Designing for the urban climate: an integrated methodology to assess the impact of the urban climate on building performance in the United Kingdom

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I, Gurdane Virk confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

There are a wide range of weather data sources and modelling tools that measure and simulate urban environments. There is a current lack of guidance or best practice recommendations as to how to factor the outputs from these resources into building design.This is in part due to the inherent complexity of urban climate. In a warming climate and with increasing urbanisation, the impact of design interventions and mitigation measures needs to be understood both qualitatively and quantitatively.

In acknowledgement of these challenges, this thesis aimed to investigate novel methods of integrating climate data from varying spatial and temporal scales and sources into building design through a series of case studies.

The first study analysed how modelled city-scale climate data for London can be used to quantify the Urban Heat Island (UHI) effect. Modelled data has the advantage of varying spatial scales and resolutions. Comparisons between modelled and observed data in London demonstrated how the choice of urban and rural reference point can impact the magnitude of the estimated UHI effect.

The second study assessed whether observed data from urban weather stations in Birmingham and Manchester can be used to create new urban weather files. The analysis showed that the local microclimate can substantially impact measurements of point observations. New CIBSE weather files for London were released during the research, featuring an urban weather station. A third case study showed that London's UHI can now be more usefully factored into building design and how the effectiveness of design adaptations for an office varied with location. These studies focused on city-scale effects, however building performance is also influenced by its surrounding neighbourhood and the local-scale microclimate.

The final case study outlined a novel methodology of incorporating microclimate modelling results into building performance simulation. The microclimate model simulated how retrofitted green and cool roofs can reduce local air temperatures in Central London. The study demonstrated the effectiveness of these neighbourhood-scale mitigation measures at reducing overheating and energy use within an office.

Impact Statement

This research aimed to investigate novel methods of integrating climate data from varying spatial and temporal scales and sources into the design process using building simulation. As an Engineering Doctorate (EngD) sponsored by the Chartered Institution of Building Services Engineers, the outputs of this work will be of particular interest to disciplines associated with architecture, building services, urban planning and environmental design and engineering.

The thesis identified knowledge gaps between building simulation and climate research areas. The gaps suggest a need for decision support tools in the form of dynamic thermal simulation building models and climate models at a variety of spatial and temporal scales to identify and prioritise any climate mitigation and building adaptation strategies and to be able to effectively comply with demands for sustainable design and stricter regulations.

The research and findings within this thesis have been published and presented within a variety of industry and academic platforms. A conference paper was presented at the 2013 CIBSE Technical Symposium on developing and expanding current CIBSE design guidance on urban climates. A second conference paper at the 2015 CIBSE Technical Symposium reported Urban Heat Island analysis of weather data in Birmingham and Manchester for the creation of new CIBSE Design Summer Years (DSY) weather files. The analysis within the thesis were included in the update of the Urban Heat Island section CIBSE Guide A, which is a key industry reference guide.

The author led the publication of three academic journal publications. The first investigated the effectiveness of retrofitted green and cool roofs at reducing overheating in a naturally ventilated office in London. This was followed by a related paper with a focus on annual energy use. The final journal paper was the first to test new CIBSE DSY weather files, published in an industry focused journal. The author contributed to industry guidance on overheating in homes, with a section on Urban Modelling resources for the Zero Carbon Hub in 2015.

As a direct contribution to industry, the author was involved in the development of new CIBSE design guidance and CIBSE weather files. The author was a member of the team that developed Technical Memorandum (TM) 59 in 2017, the guidance provides a new methodology for overheating risk assessment in homes. TM59 is required for compliance with local planning requirements in cities such as London. The author contributed to the development, testing, and writing of the technical guidance on new CIBSE Design Summer Years and Test Reference Year weather files. These are used in compliance with Part L of Building Regulations, in local planning requirements, school design (as outlined in Building Bulletin 101) and BREEAM accreditation.

The research in this thesis contributes to an increased awareness of how the urban climate impacts building design and what tools can be used in the design process. The direct industry outputs from the EngD will result in better design practice and compliance with new and existing standards and planning requirements. The outputs are of particular interest to several building-related disciplines as urban climate design mitigation measures and interventions vary by spatial scale. These interventions impact the surrounding landscape, physical form and materials used in the buildings and the design of its services.

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Abbreviations and acronyms

ADMS – The Atmospheric Dispersion Modelling System model

CIBSE – Chartered Institution of Building Services Engineers

CFD – Computational Fluid Dynamics

DSY – Design Summer Year weather file

EngD – Engineering Doctorate

GLA – Greater London Authority

LES – London Environment Strategy

LSSAT – London Site Specific Air Temperature model

LWC – London Weather Centre

MIDAS – Met Office Integrated Data Archive System

MORUSES – Met Office Reading Urban Surface Exchange Scheme

NWP – Numerical Weather Prediction

TM – Technical Memorandum

TRY – Test Reference Year weather file

UHI – Urban Heat Island

UK – United Kingdom

UKCP – United Kingdom Climate Projections

WMO – World Meteorological Organisation

WRF – Weather Research and Forecasting model

Background

1 Introduction

1.1 Research context

1.1.1 Current context

The work within this thesis concerns urban climates and the cities and buildings that form them within the United Kingdom, with a focus on London. Urban areas are where most of the world's population work and live. In 2018, 55% of the global population lived in urban areas (UN, 2018b). In the context of the UK, 83% of the population resided in urban areas in 2017 (UN, 2018a). There will be increased urbanisation globally due to urban migration and population growth (UN 2018). The Office of National Statistics 2018 population projections estimates the overall population of the UK will grow from 66.4 million in 2018 to 72.4 million in 2043 (ONS, 2019b)[1]. In the short term, urban populations are predicted to increase in size by 6.7% nationally from mid-2015 levels to mid-2025 (ONS, 2016). A government review of populations in the UK's 63 cities predicts that they will contain 17.7% more people in 2036 than in 2011 (Chapman, 2015). With increasing rates of urbanisation, the demand for new and refurbished building developments is increasing across cities in the UK. This introduction will focus on London as an example UK city to provide the research context.

