, it is still the choice of individuals to reject such direction and act otherwise; thereby ensuring the liberty of the individual is preserved (Thaler

& Sunstein, 2008). As climate risks such as overheating are significantly modified by individual behaviours, the potential for employing libertarian paternalism to direct populations to utilise low-energy passive solutions in their everyday lives, may eventually lead to the scale of community adaptation needed to flourish in a changing climate. The promise of this eventuality has therefore encouraged recent policymakers (present Government in particular) to embrace 'nudging' as a significant tool in the delivery of climate change and public health objectives.

Source: © Google Images.

Figure 33. Nudge theory, by Thaler and Sunstein (2008).

The design of a building determines what adaptive behaviours are achievable and the eventual success of occupant engagement achieved. Nudging building occupants to engage effectively first entails the monitoring of current practices in dwellings and comprehending how and when automatic thinking processes of individuals are engaged. Occupant actions, particularly in times of excessive heat, should inform how the most beneficial of behavioural traits (both automatic and rational decision-making) may be utilised to create design nudges that facilitate heat mitigation to become a part of future rituals of habitation. It must be noted that the design of a building is never a neutral act, with architects inherently acting as 'choice architects' that design-out adverse effects on matters such as health, safety, overheating, etc., by means of nudges of some form or another. Nudging therefore should not be an unfamiliar concept to any building designer.

Critics of nudging argue that although improvements in individual behaviours may be noticeable, such changes may not provide the magnitude and rapid influence needed to address urgent climate change issues such as worsening urban heat risks. Urban built environments in the UK are shaped largely by market interests, particularly in the case of housing. Nudges employed by one party to direct individual behaviour in one direction may be counter-nudged by market interests that may not be driven by paternalistic goals. The use of air-conditioning serves as a pertinent example here, as designers and the state together argue against its wide-spread uptake, the air-conditioning industry provides the counter-nudge to take-up the technology as the default and convenient solution for heat risk mitigation. In such circumstances addressing market indifference requires, as the Committee on Climate Change, Adaptation Sub-Committee (2014) stresses, regulatory measures to give firm direction. Attempts to rely only on nudging strategies are likely to be ineffective against counter market nudging, which may even lead to wasteful resource allocation and public/consumer confusion. Nudging behavioural adaptations could only be effective thus as a collaboration with regulatory measures, with the designer representing a choice architect who nudges for adaptation, while being reinforced by regulatory measures that unequivocally secures the intended paternalistic aims.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Chapter 5

Concluding remarks

This dissertation has examined a novel pathway for identifying residential overheating risk in urban areas, and discussed ways in which both authorities and designers may seek to address heat mitigation, while adhering to the UK carbon reduction commitment. The method for addressing this considered the simulation of a residential street canyon within the London heat island, and presented a series of studies that addressed the logical steps of generating the canyon's urban microclimate profile; quantifying overheating risk at the representative unit (summarised in Table 14, p. 90); and the implementation of adaptive measures to assess energy use and CO_2 emissions implications for the unit, as well as the aggregated street canyon (summarised in Table 15, p. 92).

Key findings:

- The comparison between the generated UWG microclimate profile and existing data from nearby LUCID project monitoring stations, highlighted site WW04 (4 km west) to be statistically proximate. Although the dynamic distribution of temperatures is unique to each station and measurement process, this suggested the generated UWG profile to be reasonably representative of the local climate, and therefore suitable for inclusion in a pathway for simulating energy and CO_2 emissions scenarios with urban microclimate loading represented.

- The assessment of overheating risk using both fixed and dynamic thresholds presented different interpretations and degrees of risk. Most observations related to previous domestic studies discussed, with some assessment methods amplifying certain trends. At Gloucester Terrace, midlevel rooms notably demonstrated greater severity of overheating, which was highlighted by the Energy Saving Trust (2005) and CIBSE (2015) adaptive comfort assessments to contradict typical findings. This exception is attributed to the unique configuration of the unit at the attic level modifying its gains, which in turn highlighted the significance of typology specific characteristics in identifying overheating risk.

- Although improving thermal properties of the building envelope had patent benefit for building energy performance, the influence on overheating was mixed; with the occupied hours >26°C criterion having presented a 27% increase, the degree-hrs >27°C criterion estimated a 5% reduction, and the adaptive comfort assessment having reported reductions and gains dependent on the room. These mixed results suggested that although threshold exceedance was typically increased, overheating severity to be lessened by the improvements. Gains analysis showed this to be explained by the reduction in the severity of solar gain penetration, while the reduced fabric thermal transmittance (from internally applied insulation) led to internal gains being trapped in rooms and cause the exceedance hours to increase.

- Using the adaptive comfort assessment relative to the recently superseded CIBSE (2006a) hours of exceedance (>26°C) criterion highlighted almost all floors to demonstrate significant reductions in reported overheating failure-days. With the same adaptive assessment, using full adaptations including *INS* fabric thermal upgrades and fan usage, reported almost all rooms of both profiles to achieve 'comfort'. Fan usage (a low energy adaptation that induces forced convective cooling), was highlighted as the most effective measure in resolving residual overheating risk. It is worth noting that despite achieving adaptive comfort, higher floor levels, particularly with the *FamOcu* profile, still demonstrated significant percentages of daily average temperatures to exceed the London mortality threshold.

- The energy use simulation for the unit showed that accounting for urban microclimate conditions simulated by the UWG, resulted in 12.9% and 8% reductions in estimated annual energy use and CO_2 emissions, respectively. This was attributed to a 23.9% reduction in the annual central heating energy usage estimate, and is explained as the winter warming effect of the heat island. The aggregated benefit of this effect is significant for the estimation of urban district heating requirements.

- If domestic air-conditioning was implemented at the unit, the impact of accounting for the heat island effect on cooling estimated a 24.6% increase in the chiller load. The simulation of widespread use of domestic air-conditioning resulted in the nocturnal microclimate temperature of the canyon being elevated by an hourly average of 0.4 K for the summer period. This simulation scenario also resulted in an additional 70 metric tons of CO_2 being released to the climate from the 40 mid-terraced units of the 100 m canyon. If on the other hand thermal upgrades (as in *INS*) were applied to all units with summer air-conditioning used only to address residual overheating risk (i.e., minimised capacity), the estimated CO_2 release to the climate was reduced by 244 metric tons relative to the free-running *LGW+UHI* simulation. This result reiterates the significance of prioritising widespread fabric thermal retrofitting to facilitate the delivery of energy conservation aims.

Strategies that prioritise low impact solutions, such as built environment planning practices directing morphological and socioeconomic modifications, initiatives such as the ‘green deal’ targeting the retrofit enhancement of existing building efficiencies, and nudging that encourages individual behavioural adaptation, should be fully exhausted prior to engaging with active cooling solutions as only a means to address residual overheating risk. At an urban scale, London has potential to take advantage of its coastal siting to consider strategic cooling practices, such as district cooling networks for addressing any future demand for summertime cooling in ‘hard-to-cool’ residential districts.

As this study has demonstrated, low impact adaptations alone may be sufficient to achieve comfort, and thereby resolve the current risk of overheating at Gloucester Terrace units. This however is dependent on comfort being synonymous with safeguarding health in assessing overheating risk. As previously noted, the debate on whether this equivalence could be claimed is inconclusive. The issue is further complicated when considering cognitive vulnerabilities of occupants, as the adaptive comfort assessment is reliant on thermal memory for adaptation. Older occupants with compromised faculties for example, may still be vulnerable in ‘objective comfort’ as the association between their thermal memory and adaptive action is compromised. Another complication is highlighted for nocturnal conditions when adaptive practices are restricted for all, including infants who have no self-reliant external adaptive capabilities. These vulnerability areas are therefore stressed here as requiring further attention and research to provide an understanding of how ‘comfort’ relates to ‘safety’, and whether both can be regarded as the same in assessing overheating risk.

Avoidance of risk is a rational approach to addressing climate challenges. As the CREW project has advocated (Hallett, 2013), it is sensible to direct the most vulnerable of occupants away from dwellings prone to overheating. This reallocation would ensure habitation efficiencies that utilises the least resources necessary for meeting the UK carbon reduction commitment. Although this is pragmatic from a resource management perspective, the social and moral aspects of controlling where and how people should reside is a matter for political debate. Direct regulation of this nature would in any case be contentious in the UK, and not foreseeable given the current Government’s agenda to empower local communities and decision-making. Current political thinking is thus limited to supporting such climate challenges to be overcome by adaptive behavioural modifications brought about by the application of nudge theory. Nudging however has its limitations, as the same behavioural traits it seeks to take advantage of in encouraging adaptive modifications, can be utilised by non-paternalistic agents to counter-nudge. Nudging behavioural adaptation must therefore seek to work collaboratively with regulatory measures to create the large-scale shifts in environmental and behavioural adaptation required to ensure health and wellbeing in a warming climate.