London's current population of 8.7 million is projected to grow to 10 million by 2035 (GLA, 2015a) and to 11.1 million by 2050 (GLA, 2018a). This population will need to be housed; from the 2011 census data there were 3.28 million households, growing to 4.26 million by 2036 (GLA, 2016c). London requires an estimated 42,000 new homes per annum to keep up with this demand (GLA, 2014a), only 24,100 homes were built in London between 2011 – 2015 (GLA, 2017). The total office floorspace stock within London increased by 12.1% between 2000 – 2012 (GLA, 2014b). With projected employment increases, the demand for office floor space is set to increase (GLA, 2015b).

Cities like London have to meet this demand for new developments whilst reducing carbon emissions to tackle climate change and adapt to the potential risks of climate change (London Resiliance Group, 2018). In the UK, the risks of climate change include overheating, flooding, water shortages, risks to natural capital and food production (CCC, 2018). Directly related to the built environment are associated risks from flooding and risks to health, wellbeing, productivity and associated infrastructure from increasingly high temperatures. The Committee on Climate Change classified heat as one the top 6 inter-related climate change risks for UK (CCC, 2018). Recent heatwaves have resulted in excess deaths, in 2018 there were 863 excess deaths, an increase from 2017 where there were 778 excess deaths (PHE, 2019). Previous severe heatwaves resulted in over 2234 excess deaths in 2003 and 2323 excess deaths in 2006 (PHE, 2019).

The 2018 Environmental Audit Committee (EAC) report on heatwaves reviewed the current and future impacts of heatwaves in the UK (House of Commons, 2018). The report concludes heatwaves are predicted to increase in severity and severe heatwaves are projected to become common in the 2040s. The committee state that overheating and the risk to heat-health are a threat to public health and government organisations such as Public Health England the Met Office should make the public more aware of the impact this future threat will have on human health (House of Commons, 2018). The report projects that the average number of heat-related deaths in the UK will exceed 7,000 a year by the 2050s (House of Commons, 2018)[2].

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[1] These projections assume lower long-term net international migration than previous projections in 2014 and do not predict the impact of political circumstances such as Brexit (ONS, 2019b).

[2] Winter excess mortality is far greater than summer excess mortality. In winter 2018 to 2019, there were 23,200 excess winter deaths in the UK (ONS, 2019a).

1.1.2 Projected climate change impacts

The latest State of the Climate report released by the Met Office outlined the recent observed changes to the UK's climate (Kendon et al., 2018). For the most recent decade (2008 – 2017), annual average land temperatures were 0.8 ° C warmer than 1961 – 1990 and 0.3 ° C warmer than 1981 – 2010 (Kendon et al., 2018). The frequency of warm years continues to increase, 9 of the 10 warmest years for the UK have occurred since 2002 (Kendon et al., 2018). Summer 2018 was a particularly warm year and equalled other notable heatwave years, 1976, 2003 and 2006 (Met Office, 2018). Across the UK, the mean average temperature was 1.4 ° C above the 1981 – 2010 average. In South East England, the average maximum temperatures were 3.2 ° C warmer than the 1981 – 1990 averages and 2.4 ° C warmer than the 1981 – 2010 averages (Met Office, 2018).

The UKCP18 climate projections express future scenarios in terms of future greenhouse gas emissions, namely representative concentration pathways (RCP) (Lowe et al., 2018; Met Office, 2019; Murphy et al., 2018). RCPs specify concentrations of greenhouse gases that will result in total radiative forcing increasing by a target amount by 2100, relative to pre-industrial levels. Total radiative forcing is the difference between the incoming and outgoing radiation at the top of the atmosphere (Lowe et al., 2018; Met Office, 2019; Murphy et al., 2018). Each pathway represents a different range of projected global mean temperatures increases and future radiative forcing targets in 2100 of 2.6, 4.5, 6.0 and 8.5 W/m^2. RCP 2.6 represents a future where global mean temperatures are limited to 2°C following reduction in greenhouse gas emissions. RCP 8.5 represents a future where greenhouse gases continue to rise with much higher temperature increases than RCP 2.6. Table 1 and Table 2 shows the probabilistic projected annual temperature increases for different RCP scenarios from UKCIP 18 for different percentile ranges for the UK (Lowe et al., 2018).

Table 1 Projected change in annual temperature for the UK region from 1981-2000 to 2080-2099 using the UKCIP 18 probabilistic projections.

Scenario	**5th**	**10th**	**50th**	**90th**	**95th**
RCP 2.6	0.3	0.5	1.4	2.3	2.6
RCP 8.5	1.9	2.3	3.9	5.7	6.3

Table 2 Projected change in annual temperature for the UK region from 1981-2000 to 2041-2060 using the UKCIP 18 probabilistic projections.

Scenario	**5th**	**10th**	**50th**	**90th**	**95th**
RCP 2.6	0.3	0.5	1.2	2.0	2.3
RCP 8.5	0.7	0.9	1.8	2.7	3.0

The UKCP18 project that by the middle of the century, the UK could see annual temperature increases of 2.6°C for RCP 2.6 and 3.0°C for RCP 8.5 (95th percentiles).

As shown in Figure 1, the projections vary spatially across the UK and UKCP18 includes mapped projections, where for the South East of the UK the temperature increases are even greater (Lowe et al., 2018).

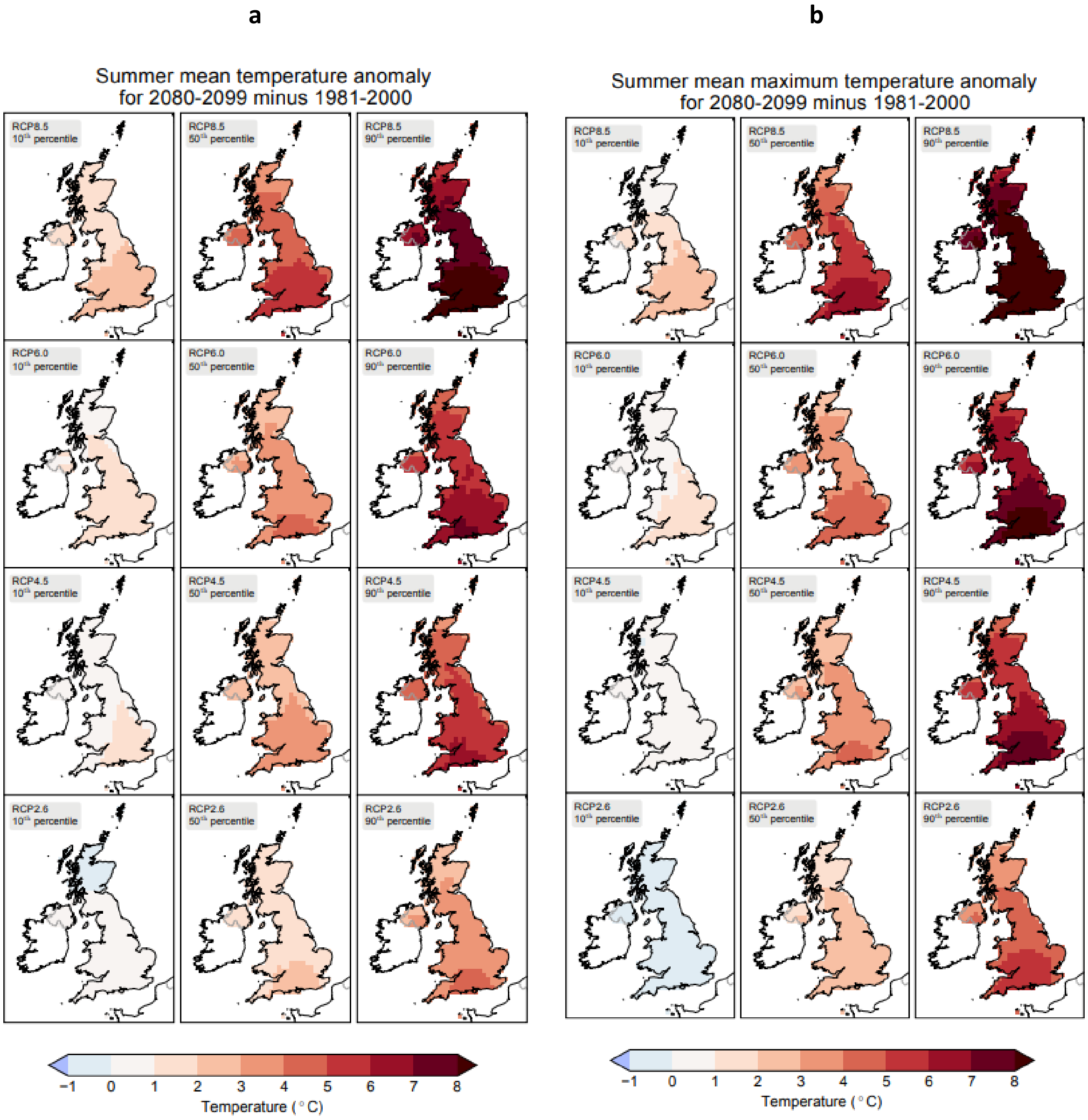

Figure 1 Changes in 20-year for a) summer mean temperatures and b) summer mean maximum temperatures for 4 RCP scenarios using UKCP18 for 3 different percentiles for the period 2080-2099 to a 1981-200 baseline. Source: (Lowe et al., 2018).

As shown in Figure 1a, the South East region has projected summer mean temperature increases of 0-4°C for RCP 2.6 (10th to 90th percentile) for the period 2080 to 2099 relative to 1981-2000 baseline a range of 2-8°C for RCP 8.5 (10th to 90th percentile).

Hot summers are also expected to become more common (Met Office, 2019). As an example, the probability of a summer like 2018 or warmer occurring is predicted to be greater than 90% for RCP 8.5 and 50% for RCP 2.6 by 2100 (Lowe et al., 2018). Recent assessments have suggested that the risk of extremely hot summers has increased in the last decade (Christidis et al., 2015), from 2003 to 2015 there was an observed summer temperature increase of 0.81 K.

In response to the need to reduce carbon emissions, the UK is legally committed to reducing carbon emissions by 100% from 1990 levels by 2050 under the Climate Change Act 2008 (2050 Target Amendment) Order 2019 (Government, 2019; Priestly, 2019). The new target is a 'net zero' target, any remaining emission are to be offset by removal from the atmosphere and/or by trading in carbon units (Priestly, 2019).

Since 1990, UK emissions have reduced by 43% (CCC, 2018). However, as the power sector progresses from fossil fuels to low-carbon electricity, emission reductions in other sectors such as transport, industry and buildings has stalled (CCC, 2018). In 2017, buildings accounted for 19% of the UK's carbon emissions (CCC, 2018). In terms of direct CO_2 emissions, dwellings contribute 77%, commercial buildings contribute 14% and the public sector contributes 10% (CCC, 2018). The domestic sector currently accounts for 27% of energy consumption in the UK, of which 54% is attributed to space heating (DECC, 2015). To achieve the statutory reductions, there will need to be significant reduction in emissions from all sectors. To meet 2030 emissions set by the legislated carbon targets, building emissions need to be reduced by 16% from 2017 levels (CCC, 2018).

1.1.3 Policy response

These pressures and demands have had a noticeable impact on policy and planning at all levels of governance. At the national level, building regulations such as Part L set out statutory standards of energy efficiency and set out the maximum carbon dioxide occupied buildings are to emit (DCLG, 2013)[3]. There are issues with current government adaptation measures and legislation. The EAC report on heatwaves found that alert systems and planned heatwave adaptation measures are not being implemented adequately at the national and local level (House of Commons, 2018) and included the following conclusions:

- Current policy in the form of regulations do not account for the health risks of overheating and thermal comfort in buildings and cities.
- This lack of regulation could result in houses having to pay for remedial works in the future due to the increased heatwave risk.
- The National Planning Policy Framework (NPPF) should include policies to assess the UHI effect and include measures to mitigate their impacts on health risks from heatwaves, and include a green infrastructure target to ensure towns and cities are adapted to more frequent heatwaves in the future.