5.1 Limitations

The case study presented in this dissertation was of a single mid-terrace unit aggregated for the assessment of an urban canyon of relatively uniform morphology. Dwellings in London however are characterised by various typologies and conditions. Furthermore, the study only considered a single orientation and location within the heat island, both of which have been established to impact on energy use and CO_2 emissions. For a comprehensive analysis of microclimate loading influence, multiple typologies, locations within the heat island, and orientations, requires further investigation.

A key limitation of the current version of the UWG is its focus on canyon configurations, which in turn neglects the diversity of urban form and residential developments experienced in cities such as London. In addition, the model's accuracy (within 1 K) is reported to be greater for cities with relatively uniform morphologies (as averaged values are used) and low vegetation cover (as the latent heat flux from evapotranspiration is simplified) (Bueno, et al., 2013). Considering that circa 47% of London's total area is greenspace (ARUP, 2014), and its morphology representing a high degree of variability, the accuracy of UWG outputs may be regarded as at the limit of this error margin. Although the selection of Gloucester Terrace considered these shortcomings (with its uniform canyon morphology with low vegetation cover), the proximity influence of Hyde Park in particular, requires further consideration.

5.2 Further refinements

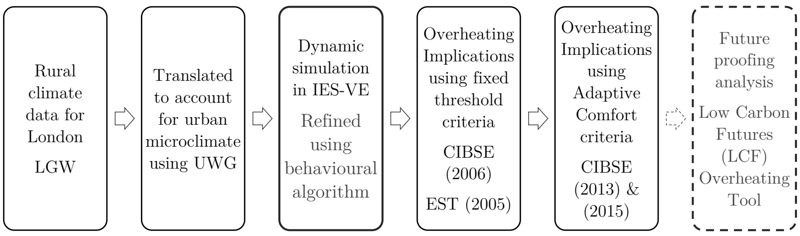


Figure 34. Method pathway improvements and potential extension.

As further refinements to this study, algorithms that capture adaptive behavioural practices may be applied. The pathway could also be extended to consider future proofing options using probabilistic future weather files from the PROMETHEUS project (Eames, et al., 2011). The UWG however was unable to translate the latter files, which in turn impeded the pathway. As an alternative, the Low Carbon Futures (LCF) future proofing tool may be utilised, although at the time of writing this dissertation, both an adaptive algorithm and the LCF tool were unavailable for inclusion.

Table 14. Summary of overheating risk for scenarios.

	Basement N	Basement S	Ground floor N	Ground floor S	First floor N	First floor S	Second floor N	Second floor S	Attic N	Attic S
FamOcu Profile*										
Fixed >26°C exceedance (% of failure-days relative to May-September period, N = 153)										
Base-LGW	3%	12%	18%	40%	22%	47%	22%	48%	22%	39%
LGW+UHI	10%	18%	29%	44%	30%	51%	30%	52%	29%	48%
Effect of UHI	+7%	+6%	+11%	+5%	+8%	+4%	+8%	+4%	+7%	+8%
LGW+UHI+INS	11%	16%	29%	38%	31%	44%	35%	50%	43%	52%
Effect of *INS* upgrade	+1%	-1%	-1%	-7%	+1%	-7%	+5%	-2%	+14%	+5%
Fixed >27°C degree-hrs (% relative to May-September period, N = 153)										
Base-LGW	0%	2%	4%	15%	4%	25%	5%	26%	4%	17%
LGW+UHI	1%	5%	11%	26%	12%	41%	14%	43%	14%	34%
Effect of UHI	+1%	+3%	+7%	+12%	+8%	+15%	+9%	+17%	+10%	+17%
LGW+UHI+INS	2%	4%	11%	19%	14%	29%	19%	36%	32%	46%
Effect of *INS* upgrade	+1%	-1%	+1%	-8%	+2%	-12%	+5%	-7%	+18%	+12%
Adaptive comfort (% of failure-days relative to May-September period, N = 153)										
Base-LGW	0%	0%	0%	5%	0%	10%	1%	10%	0%	5%
LGW+UHI	0%	0%	1%	10%	1%	14%	1%	15%	1%	13%
Effect of UHI	0%	0%	+1%	+5%	+1%	+3%	0%	+5%	+1%	+8%
LGW+UHI+INS	0%	0%	1%	7%	1%	8%	5%	13%	9%	16%
Effect of *INS* upgrade	0%	0%	0%	-3%	0%	-5%	+4%	-2%	+8%	+3%
LGW+UHI+INS+Fan	0%	0%	0%	1%	0%	0%	0%	1%	0%	1%
Effect of Fan use	0%	0%	-1%	-7%	-1%	-8%	-5%	-12%	-9%	-15%
EldOcu Profile*										
Fixed >26°C exceedance (% of failure-days relative to May-September period, N = 153)										
Base-LGW	8%	16%	25%	43%	27%	48%	27%	48%	22%	40%
LGW+UHI	9%	16%	25%	43%	27%	48%	27%	48%	25%	42%
LGW+UHI+INS	9%	13%	16%	27%	16%	37%	20%	39%	17%	29%
Effect of UHI & *INS*	0%	-3%	-10%	-16%	-11%	-11%	-8%	-10%	-8%	-13%
Adaptive comfort (% of failure-days relative to May-September period, N = 153)										
LGW+UHI	0%	1%	7%	12%	7%	24%	7%	24%	6%	14%
LGW+UHI+INS+Fan	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

* For core non-heating days between May-to-September (N = 153 days); sources: IES-VE simulations and calculations.

Table 15. Summary of energy, cost, and CO_2 implications for FamOcu scenarios.

Simulation Scenario	Total energy (MWh)	Relative %	Total electricity (MWh)	Electricity Cost* (£)	Total Natural gas (MWh)	Natural gas Cost** (£)	Total CO_2 emissions (kg)	Total annual Cost (£)	Relative %	Canyon* aggregated Cost (£)	Canyon* aggregated CO_2 emissions (kg)
Effect of accounting for the UHI effect for unit											
Base-LGW	122		56	7,905	66	3,282	43,485	11188			
LGW+UHI	106		56	7,905	50	2,497	40,093	10402			
Savings	16	12.9%	0	0	16	785	3,392	785	7.0%	31,410	+135,680
Effect of insulation retrofit (INS) for unit											
LGW+UHI	106		56	7,905	50	2,497	40,093	10402			
LGW+UHI+INS	73		54	7,582	19	933	32,589	8515			
Savings	34	31.6%	2	323	31	1,564	7,504	1887	18.1%	75,499	+300,160
Effect of adding summer air-conditioning as the principal adaptation to address overheating at unit											
LGW+UHI	106		56	7,905	50	2,497	40,093	10402			
LGW+UHI+AC1	110		60	8,415	50	2,502	42,004	10917			
Savings	-3.7	-3.5%	-4	-510	0	-5	-1,911	-515	-4.9%	-20,588	-76,440
UHI effect on summer air-conditioning as principal adaptation to address overheating at unit											
Base-LGW+AC0	123		59	8,270	64	3,185	44,867	11455			
LGW+UHI+AC1	110		60	8,415	50	2,502	42,004	10917			
Savings	13	10.3%	-1	-145	14	683	2,863	538	4.7%	21,502	+114,520

Table 15 contd. Summary of energy, cost, and CO_2 implications for FamOcu scenarios.

Effect of insulation retrofit (INS) and adding AC2 to address residual overheating at unit											
LGW+UHI	106		56	7,905	50	2,497	40,093	10402			
LGW+UHI+INS+AC2	77		59	8,196	18	909	34,311	9105			
Savings	30	27.9%	-2	-291	32	1,588	5,782	1297	15.2%	51,885	+231,280
Effect of widespread summer air-conditioning for entire canyon on individual free-running unit											
LGW+UHI	106		56	7,905	50	2,497	40,093	10402			
LGW+UHI+UAC	105		56	7,905	48	2,415	39,739	10320			
Savings	2	1.5%	0	0	2	82	354	82	0.8%	3,276	+14,160
Effect of widespread summer air-conditioning for entire canyon on cooling load for individual unit											
LGW+UHI+AC1	110		60	8,415	50	2,502	42,004	10917			
LGW+UHI+AC1+UAC	110		68	9,515	42	2,124	41,838	11638			
Savings	-0.3	-0.3%	-7.86	-1,100	8	378	166	-721	-6.6%	-28,859	+6,640
Effect of widespread summer air-conditioning for entire canyon (without and with widespread INS retrofits)											
LGW+UHI	106		56	7,905	50	2,497	40,093	10,402			
LGW+UHI+AC1+UAC	110	-3.8%	68	9,515	42	2,124	41,838	11,638	-11.9%	-49,446	-69,800
LGW+UHI+INS+AC2+UAC	76		58	8,155	17	872	33,996	9,026			
Savings	31	28.9%	-2	249	33	1,626	6,097	1,376	13.2%	55,047	+243,880

Notes: average variable unit price for London, Electricity*: £140 per MWh; and Gas**: £50 per MWh; * DECC Table 2.2.4 for electricity in 2014 for UK; ** DECC Table 2.3.4 for gas in 2014 for UK.