Large reductions in energy use from space heating from current and future housing stock can be achieved using technologies such as building fabric thermal insulation that are already available (CCC, 2019a, 2019b; Lowe, 2007). However, there are potential unintended consequences of adapting the building stock. Passive measures such as improving insulation, the quality of glazing and greater air tightness could have knock on effects which result in lower air quality and overheating, if not combined with appropriate ventilation and cooling means (Shrubsole et al., 2014). The existing building stock is not adapted to cope with increasing air temperatures due to climate change, with an estimated 20% of current dwelling stock overheating (CCC, 2014). Due to the nature of the building stock, dwellings are particularly prone to overheating, but offices and schools are also affected (CCC, 2016)(Zero Carbon Hub, 2015). In urban environments the use of passive measures might be limited and mechanical cooling is needed to protect health and reduce overheating, this in turn could amplify the urban heat island effect (House of Commons, 2018).

As the largest city in the UK, London has introduced policies to mitigate and adapt to climate change whilst growing. The London Plan outlines policies for the city's spatial development strategy,

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[3] As part of the Future Homes Standards, Part L and Part F are currently being reviewed and are under consulation (MHCLG, 2019). This includes a consulation on the method for reducing overheating risk in new homes.

including those that aim to mitigate climate change through reducing emissions and adapting to future warmer temperatures (GLA, 2018b). Policies aim to increase efficiency and resilience, but not contribute to UHI effect (working under the assumption that cold-related risks will be minimised through energy efficient retrofit). Key policies relating to the urban climate are to increase the amount of urban greening through the use green roofs and walls and urban drainage schemes. Policies aim to manage heat risk through minimising the impacts of new developments contributing to the warming the UHI through their design, layout, orientation and materials. Developers must also demonstrate the use of the cooling hierarchy, prioritising passive systems over mechanical and active cooling:

1) Minimise internal heat generation through energy efficient design.
2) Reduce the amount of heat entering a building through orientation, shading, albedo, fenestration, insulation and the provision of green roofs and walls.
3) Manage the heat within the building through exposed internal thermal mass and high ceilings.
4) Provide passive ventilation.
5) Provide mechanical ventilation.
6) Provide active cooling systems.

The EAC report recommends that such a 'cooling hierarchy' should be used and enforced by all local planning authorities to avoid the exacerbating impact of air conditioning on heatwaves (House of Commons, 2018).

The London Environment Strategy (LES) sets out the GLA's integrated approach to reducing carbon emissions by 2050 and emissions targets for the city (GLA, 2018a). The strategies outlined in the report inform the policies in the London Plan. London aims to be a zero-carbon city by 2050, key policies to achieve this include decarbonising the electricity and gas grids and decarbonising buildings through energy efficiency measures such as retrofitting existing homes and setting zero carbon building standards for new developments.

The LES sets out policies relating to adapting the city to climate change. Policies are proposed to understand the risks and impacts of severe and future climate on buildings and occupants, including identifying mitigation measures such as green roofs, reflective paints, blinds and shading from trees. The LES outlines how policies within The London Plan aims to the minimise risk of new developments overheating and reduce impact of UHI through the following measures:

- Overheating modelling against extreme weather scenarios.
- Following the cooling hierarchy.
- Reduce risk of overheating and reduce impact of mechanical cooling on UHI.
- Develop guidance on how new developments can be designed to minimise the amount of heat absorbed by them.
- Green infrastructure to provide cooling and shading.
- Heat mitigation measures such as solar shading, cool and green roofs.
- Ensure energy efficiency measures do not result in overheating risk and to avoid unintended consequences of retrofitting measures.

Future developments will have to demonstrate how their design and operation minimise overheating, whilst avoiding the use of air conditioning as much as possible. At present, 96% of London's CO_2 emissions associated with heating and cooling buildings are for heating and only 4% for cooling, almost all of which is for the cooling demand within non-domestic buildings (GLA, 2016c). However, air conditioning installed capacity is increasing across the building stock. Using street surveys, researchers at UCL found that 62% of the UK's commercial offices were air conditioned (Caeiro et al., 2008). A study estimated the future cooling demand in London would increase installed capacity (spread across offices, retail, hotels and residential buildings) by 40% between 2006 and 2030 (Day et al., 2009). This estimated increase was due to changing occupant preferences rather than a projected response to climate change. The actual increases in energy consumption could be much larger.

To ensure that that infrastructure providers and building occupants are aware of the impacts of increased temperatures and the Urban Heat Island, the LES proposes to (GLA, 2018a):

> *'Provide locally specific data and modelling to demonstrate and evidence the impacts of the Urban Heat Island'*

Considering this need, there are still a lack of case studies that show quantitative evidence of how both the urban climate can be factored into design and also how building design decisions will impact the surrounding climate. This is in part due the complexity of designing in urban climates. The physical processes that influence the urban climate vary depending on the spatial scale of the effects and therefore the subsequent impact on buildings also varies spatially.

There are methodological challenges with quantifying these effects, such as simultaneously modelling the impact of the local urban climate on building performance and the impact of the building on the local urban climate. Designing new developments and adapting existing developments within cities in the UK poses a particular challenge.

As cities continue to grow, the addition and refurbishment of the building stock will inevitably impact the surrounding urban environment. Currently, there is no statutory requirement to show quantitative evidence of how a building development or any potential land use change impacts the surrounding climate. However, future policies as recommended by the EAC could require evidence of how developments impact the UHI.

1.2 Research questions

The previous section introduced the context of the research within this thesis, highlighting the issues facing the industry in terms of building design, climate change and future policy requirements. This section outlines the research questions within the thesis.

There is limited guidance on how urban climates impact building developments and how designers can incorporate the effects of urban climates into the design process. There is a need for detailed quantitative and qualitative design guidance on urban climates and the assessment tools that can be used as part of the design process. Due to the inherent complexity of the urban climate and the various spatial and temporal factors to consider, the choice of which data source or design tool to use is context dependent.

Designers, planners and architects need decision support tools in the form of dynamic thermal simulation building models and climate models at a variety of spatial and temporal scales to identify and prioritise any climate mitigation and building adaptation strategies and to be able to effectively comply with demands for sustainable design and stricter regulations. The scope of the research within this thesis can be framed into the following research questions:

1. How can new and existing sources of climate data and modelling tools be factored into building design?

2. How can climate data be used to provide a more in-depth analysis of how features of urban climates, such as the UHI, vary across UK cities?
3. What impact do simple climate adaptation design strategies have on building performance in terms of thermal comfort and energy use?

1.3 Research objectives

The aim of this research is to investigate novel methods of integrating climate data from varying spatial and temporal scales and sources into the design process using building simulation. The work in this thesis used climate data at two different scales, the city scale and the neighbourhood scale. The reason for focusing on these scales is that building level interventions and modelling tools are accessible and commonly used within industry. For example, the overshadowing of an adjacent building can already be modelled within dynamic thermal models, but the impact of neighbourhood scale effects requires further modelling inputs. The thesis presents case studies to achieve the following objectives:

- Chapter 3:
    - Analyse how modelled city scale climate data for London be used to quantify the Urban Heat Island effect.
    - Provide a methodology of how outputs from a city-scale climate model can be analysed and then inform building design, including an analysis of the spatial variation of the UHI using this data.
- Chapter 4:
    - Analyse how observed climate data for Birmingham and Manchester can be used to quantify the Urban Heat Island effect.
    - Using the quantified UHI effect from the analysis, assess if observed data from urban weather stations in Birmingham and Manchester can be used to create new weather urban weather files.
- Chapter 5:
    - Analyse how CIBSE weather files be used to quantify the impacts of the Urban Heat Island effect on overheating within an office.
    - Provide an analysis of the differences in climate variables between weather files and how this captures the UHI effect in London. The effect of these differences can then be tested on an example building model.
    - Assess the effect of simple climate adaptation design strategies such as insulation, low-albedo roofs and shading in both a current and future climate scenario.
- Chapter 6
    - Provide integrated methodologies to assess how neighbourhood scale climate data be factored into building simulation.
    - Assess what the impact of neighbourhood scale urban climate mitigation measures in the form of green and cool roofs have on the annual heating and cooling energy balance and thermal comfort of an office. These effects can be assessed both in terms the direct heat transfer into the building and the effect on the local microclimate.
    - Compare the effect of green and cool roofs to traditional retrofitted design adaptations such as insulation.
    - Assess if integrating the neighbourhood scale results into building simulation is an effective methodology.

The work in this research project was focused on transferrable knowledge and design tools that would be useful to CIBSE members. As a result of this focus, much of the work consists of case studies and assesses if they can be applied or replicated as part of a design process.

1.4 Industrial Sponsor: Chartered Institution of Building Services Engineers (CIBSE)

CIBSE is the international body that represents and provides services to the Building Services profession. Members are traditionally building services engineers. The Institution covers all aspects of the built environment, including design, installation, maintenance and manufacturing associated with building services and has the following functions:

- It confers an internationally recognised badge of quality.
- It undertakes a wide range of learned society activities ranging from producing information services and acknowledged industry good practice guidance in publications, to running a wide range of events, and to providing extensive networking activities through a series of regional and special interest groups.

Part of CIBSE's good practice guidance is to produce design guidance, which focus on specific areas of expertise and provide in-depth technical knowledge. Previous CIBSE guidance has included how to factor the UHI effect into manual steady state calculations as part of CIBSE Guide A: Environmental Design (CIBSE, 2015). The author contributed to updating and expanding this section of the guidance as part of the research project, the work is outlined in Chapter 3. CIBSE produces weather files which are used as part of Part L compliance modelling and overheating assessments. CIBSE released new weather files in 2016 and the work in Chapter 5 was the first published testing of these files.

The topics covered within the thesis had not been featured in previous CIBSE guidance and as outlined in this thesis, there is currently a knowledge gap within the industry for design guidance on urban climates.

1.5 Thesis outline

Chapter 2 starts with the theoretical background of different aspects of the urban climate. A major contribution to the production of new CIBSE design guidance is to ensure designers understand how the urban climate can impact their developments. Chapter 2 includes an extensive literature review which aimed to cover the knowledge gaps between academia and industry research. The chapter starts with a review and discussion of the tools and data which are available, which could then be used as inputs into building simulation as a means of factoring in the urban climate into building design. This is followed with an evidence review on what the drivers of the urban climate are, the subsequent impact on building performance are and the potential design adaptations available. The new data and tools identified by this review are discussed in terms of their applicability to building design and research gaps are highlighted.

The initial work in this thesis compares how different climate data sources can be used to analyse how the city-scale UHI intensity varies in cities in the UK. The work aimed to answer the first research question of how new and existing sources of climate data can be analysis and includes data from 2 different sources. At the early design stages, the UHI intensity can be a useful indicator of how the climate varies across a city. Chapter 3 outlines the methodology of calculating the UHI intensity in London from modelled data and then comparing these intensities to observed data. The modelled data allows the UHI intensity to be investigated at a variety of transects compared to the overserved data. This analysis aimed to answer the second research questions as the methodology developed uses the spatial scale of the modelled data to provide more in-depth analysis of the UHI effect in London.

The EAC report on heatwaves (2018) recommends it should be a regulatory requirement to use dynamic thermal modelling and CIBSE TM59 and TM52 overheating assessments for compliance (House of Commons, 2018)(CIBSE, 2013b, 2017). These overheating risk assessment use CIBSE Design Summer Year (DSY) weather files (Levermore and Parkinson, 2006). CIBSE provide DSYs for 14 locations within the UK. The majority of these locations are rural. The work in Chapter 4 analyses if potential new weather stations located in urban areas in Birmingham and Manchester are suitable for the creation of new DSY weather files. A methodology quantifying the UHI effects is used to assess this suitability. The work aimed to answer both the first and second research questions as any new urban weather station would provide a new climate data source for input into building simulation and it provides additional in-depth analysis of the UHI effect in these cities.