* Forty mid-terraced units for canyon considered in aggregated analysis, based on the assumption that dwelling features are reasonably similar.

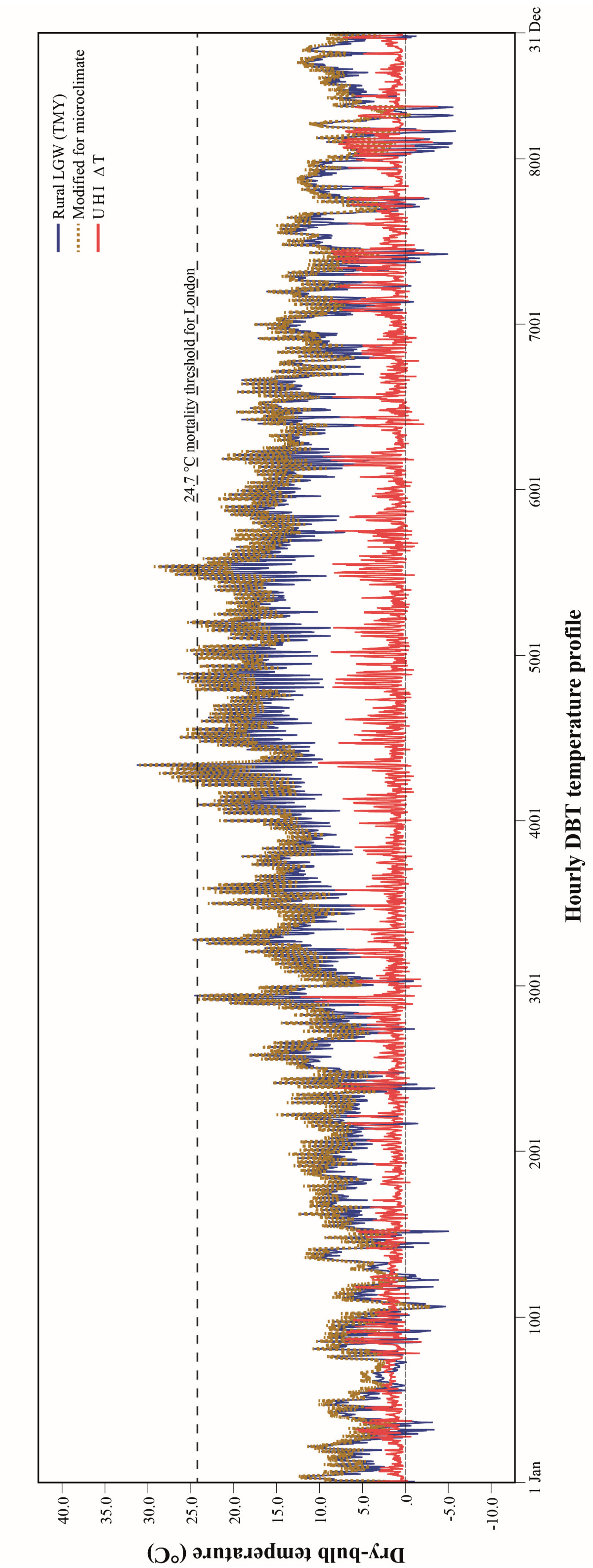


Figure 35. Annual heat island profile from UWG for the Gloucester Terrace canyon.

Appendix A

A. Expanded overheating method review

The following considers alternative methods and tools for assessing overheating risk at both building and urban scales. They are included here as an expansion of the concise review presented in Chapter 2.

A.1 Building Regulations Part L

Building Regulations Part L1A, Criterion 3 (of 5) (DCLG, 2013), addresses overheating risk in domestic buildings, and is required irrespective of air-conditioning use (the objective is to mitigate requirement or any installed capacity). As part of the Building Control assessment of the SAP rating, the *Appendix P* calculation (BRE, 2012) is often requested (discussed below), irrespective of it having no bearing on the outcome of the rating. The assessment, which is defined against threshold temperatures (noted in Table 5, p. 34), is considered a part of the building compliance process, with 'medium' or 'lower risk' typically deemed acceptable (ZCH, 2015a). Part L2A, Criterion 3, addresses the need for limiting summer heat gains mainly for non-domestic buildings, although includes provisions for 'rooms for residential purposes' in buildings such as care homes, student accommodation, circulation and public spaces in communal living or mixed-use schemes (DCLG, 2013). The methodology discussed however is considered incomplete for assessing overheating as it only limits solar gain (excludes other gains) and does not provide thresholds (ZCH, 2015a). Currently, regulation Parts L1B and L2B (DCLG, 2013) for domestic and non-domestic refurbishments, do not include any form of overheating/solar gain assessments, or thresholds for compliance.

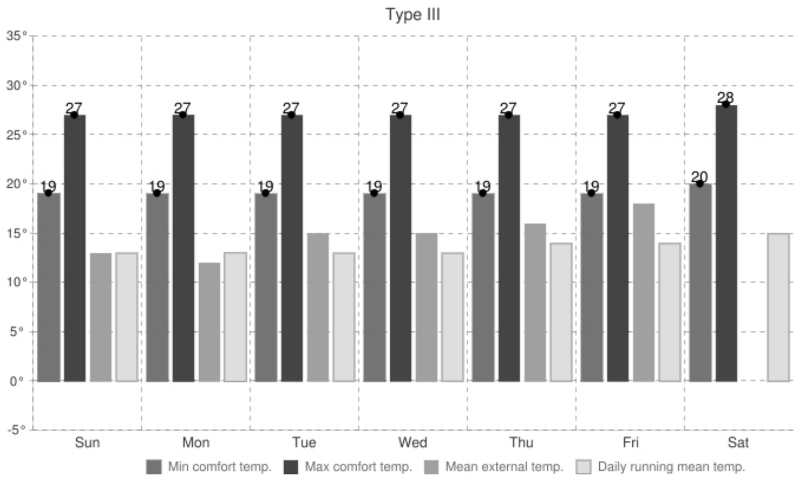
A.2 Compliance monitoring tools

Although dynamic relationships between indoor and outdoor environments are not addressed by compliance monitoring methodologies such as SAP or Passive House Planning Package (PHPP), they provide a useful initial approximation of overheating risk in residential buildings. The SAP methodology describes calculation methods for satisfying Building Regulations Part L1A (DCLG, 2013), with Building Research Establishment approved software tools (BRE, 2012). In

Appendix P of the methodology, an approach is presented to calculate a single predicted average indoor temperature that is assessed against thresholds (with regional variations accounted), to determine the monthly risk of overheating (Table 5, p. 34). The averaging nature of this calculation however disregards peaks and duration of warm periods, which represents the reason why it was not considered for this dissertation project. The PHPP methodology calculates the annual percentage of hours above an established comfort limit (25°C default), to predict thermal performance. It is mandatory to meet a target of <10% to achieve Passivhaus Certification, with 2-5% as 'Good', and 0-2% considered 'Excellent'. As this Certification is irrelevant for existing dwellings as at Gloucester Terrace, the method was not considered for this dissertation project. The key difference to note between SAP (BRE, 2012) and PHPP (iPHA, 2011), is that the latter is able to use measured data for internal gains in its calculation, as oppose to floor area based assumptions (ZCH, 2015a). Notably, no requirement at present is placed by both for assessing overheating risk when refurbishing existing dwellings. Although refurbishment is a significant aspect of the UK residential development sector and essential for improving climate resilience, compliance tools have yet to acknowledge this requirement (DEFRA, 2012a; ASC, 2014).

A.3 Estimation tools

Following the release of UKCP09 climate projections (Murphy, et al., 2009), various guidance documents and tools have been published by EPSRC funded projects belonging to the Adaptation and Resilience in the Context of Change (ARCC) network, which seek to increase the resilience of buildings to climate change risks. The CREW project for example, introduced a domestic retrofit tool that estimates the effectiveness of adaptation options. The usage of the tool however is intended for decision-making estimation purposes (not for design analysis or compliance monitoring), and is principally representative of performance typical to London dwellings (Hallett, 2013). As a tool for future proofing dwellings, the Low Carbon Futures (LCF) project presented an overheating tool that evaluates the statistical relationship between climate variables and building performance. A simulation of a project (e.g., in IES-VE) can consequently be assessed for multiple future climates for the probability of the dwelling exceeding a defined overheating threshold (Jenkins & Gul, 2012). Although this LCF tool was considered for the method pathway of this dissertation project, it was unavailable for release by its authors. CIBSE together with the Met Office have also developed a web-based tool for estimating adaptive comfort and overheating risk in free-running buildings. The tool provides graphical illustration of a seven-day forecast for daily local running mean temperatures (T_{rm}, Figure 36A), and acceptable adaptive comfort and overheating risk for specific locations and building categories as defined by BS EN 15251 (BSI, 2007). This information is intended for use by building managers, although has potential to be integrated into future Heatwave Plan response strategies.



Source: *www.cibse.org/Knowledge/Assessment-tool*, accessed on 06 June 2015.

Figure 36A. CIBSE seven-day comfort forecast for Gloucester Terrace.

A.4 Statistical regression methods

Urban microclimate temperatures may be estimated by utilising existing correlations derived from field observations. Oke (1988a) for example, presented a correlation between $UHI\ \Delta T$ and urban geometry considering field data gathered from mid-latitude cities (Equation 9A). The regression equation derived presents a constant figure for the $UHI\ \Delta T$ as experienced under ideal conditions of calm and clear weather (Oke, 1988a). This constant value however contradicts Oke's own field observations demonstrating significant diurnal/nocturnal and seasonal variations of the heat island effect. Considering further measured data and Oke's (1982) profile diagrams, Crawley (2008) presented an algorithm (Appendix B.5, p. 105) to discern the diurnal/nocturnal temperature patterns of the heat island effect by modifying only the DBT of existing weather data. Based on LUCID project data, Kolokotroni et al. (2010) presented an Artificial Neural Network (ANN) model named as the London Site Specific Air Temperature (LSSAT) for estimating air temperatures within the heat island at a specific time and location, using data from a single TMY station and historic measured air temperatures. The method is applicable to any city where historic hourly air temperatures for several locations are available (e.g., London). Local weather files from this model have been used in this study for comparison with the UWG profile (discussed in section 3.1, p. 40).

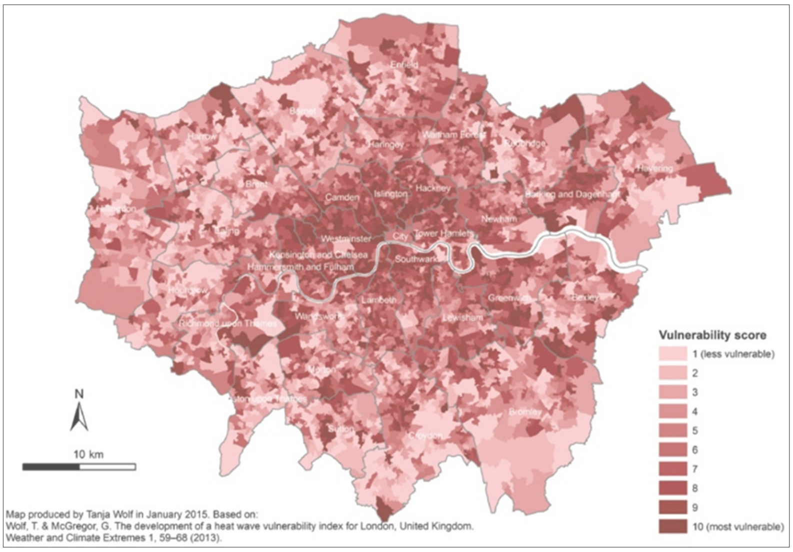
$$UHI\ \Delta T_{(max)} = 7.54 + 3.97\ \text{In}\left(\frac{H}{W}\right)$$ *Equation 9A*

Such statistical and mathematical morphing approaches in general play a role in most methodologies described in this dissertation; particularly in the development of tools such as the LCF overheating tool (Jenkins & Gul, 2012), and climate data morphing and climate prediction methods discussed.

A.5 Computational fluid dynamics models

Computational fluid dynamics (CFD) uses numerical algorithm-based solvers to resolve fluid-flow and heat transfer processes. In contrast to a heat balance model's assumption that the air in a thermal zone is mixed to create a uniform temperature distribution, the CFD approach seeks to detail thermal variance to approximate real-world conditions as much as possible. It achieves this by splitting the examined zone or domain into many cells with the heat and fluid transfer equation sets solved for each cell. Depending on the resolution required, a CFD domain may contain numerous cells, which in turn could generate significant computational demand (reason for its exclusion from this dissertation project's pathway). The models therefore are mostly used for steady-state analyses, with dynamic models produced only for specific conditions. In addition to application in building thermal zone assessments, advancements in computational power are encouraging the method's use in urban scale studies (ZCH, 2015a). The advantage of using such advanced urban scale models is that specific urban microclimate scenarios (e.g., wind tunnel effect or downdraught effect) can now be investigated as reasonably accurate representations.

A.6 Strategic heat risk mapping



Sources: Wolf & McGregor (2013) and ZCH (2015).

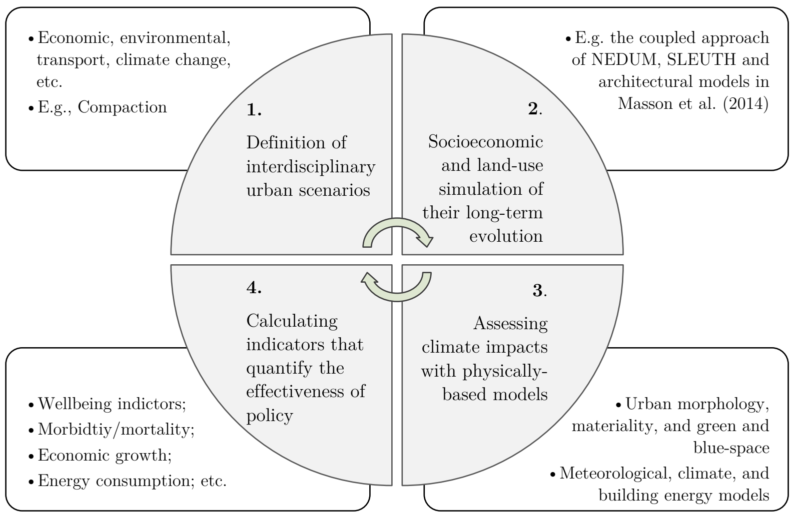
Figure 37A. Greater London Heat Vulnerability Index.

Heat risk mapping entails an analysis of factors relating to overheating reviewed and represented at the urban scale. They seek to quantify the parameters that explain heat risk and may be achieved solely in the form of quantitative measures, or a combination of quantitative and qualitative indicators. Different mapping methods and indices identify the spatial and temporal dimensions of risk and potentials for adaptation (ZCH, 2015). Such approaches in turn assist state and private interests to identify the nature of these risks and prioritise resources (emergency and future adaptation) towards areas with the greatest need. The mapping of heat vulnerability in published research is however limited, particularly as a combined consideration of the epidemiological, socioeconomic, and heat island factors (Reid, et al., 2009; Benzie, et al., 2011; Lindley, et al., 2006). While some studies have attempted to situate heat vulnerability spatially at different scales and variables, most make no cumulative analysis of the variables. A notable exception was provided by a study that mapped the entire United States with a cumulative heat vulnerability index based on an analysis of ten variables (Reid, et al., 2009). In the UK, a recent study of Birmingham used nocturnal Land Surface Temperature (LST) data to consider the spatial distribution of the heat island linked with GIS data to create a ‘hazard layer’ (Tomlinson, et al., 2011). Another recent study considering Greater London (Figure

37A), proposed an index by mapping the co-occurrence of risk factors mainly adapted from census data (Wolf & McGregor, 2013). All three of the above studies however associate risk factors to spatial scales based on either historical or current data for larger cities. A predictive mapping of heat risk that considers climate projections (e.g., UKCP09), remains to be presented (ZCH, 2015).