New DSYs for London were released during the course of this research project. The new files allow designers to factor in London's UHI into their building simulations. They represent point observations at different locations within London for a single continuous year of data. Chapter 5 outlines the study that carried out initial testing of these new weather files. The study coincided with the public release of the new DSY weather files and is the first study to test them. The chapter analyses how weather data varies between the new weather files and an analysis the effectiveness of retrofitted design interventions at reducing summertime overheating in varying locations. The work aimed to answer both the first and second research questions as the new weather stations would provide a new climate data sources for input into building simulation and the testing provides additional analysis of the impact of the UHI effect in London. The testing of the simple climate adaptation strategies also aimed to answer the third research question and practitioners will be able to use these findings to inform their future design.

The new DSYs usefully represent the city-scale UHI effect, but they use weather data that consist of point measurements at specific locations. Designers will need to use other tools if they want to assess how specific building design decisions impact both building performance and the surrounding climate. Green and cool roofs are simple design interventions that can be retrofitted onto buildings. Their use will impact building performance and have the potential to mitigate urban warming. In London, there are a limited number of case studies that have investigated these linked effects. Chapter 6 outlines two studies that used the outputs from a neighbourhood scale microclimate model that simulated the effect of green and cool roofs on near surface air temperatures and humidity for a location in Central London. The work incorporates results from previous microclimate modelling (Jansz, 2011, 2012) into the building simulation. The work aimed to answer the first research question, the novel integration of the neighbourhood modelling outputs presented provides a methodology to factor in this data into building simulation. The analysis of the effectiveness of the simple climate adaptation strategies aimed to answer the third research question. Practitioners will be able to use these findings to inform their future design.

Chapter 7 assesses how useful the climate tools and data used within this thesis are to building designers. This includes a summary of the key findings of each chapter and a discussion of the limitations and further work needed.

1.6 Engineering Doctorate: structure and outputs

The structure of the EngD is outlined in Table 3.

Table 3 Structure of EngD

1-year MRes	Adaptive Architecture and Computation, including MRes dissertation on topic associated with overall research topic.
2 - 4 year Doctorate	Including progress reports and review at month 23 and 35.

Table 4 lists the conference papers, chapter contributions and journal articles that have been which are based on research carried out as part of this thesis. Contributions to CIBSE and the wider industry are also listed.

Table 4 Outputs and contributions of the author[4]

Type	Role	Citation or description
Outputs and contributions of Engineering Doctorate		
Conference Paper	Led paper	Virk D (2013) Developing and expanding current CIBSE design guidance on urban climates. In: CIBSE Technical Symposium, Liverpool John Moores University, Liverpool, UK, 11-12 April 2013, Liverpool: CIBSE.
Chapter Section	Updated section	Contributing author to CIBSE (2015) CIBSE Guide A: Environmental Design, *Chartered Institution of Building Services Engineers,* Chapter 2, specifically the Urban Heat Island section.
Journal Paper	Led paper, research contribution was building modelling	Virk G et al. (2014) The effectiveness of retrofitted green and cool roofs at reducing overheating in a naturally ventilated office in London: Direct and indirect effects in current and future climates. *Indoor Built Environment.*
Journal Paper	Led paper, research contribution was building modelling	Virk G et al. (2015) Microclimatic effects of green and cool roofs in London and their impacts on energy use for a typical office building. *Energy and Buildings.*
Journal Paper	Led paper, main researcher	Virk G et al. (2015) Using the new CIBSE design summer years to assess overheating in London: Effect of the urban heat island on design. *Building Services Engineering Research and Technology*.
Conference Paper	Led paper	Virk G et al. (2015) Urban Heat Island analysis of Birmingham and Manchester for the creation of new Design Summer Years. In: CIBSE Technical Symposium, London, UK 16-17 April 2015, London: CIBSE.
Outputs and contributions outside of Engineering Doctorate		
Chapter Section	Led section	Zero Carbon Hub (2015) Overheating in Homes – contributed to modelling section, specifically on Urban Models
Technical Guidance	Lead author	CIBSE (2016) CIBSE Weather Files 2016 release: Technical Briefing and Testing – release notes for weather files.
Technical Guidance	Contributing author – part of development team, responsible for testing the	CIBSE (2017) CIBSE Technical Memorandum 59: Design methodology for the assessment of overheating risk in homes. *Chartered Institution of Building Services Engineers.*

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[4] Full references and author list found in Chapter 8.

	methodology and inter-model comparison	
Conference Presentation	Presenter	Virk, G (2017) Characteristics of design summer year weather files. *CIBSE Natural Ventilation Group seminar, CIBSE Build2Perform 2017, November 2017, London.*
Webinar	Presenter	Virk, G (2017) Update of design summer years and test reference years weather files – Technical overview. *CIBSE Weather Data Sets Webinar, February 2017.*
Conference Paper	Contributing author- acted as supervisor and reviewer providing industry input	Petrou, G et al. (2017) Inter-model comparison of indoor overheating risk prediction for English dwellings. In: Proceedings of the 38th AIVC Conference “Ventilating healthy Low-energy buildings”, Nottingham, UK.
Conference Paper	Contributing author- acted as supervisor and reviewer providing industry input	Petrou, G et al. (2018) What are the implications of building simulation algorithm choice on indoor overheating risk assessment? In: Proceedings of the Building Simulation And Optimization 2018, Cambridge, UK.
Journal Paper	Contributing author- acted as supervisor and reviewer providing industry input	Petrou, G et al. (2018) Can the choice of building performance simulation software significantly alter the level of predicted indoor overheating risk in London flats? *Building Services Engineering Research & Technology.*
Technical Guidance	Advisory group member	EFA (2018) BB101: Guidelines on ventilation, thermal comfort and indoor air quality in schools.
Technical Workshop	Working group member	CIBSE (2019) Climate change adaptation kick-off workshop – CIBSE Schools Design Group working group.

1.7 Novel contributions of research and outputs for CIBSE

The research within this thesis provides new knowledge and analysis of the urban climate and how it can be factored in the building performance simulation. As an engineering doctorate the work also focuses on outputs that can be used to inform the wider industry through design guidance. Novel contributions of the work in this thesis include the following:

1. Chapter 3 – analysis of UHI effect for London using modelled climate data. The analysis in this Chapter was included the UHI section update of CIBSE Guide A (2005).