A.7 Systematic modelling methods

The systematic modelling approach combines potential scenarios and spatially explicit models to illustrate the interdisciplinary nature of the assessments required to address the interactions between climate change, city structures, economics, and future growth. Masson et al. (2014) for example presented a four-step methodology consisting of: the definition of interdisciplinary scenarios; socioeconomic and land-use simulation of the long-term evolution of such scenarios; assessing their impacts with physically-based models; and calculating indicators that quantify the effectiveness of proposed adaptation policies (Figure 38A). The analysis of heat-related risks may similarly be integrated to such assessment frameworks that intend to predict future urban growth patterns and their interaction with climate risks to prepare and plan adaptation policies. These frameworks however are resource intensive and require the collaborative efforts of multiple experts to deliver effective outputs, and thus is beyond the scope of this project.



Based on: Masson et al. (2014).

Figure 38A. Process diagram of a systematic modelling approach.

A.8 Future climate metadata

As many dwellings have a lifespan greater than 50 years, overheating risk needs to be evaluated for the entire lifespan to ensure that habitable and safe environments can be maintained without the need for burdening the UK carbon budget. The response to this need is reflected in the latest UK Climate Projections (UKCP09), produced using the HadRM3 regional climate model developed by the Met Office Hadley Centre (Murphy, et al., 2009). The main advantage of UKCP09, in comparison to the deterministic projections of its predecessor UKCP02, is that the probabilistic projections quantify uncertainties in modelling processes and natural climate variability (Kershaw, et al., 2010). It is worth noting that UKCP09 projections do not address the heat island effect, as urban areas are not included in the HadRM3 model. This exclusion is attributed to scale, as the influence of urban areas on the simulated climate is negligible in climate models (25-100 km grid). As means of addressing this shortcoming, Kershaw et al. (2010) has presented a mathematical morphing process to include heat island influence in UKCP09 projections. Based on the same projections, CIBSE provide Probabilistic Climate Profiles for 14 locations, that have been extended to include many other sites by the PROMETHEUS project (Eames, et al., 2011).

Appendix B

B. Background data and calculations

The following sections include simulation parameters, calculations, licences, and other supporting data utilised for this project.

B.1 Gloucester Terrace: representative unit

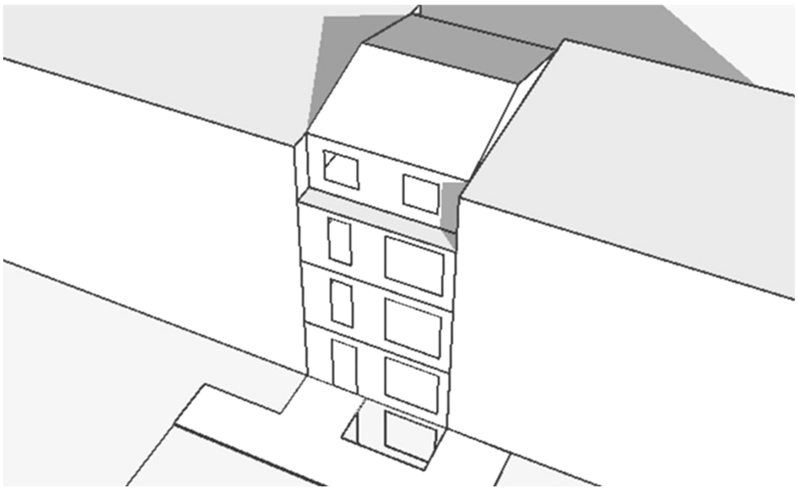


Figure 39B. Simulation model in IES-VE modeller.

Typical mid-terraced unit containing six flats, divided between five storeys including occupied basement and attic. Each storey is divided to north and south-facing rooms for simulation in IES-VE.

B.2 Unit parameters used for simulations

Table 16B. Key parameters used for simulations.

Parameter	Description	Gloucester Terrace unit
Unit profile		
Conditioned area	Main unit only; mews extension omitted	366 m^2
Each floor	Two equal room volumes, single-aspect (i.e., no cross-ventilation considered)	Rooms facing north considered as bedrooms Rooms facing south (front elevation) considered as living rooms

Parameter	Description	Gloucester Terrace unit
Occupational profile, *FamOcu*	*Young (working) couple / small family (two adults + one child) assumed for all six units as typical scenario*	
Occupation	61 m^2 per flat = two-bed, three persons per flat (DCLG, 2015) 3 × 6 flats	18 persons considered for full occupation Density ~20 m^2 per person
Weekdays	Working week	6 AM-6 PM at 60% 6 PM-11 PM at 100% 11 PM-6 AM at 10% of load
Weekends	Full occupation	8 AM-12 AM at 100% 12 AM-8 AM at 10% of load
Holidays	UK profile	24 hrs at 10% load
Summer profile	British Summer Time 2015 Adaptive Comfort assessment (CIBSE, 2013; 2015)	29 March to 25 October May-to-September (153 days)
Occupational profile, *EldOcu*	*Older couple assumed for all six units as non-typical scenario*	
Occupation	Two persons per flat 2 × 6 flats	12 persons considered for full occupation Density of ~30.5 m^2 per person
Full week	Full occupation	6 AM-10 PM at 75% 10 PM-6 AM at 10% of load
Thermal performance		
Heating	Natural gas central heating DHW not served by HVAC boiler	ScoP: 0.80 Seasonal efficiency: 0.89 Setpoint: 19°C
Relative humidity	(CIBSE, 2005a)	Maximum 70%
Ventilation	Natural ventilation requirement 61.2 m^3·h^{-1}× 6 (flats) - Part F, Table 5.1b (DCLG, 2010a)	0.3 ach
Cooling	Natural ventilation for one-sided building (single-aspect rooms) with vents open at day and closed at night. Table 5.21 (CIBSE, 2015)	3.0 ach @summer profile
Air leakage	UK average rate applied (CIBSE, 2005a)	0.7 ach On continuously

Parameter	Description	Gloucester Terrace unit
Internal gains	*As per occupancy profile*	
People	Sensible gains Latent gains Table 6.3 (CIBSE, 2015)	70 W·P^{-1} 45 W·P^{-1}
Lighting	Sensible gains	7 W·m^{-2}
Equipment	Sensible gains	5 W·m^{-2}
Cooking	Sensible gains Latent gains	3 W·m^{-2} 1 W·m^{-2}
Default construction		
Ave. floor height	Height varies per floor	3.0 m
Window ratio	Main unit (mews omitted)	23% (77 m^2)
Windows	6 mm single glazing	U-Value: 5.1 W·m^{-2}·K^{-1} G-Value: 0.82
Walls	Stuccoed brickwork	1.33 W·m^{-2}·K^{-1}
Upper floors	Timber joisted with boards	0.35 W·m^{-2}·K^{-1}
Basement floor	Limestone on screed	2.26 W·m^{-2}·K^{-1}
Roof	Slate-lined timber structure	0.50 W·m^{-2}·K^{-1}
Urban site		
Ave. building height	Estimate for canyon	17.5 m
Coverage ratio	Estimate	54%
Tree/green cover	Estimate	8%
Non-building Q_F	Based on Greater London averaged estimate (Iamarino, et al., 2012)	5.1 W·m^{-2}

Sources: general information from WCC (2000; 2015); others as indicated.

B.3 INS (insulation) upgrade parameters

Table 17B. INS upgrade (insulation) parameters for simulation.

Parameter	Strategy	Description	Upgraded values
Construction upgrades	*Table 3 Upgrading retained thermal elements (b) Part L1B* (DCLG, 2013)*, and English Heritage Guidance* (EH, 2011).		
Windows	Preserve appearance and features of existing window frames (Part L1B non-compliant)	6 | 75 | 6 mm, Low-e secondary glazing to inner face	U-Value: 1.9 W·m^{-2}·K^{-1} G-Value: 0.33

Parameter	Strategy	Description	Upgraded values
Walls	Internal lining with thermal-break details; subject to condensation analysis	Stuccoed brickwork with 100 mm mineral fibre slabs	0.28 $W \cdot m^{-2} \cdot K^{-1}$
Roof	Warm roof, as loft is occupied	Slate-lined timber structure with 120 mm mineral fibre slabs between rafters	0.18 $W \cdot m^{-2} \cdot K^{-1}$
Basement floor	Not considered, highly disruptive with limited effectiveness (EH, 2011)	As base	As base
Air infiltration upgrade			
Air leakage	Improving air tightness to 'good practice' guidance	10.0 $m^3 \cdot h^{-1} \cdot m^{-2}$ at 50 Pa, Table 1 (CIBSE, 2000)	0.184 ach On continuously

B.4 Additional AC (0-2) parameters

AC0: Cooling load applied to Base-LGW unit @summer profile

AC1: Applied to LGW+UHI

AC2: Applied to +INS option above (Table 17B)

UAC: Widespread use in the urban canyon area

Table 18B. Upgrade options, AC0-2 parameters for simulation.

Parameter	Strategy	Description	Upgraded values
Cooling system upgrade			
Unit cooling (AC 0-2)	Air-conditioning to address overheating risk	Minimum EER: 2.4 (NBS, 2013)	Included EER: 3.125 CoP: 0.92 @summer profile
		Setpoint	23°C
		Cooling capacity	2,600 BTU per flat 12.5 $W \cdot m^{-2}$

Parameter	Strategy	Description	Upgraded values
Urban cooling (UAC)	Widespread use of domestic air-conditioning	Building heat release ($Q_{F,B}$) GL average (Iamarino, et al., 2012)	4.6 W·m^{-2}
		UWG factor used for domestic units	1.0*

* As advised by Aiko Nakano (E-mail correspondence, MIT, 2015).

B.5 Crawley algorithm application

Oke's (1988a) correlation applied to determine upper UHI limit:

$$\text{Average canyon Height} = 17.5 \text{ m}$$

$$\text{Average canyon Width} = 23.7 \text{ m}$$

$$\text{Aspect ratio} = \frac{H}{W} \approx \mathbf{0.7}$$

For European cities, the typical central core aspect ratios range between 0.75-1.7, and is regarded as conforming better to Oke's (1988a) correlation. The study concluded aspect ratios above 0.65 to provide the canyon conditions that ensure a degree of shelter to retain a reasonable proportion of the heat island warmth for winter warming, along with atmospheric dispersion and solar access, which would be satisfied by Gloucester Terrace and its 0.7 aspect ratio.

By applying Equation 9A:

$$\Delta T_{max} = 7.54 + 3.97\ \text{In}(0.7),$$

$$\Delta T_{max} \approx \mathbf{6.1\ K}$$

> This value is valid for calm, cloudless, and nocturnal (ideal) conditions.

Table 19B. Crawley (2008) algorithm.

Condition	Equation
If sun is down	$DBT_{(mod)} = DBT + \Delta DBT$
If hour is first or last hour of daylight	$DBT_{(mod)} = DBT + 0.5\ \times \Delta DBT$
If hour is second or next to last hour of daylight	$DBT_{(mod)} = DBT + 0.25\ \times \Delta DBT$
If hour is third or second to last hour of daylight	$DBT_{(mod)} = DBT + 0.0755\ \times \Delta DBT$
All other hours when sun is up	$DBT_{(mod)} = DBT + 0.1\ \times \Delta DBT$

The above algorithm is applied to LGW weather data in Figure 13, for higher (ΔT_{max} from Oke's correlation above = 6.1 K) and lower limit ($\Delta T_{min} =$ 1 K) of the estimated heat island range (Crawley, 2008), for both summer and winter peak-days for the year.

B.6 Parameter inputs to the UWG

UWG xml input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UWG xml input


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* Albedo and emissivity values as per default values from UWG/MIT database.

B.7 Data release and licences

Centre for Environmental Data Archival
SCIENCE AND TECHNOLOGY FACILITIES COUNCIL
NATURAL ENVIRONMENT RESEARCH COUNCIL

Application agreement for	Met Office - MIDAS Land and Marine Surface Station Data
Personal details	
First name:	KANCHANE R. A.
Surname:	GUNAWARDENA
AccountID:	kgunawardena
Institution	
Name:	University of Cambridge Department of Architecture
Country:	UK
Type:	University
Link:	www.arct.cam.ac.uk
Research details	
Funding type:	Other
Research description:	Project: Determining overheating risk and energy consumption implications for residential buildings in London. Principal: Kanchane R. A. Gunawardena (only user) Supervisor: Prof. Alan Short

This agreement will expire on or before 2018-06-02

CEDA reserves the right to reduce the length of validity of this agreement in certain cases. You will be notified of the expiry date if your application is approved. When the agreement expires you will have the opportunity to renew it.

Generated on 2015-06-03 13:36:21 by services.ceda.ac.uk

A project specific licence to the dataset is requested in order to gain access and utilise weather files generated by the LUCID project, which uses this Met Office dataset as its base. The obtained LUCID weather files will be used to determine overheating risk and energy consumption implications for a residential area in London. The project will be submitted in part fulfilment for the MPhil degree in Architecture and Urban Studies at the Department of Architecture, University of Cambridge. The outcome is therefore entirely academic in nature and all data used will be duly attributed.

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

Project specific licence: Meteorological Office (UKMO) data supplied through NERC Data Centres to bona fide research programmes. Met Office, *'MIDAS Land and Marine Surface Station Dataset'*, which includes diffuse solar radiation data from the London Weather Centre (LWC) and hourly weather data from the London Heathrow (LHR) weather station.

LUCID project data release: obtained through email correspondence with Dr Anna Mavrogianni, lecturer in Sustainable Building and Urban Design at the Institute for Environmental Design and Engineering, University College London. Release approved by Professor Maria Kolokotroni at Brunel University (principal for the LSSAT model), and Professor Mike Davies, Professor of Building Physics and the Environment at UCL and Principal Investigator for the LUCID project.

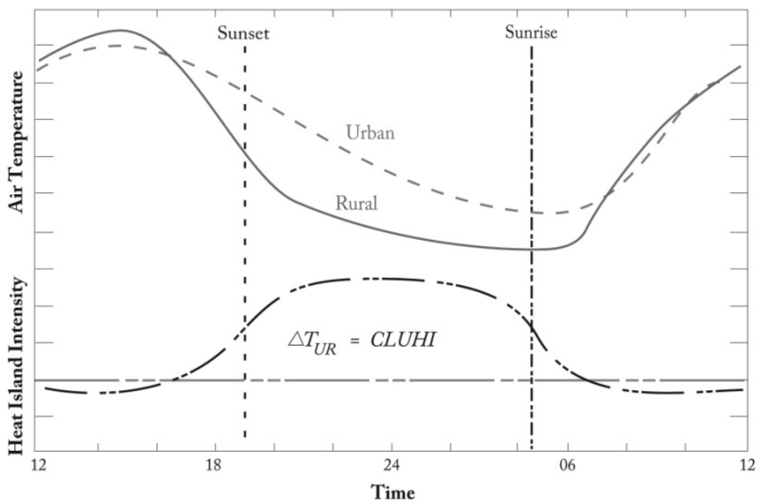
Appendix C

C. Urban heat islands

The following is a summary of current understanding on heat islands and their significance to the unique climate experienced in cities. This section is included here as background material to the study of overheating risk in urban climates.

C.1 Introduction

Since Luke Howard's (1833) original study of London, the urban heat island effect has been investigated by numerous researchers over the years (Sundborg, 1951; Chandler, 1965; Landsberg, 1981; Oke, 1987; Taha, 1997; Arnfield, 2003). A significant body of research on city specific heat islands is presented by North American (Taha, et al., 1988; Akbari, 2008) and European studies (Sundborg, 1951; Chandler, 1965; Santamouris, 2001; Wilby, 2003), which represents the geographical limits of the dissertation review. From these studies, majority have assessed atmospheric heat islands (Stewart, 2011), with surface heat islands addressed to lesser extent (Gartland, 2008; Peng, et al., 2012), and the subsurface type the least considered (Ferguson & Woodbury, 2004; 2007; Menberg, et al., 2013a). Since Sundborg's (1951) energy balance explanation of the urban climate, most studies have considered the physical basis as the framework for their analyses.



Source: modified from (Oke, 1982).

Figure 40C. Theoretical profile of the diurnal evolution of a heat island.