2. Chapter 4 – analysis of Met Office weather station data for Birmingham and Manchester to assess if the data is suitable for the creation of new urban CIBSE DSYs weather files.

3. Chapter 5 – the work was the first study to test the new CIBSE DSY weather files for London and apply TM52 overheating analysis. This analysis provided an initial assessment of the differences between the weather files and how the differences between them can be used to assess overheating risk in London.

4. Chapter 6 – the work presents a novel method for integrating outputs from a neighbourhood scale climate model in London into building simulation. Other studies have integrated methods of using microclimate modelling outputs in building simulation, but this study was the first to apply this for a London case study.

2 Literature review

This chapter outlines and reviews the background knowledge that contextualises the work in this thesis. This chapter covers the following:

- How urban climates are formed and their physical characteristics.
- How to measure and model the urban climate.
- Drivers of the urban climate.
- How the Urban Heat Island effect varies across UK cities.
- Impact of climate change on urban climates.
- Impact of the urban climate in UK cities in terms of health, thermal comfort and energy use.
- Design strategies for the urban climate.
- Evaluation of current design guidance.

2.1 Physical characteristics of urban climate

2.1.1 Surface energy balance

Urbanisation affects the surface energy balance of a city compared to the rural environment often resulting in a warmer environment in temperate climates. Differences between urban and rural surfaces can be explained by the surface energy balance equation (Oke, 1987):

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S \qquad (1)$$

- Q^* is the net all-wave radiation and depends on incoming and outgoing shortwave and longwave radiation.
- Q_F is the anthropogenic heat flux from buildings, industry, transport and human activity.
- Q_H is the turbulent sensible heat flux.
- Q_E is the turbulent latent heat flux, which is dependent on the amount of moisture in the surface.
- ΔQ_S is the heat storage flux, the amount of heat and water stored within surfaces.

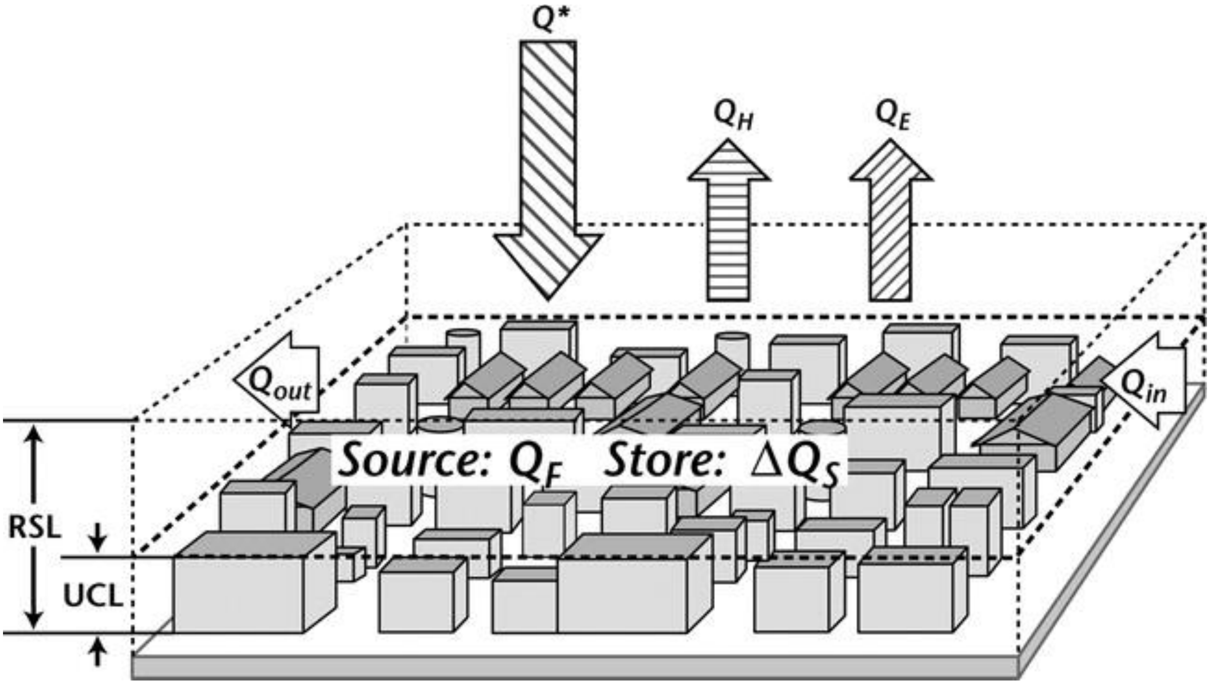

Figure 2 Urban surface energy balance, see text for abbreviations. Source: (Roberts et al., 2006) adapted from (Oke, 1988)

Urban climates differ to their rural counterparts due to the form and fabric of the buildings and streets within them. The amount of short and longwave radiation (Q^*) absorbed by surfaces is impacted by building morphology and density. Buildings and the streets increase the surface area exposed to incoming solar radiation. The materials used in urban environments also impact their climates. Materials of buildings and streets, such as tarmac, are often darker and absorb larger amounts of incoming solar radiation due to their lower albedos (the fraction of incident shortwave radiation that is reflected). The formation and density of buildings, streets and the neighbourhoods result in lower sky-view factors, which is the proportion of sky visible in a 180° field of view. The low sky-view factors of streets result in radiation entrapment. The difference in radiative balance between urban and rural areas can be relatively small: urban areas typically have a slight increase in peak values of Q^* (Oke, 1982).

Urban environments are often made up of impervious surfaces and lack vegetated surfaces. This impacts their capacity to cool through evapotranspiration, due to the reduction in latent heat flux (Q_E) away from the surface. They also impact the amount of surface runoff[5], with less storm water retention. Due to the lack of moisture and decreased evaporative cooling, there is an increased sensible heat flux (Q_H) into built fabric. Building materials, such as brick and concrete, have high heat capacities and low thermal conductivities. They store a greater amount of heat during the day and release it more slowly over a larger surface area produced by the building and street surfaces. This results in increased heat storage (ΔQ_S) within urban areas, which usually results in heat output during the night. Finally, there is an additional supply of anthropogenic heat and moisture emissions (Q_F) from buildings, industry, transport and human activity. The surface energy balance drives the urban atmosphere and the vertical structure of urban boundary layer.