A heat island is described as a relative observation between rural and urban temperatures, with a dynamic profile that varies daily and seasonally (Figure 40C). Typically, heat island intensity ($UHI\ \Delta T$) is observed to be greatest during the summer as increased solar radiation increases the thermal energy within the urban system (Kershaw, et al., 2010). The formation of a heat island follows several climatic conditions and processes. During the day, solar radiation warms the rural earth surface to result in warm air rising to the 'boundary layer', which is at its deepest during the day and rangers between 1.5-2 km from the surface, and where it mixes with the atmosphere to form a boundary layer of constant temperature. The mixing process drives warmer air to the top of the layer to form a thermal inversion (i.e., a warmer fluid above a relatively cooler fluid). At night-time, since the surface of the earth is cooler than the air above, warm air no longer rises but settles into a ground-level thermal inversion. The modification of surface properties in cities aids the release of more heat during the day, thereby causing the top of the urban boundary layer (UBL) to be warmer and deeper than in rural areas. This is referred to as the 'boundary layer heat island' and is mildly intense during both day and night, with no notable temporal features, and mostly significant from a meteorological perspective (Oke, 1987). At night-time, urban form continues to emit heat that in turn warms the surface air, causing it to rise and mix. As this occurs less intensely than during the day, the thermal inversion occurs at a lower elevation that is at the top of the urban canopy layer (UCL) rather than at the boundary layer (which at night is also contracted). This inversion then traps the air, preventing it from rising further to cause the formation of the 'canopy layer heat island'. The urban canopy layer represents a complex stratum of the urban climate including the sphere of human habitation and other active surface properties. The nocturnal canopy layer heat island is consequently considered the most significant aspect of the urban climate relevant for built environment research and overheating studies.

Although the cumulative effect of the heat island and climate change are attributed for exposing urban dwellers to significant heat-related risks, the exact association between the two phenomena remain ambiguous. This is partly due to the difference in analysis resolution considered for climate change scenario assessments that typically disregard urban areas (Wilby, 2003; Crawley, 2008). Recent regional climate model simulations that account for urban areas have suggested heat islands to not intensify with climate change. This however is dependent on the nature of high-pressure systems that may occur in the future, with enduring and higher frequency likely to increase heat island magnitude (Kershaw, et al., 2010).

Weather patterns significantly affect heat transfer between urban surfaces and the atmosphere, with wind velocity and cloud cover the main parameters to consider (Landsberg, 1981). Wind velocity is the most significant weather variable to affect heat island intensity as it influences convection efficiency (forced convection). Cloud cover affects solar radiation penetration and incidence and is dependent on both cloud type and the degree of cover (Oke, 1973). A city's geographic location that determines its topography and climate, also influences heat island formation. As examples, features like large bodies of water or greenspaces can contribute evaporative cooling, while surrounding orography can physically block or modify wind flow patterns.

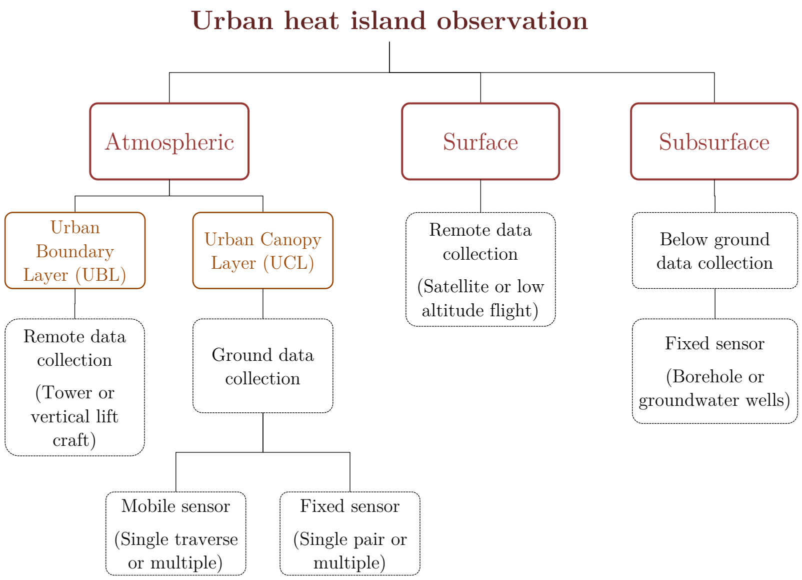
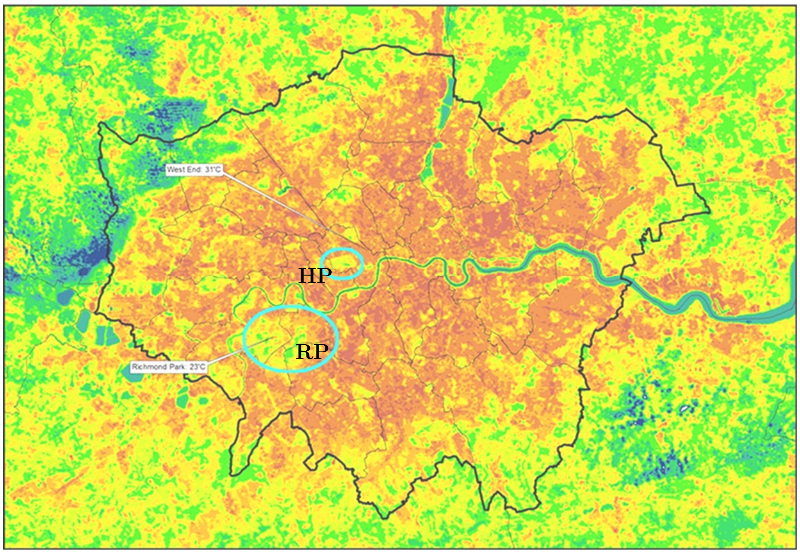


Figure 41C. The study of urban heat islands.

C.2 Heat island types

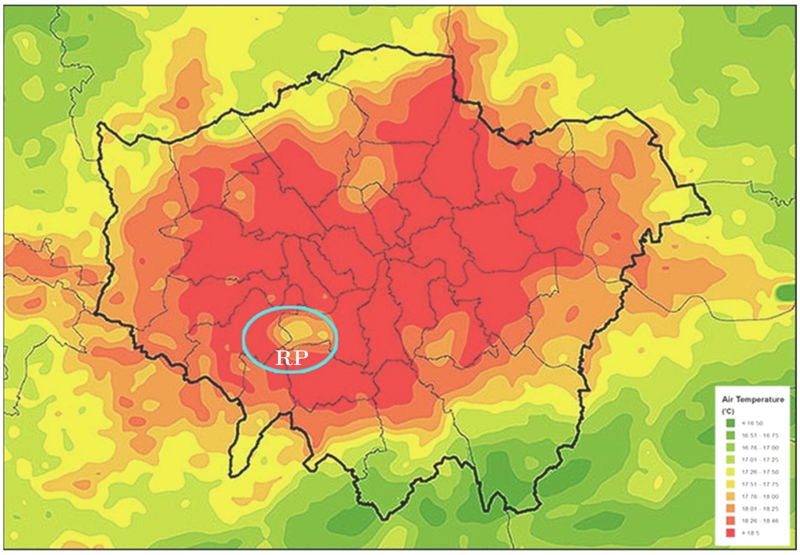
Depending on the stratum of the urban sphere considered, heat islands are described as subsurface, surface, or atmospheric (Figure 41C). Subsurface heat islands refer to belowground temperature differences between rural and urban areas. Principally affected by conduction heat flows, subsurface temperature differentials of up to 5 K have been recorded by studies. Adverse effects of the phenomenon include alterations to the chemical and biological properties of groundwater, influencing redox reactions, and modifying the diversity of aquifer bacteria and fauna, thereby altering water purification and filtration processes. Subsurface heat islands also present beneficial effects such as geothermal potential and promoting biological decontamination in urban and industrial areas (Menberg, et al., 2013a). The phenomenon is attributed to the cumulative effect of the mesoscale climate (surface and atmospheric heat island), heat losses from buildings (as highlighted by the case study in section 3.2), and land-use modifications. The climate above and subsurface processes together influence the variability of the subsurface heat island (Ferguson & Woodbury, 2007).



RP: Richmond Park; HP: Hyde Park; Sources: ARUP (2014) & UK Space Agency.

Figure 42C. LandSat image of London's surface heat island (June 2011).

Surface heat islands refer to surface temperature differences between rural and urban conditions (Figure 42C). They are typically evident day and night, although warmer during the day (particularly in the summer) as solar radiation heats surfaces, and relatively cooler at night as they purge the heat back to the atmosphere (Oke, 1982). Rural surroundings with shaded or moist surfaces are likely to remain nearer to air temperatures, while exposed urban surfaces on a dry summer's day can heat to 27-50 K warmer than the air to create a significant relative difference (US-EPA, 2008). The magnitude of this difference varies due to changes in solar intensity, time of day, ground cover (i.e., material), and weather patterns. Albedo is the main determinant of ground cover surface temperature and is defined as the percentage of solar energy reflected by a surface; higher the albedo of a material, the greater the solar energy that is reflected from its surface. Since 43% of this energy is in the visible wavelengths, material colour is correlated with albedo (US-EPA, 2008), with lighter surfaces having higher values (~0.70) than darker surfaces (~0.20) (Taha, et al., 1988).



RP: Richmond Park. Sources: ARUP (2014) and University College London.

Figure 43C. Modelled average atmospheric UHI for London (May-July 2006).

There is a significant yet indirect association between surface temperatures and air temperatures that is particularly evident in urban canopy layer observations adjacent to the surface. Air temperatures however vary significantly greater than surface temperatures as the air above mixes with the wider atmosphere. Studies of heat islands predominantly consider the atmospheric rather than surface or subsurface phenomena due to its proximity and relevance to human activity (US-EPA, 2008). It varies in magnitude and timing of peak throughout the daily cycle and from city to city. Typically, weakest in the morning/dawn, the intensity increases throughout the day as thermal energy is absorbed from the sun, and peaks at night/dusk as urban surfaces continue to release heat (Oke, 1982). The peak intensity however depends on the properties of urban and rural surfaces, the season, and prevailing weather conditions (US-EPA, 2008). Cities made of predominantly lower thermal diffusivity materials have been found to reach their peak soon after sunset, while ones with higher values reach it around sunrise. The broader peak period is referred to as the nocturnal heat island, which represents the most observed aspect of the atmospheric phenomenon (Gartland, 2008).

C.3 Urban geometry and materiality

Urban geometry can influence the surface heat balance by affecting net radiation flows (discussed earlier in section 3.1.1, p. 44, in relation to the case study canyon) and convection. Convection describes the transfer of heat between the urban surface and atmosphere following the temperature gradient. When wind speeds are low, less heat is transferred to the atmosphere by forced convection (more efficient as opposed to natural convection). Dense urban form can act as windbreakers that decrease wind speeds across cities, with studies indicating up to 60% reductions (Landsberg, 1981). The reduced forced convection that results, leads to increased heat storage during the day and slow release during the night to balance the energy flows, thereby aiding the heat island formation. The heat island formation process however can also serve to increase wind speeds, by encouraging convection driven cold air breezes drawn in from surroundings as warm air rises at the core. Described as heat island flow or the 'city-country breeze' (Oke, 1987), the effect has been particularly emphasised in coastal regions and cities such as Tokyo (Yoshikado, 1990).

The materiality of urban form influences the surface heat balance by affecting both net radiation and heat storage. The radiative properties of materials are emissivity and solar reflectance (albedo), while storage properties are affected by heat capacity and thermal conductivity. Collectively they determine how solar energy is reflected, absorbed, and emitted by urban surfaces. A surface's ability to dissipate heat or emit longwave (infrared) radiation is measured as thermal emittance. As materials with high emittance values release heat more readily, they remain cooler. Except for metals, most materials encountered in urban environments tend to have high thermal emittance values. Albedo is the main determinant of a material's surface temperature and affects building energy use both directly and indirectly. Indirectly it affects surface temperatures, which in turn affects canopy layer air temperatures. Reduced radiation absorption translates to reduced intensity of longwave radiation reradiated back into the atmosphere. Cooler surfaces also assist to lower downwind ambient air temperatures due to their reduced convective heat flux. Such temperature reductions can have a significant impact on building performance (Taha, 1997). In the case of building specific energy use, albedo directly affects heat transfer into occupied areas, thereby effecting cooling loads. Its significance to specific surfaces varies with orientation and latitude (radiation incidence angle). In tropical climates, the roof is the most critical surface in sensible heat exchanges, while moving towards higher latitudes presents surfaces facing the equator to be of greater significance. Notably, albedo tends to increase with building density, particularly in residential land-use. This is explained by building surfaces having typically higher albedo than soft landscaping that is more prevalent in less dense developments (Taha, et al., 1988).

Heat capacity, sometimes referred to as thermal mass, is a materials ability to store heat. The ease by which heat penetrates a material is considered by thermal diffusivity. A higher value of diffusivity indicates that heat reaches deeper into the material with the temperature remaining constant (Gartland, 2008). Thermal inertia is a measure of the responsiveness of a material to temperature variations. Materials with a high heat capacity also have high thermal inertia, meaning that temperature fluctuations throughout the diurnal cycle are minimal. Many urban materials tend to have higher heat capacities, thermal diffusivity, and thermal inertia than those found in rural contexts. The thermal properties of the predominant material within an urban setting affects the intensity and timing of when the heat island peak is likely to be observed. Cities made of predominantly timber or soil (lower thermal diffusivity), are likely to reach their heat island peak soon after sunset, while concrete and stone (higher thermal diffusivity) dominant cities are unlikely to reach it until sunrise (Gartland, 2008). Low permeability or porosity is also a feature of common urban materials that serves to hinder the cooling of surfaces. The principle being that impervious surfaces encourage faster surface water runoff, thereby preventing the opportunity to achieve evaporative cooling from absorbed moisture (Taha, 1997).

The selection of materials however is influenced by other factors in addition to thermal properties. Physical properties, buildability and assembly issues, supply-chain, economics, regulatory guidance, cultural and historic context, and aesthetics can all influence the materiality of a development or even the character of entire cities, depending on which factor gains precedence.

C.4 Urban activity

Source: © Google Images.

Figure 44C. Anthropogenic emissions.

A significant proportion of the energy consumed by the many activities in cities is eventually released to its climate as thermal waste. This waste thermal energy is referred to as anthropogenic emissions and is expressed as the heat flux for a given area (Q_F, W·m^{-2}). It includes the three main contributing flux components from buildings ($Q_{F,B}$), transportation ($Q_{F,T}$), and human metabolism ($Q_{F,M}$). For large cities in industrialised nations, conservative anthropogenic heat flux estimates range between 5-100 W·m^{-2} (Iamarino, et al., 2012). The value varies given the complexity of the city, season, and diurnal cycles. The complexity of London for example, provides for a range of flux values across the different densities of human activity. A recent study estimated that 50% of the city experiences annual heat flux of less than 8.0 W·m^{-2}, while only 2.5% experiences values greater than 50 W·m^{-2}. Where the density of activity is greatest as in the City of London, extreme values of up to 210 W·m^{-2} have been estimated

(Iamarino, et al., 2012). The effect of season is significant in cold-climate cities, where gains are generally larger in the winter due to intensive heating loads than in summer. A study of city cores from the United States found anthropogenic flux to range between 70-210 $W \cdot m^{-2}$ in the winter, and between 20-40 $W \cdot m^{-2}$ in the summer (Taha, 1997). Temporal variability is particularly significant when assessing microclimate conditions, as the diurnal cycle for various activities can highlight anomalous peaks in localised areas for short durations. A study of London for example, recorded such extreme peaks of up to 550 $W \cdot m^{-2}$ (Bohnenstengel, et al., 2014).

$$Q_F = Q_{F,B} + Q_{F,T} + Q_{F,M}$$ *Equation 10C*

Anthropogenic heat emissions influence the urban energy balance and facilitate the formation of heat islands by adding thermal energy to the urban system. A study of Tokyo spatially mapped and numerically modelled emissions to estimate that most of its nocturnal summertime heat island (2-3 K) was owed to anthropogenic heat emissions (Kimura & Takahashi, 1991). A simulation study of California (USA) demonstrated that in a large city core anthropogenic emissions could create nocturnal and diurnal heat islands of up to 2-3 K (Taha, 1997). Another model of Philadelphia (USA) demonstrated the inclusion of anthropogenic emissions in its simulations to increase the heat island by 0.5 K during the day and 2 K at night (Heisler & Brazel, 2010). A study of London found that from the rejected heat approximately a third increases outgoing longwave radiation, while two thirds contribute to increasing the sensible heat flux that warms the atmosphere and adds to the heat island (Bohnenstengel, et al., 2014). There is therefore ample evidence to support the limiting of anthropogenic emissions to mitigate the intensity of the heat island experienced.

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Postscript

The material included in this dissertation has been published subsequently in the following peer-reviewed publications:

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Gunawardena, K. R., Mccullen, N., & Kershaw, T. (2017). *Heat island influence on space-conditioning loads of urban and suburban office buildings.* In Cities and Climate Conference 2017, Potsdam: Potsdam Institute for Climate Impact Research, pp. 1–13.

Gunawardena, K., & Steemers, K. (2019). *Adaptive comfort assessments in urban neighbourhoods: Simulations of a residential case study from London.* Energy and Buildings, 202, 109322.

> *"… the first essential step in the direction of learning any subject is to find principles of numerical reckoning and practicable methods for measuring some quality connected with it. … when you can measure what you are speaking about, and express it in numbers, you know something about it…"*
>
> Lord Kelvin (1883)

University of Cambridge