2.1.2 Urban boundary layer

The difference between urban and rural surfaces impacts the surface energy balance and also the surface roughness. Surface roughness is a parameter used in urban meteorology affected by buildings, vegetation and materials that make up the urban surface, variations in these parameters affects wind speed and direction at different heights (Atkinson, 2003; Collier, 2006).

It can be defined from the relative change of average wind speed with height (Wieringa, 1992). Wind flows will be modified by the underlying local terrain. Urban areas will have higher roughness lengths compared to rural areas and will impact downwind wind flows. These differences result in the boundary layer in an urban area being different to that of a rural area.

An urban boundary layer (UBL) is created over cities due to the differences in urban and rural boundary conditions. The boundary layer is formed from the leading-edge of the city, where surface characteristics start to vary.

Table 5 Spatial scale of atmospheric processes in urban areas

Scale	Length	Locale
Micro	$10^{-2} – 10^{2}$ m	Building/Street to Neighbourhood
Local	$10^{2} – 10^{4}$ m	Neighbourhood to City
Meso	$10^{4} – 10^{5}$ m	Regional

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[5] Surface runoff is the flow of water occurring on the ground surface when excess rainwater, stormwater, meltwater can no longer sufficiently rapidly infiltrate in the soil.

The structure of the urban boundary layer can be split into vertical layers. These vertical layers are determined by the underlying surface type (Oke, 2007). The surface type and consequent boundary that is formed can be defined in terms of the spatial scales listed in Table 5. Within each of these surface scales, the atmospheric processes will vary, a schematic of the scales and vertical layers is shown in Figure 3.

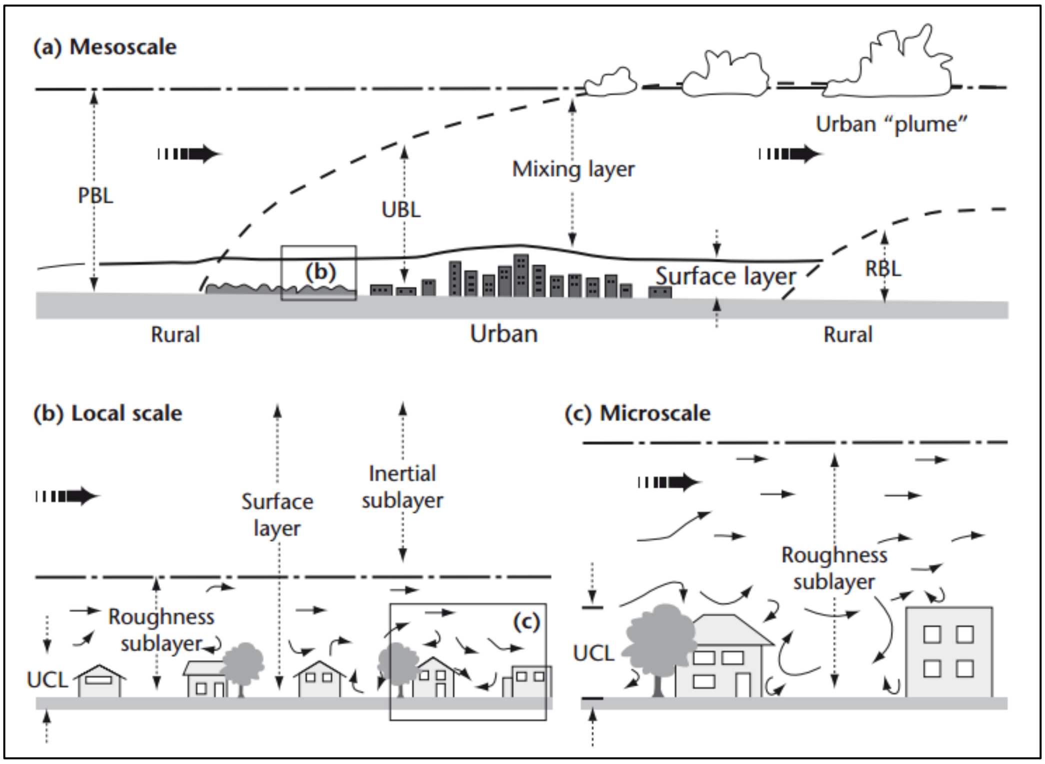

Figure 3 Schematic of climatic scales and vertical layers found in urban areas: planetary boundary layer (PBL), urban boundary layer (UBL), urban canopy layer (UCL), rural boundary layer (RBL). The bold arrow in each of the sub-figures going towards the right indicates the mean wind direction. The smaller, arrows shown in (b) and (c) indicate the nature of the mean and turbulent flow. (from (Grimmond, 2006) modified from Oke, 1997).

At the meso-scale, the increased surface roughness of the urban surface decreases wind speeds. In addition to the warming caused by urban surfaces, this causes the UBL to increase in height over the city. This results in an urban "plume" downwind of the city where above the less rough rural surface, which can reach tens of kilometres downwind. At the local scale, airflow between the inertial surface layer (ISL) and roughness sublayer (RSL) differ. In the ISL, turbulence is homogenous, and fluxes are fairly uniform. In the RSL, airflow varies according to spatial differences between locations and turbulent flow is impacted by variations in the urban surface. At the micro-scale, the urban canopy layer (UCL) is a sub-layer of the RSL which reaches up to building roof height. Atmospheric processes are influenced by buildings, streets and objects such as trees.

In summary, the urban boundary layer is a local to meso-scale phenomenon. Its characteristics are determined by the urban surface. At more local scales, the urban canopy layer is produced by micro-scale processes below roof level in street canyons resulting in local microclimates. The climate of the urban boundary layer is the net result of these microclimates, which are directly influenced by the characteristics of their local environment.

2.1.3 Urban Heat Island effect

The climate across a city will vary due to the changes in the physical characteristics of the local environment as mentioned previously, whether that is human made or natural. There is a good correlation between radial distance of a site from an urban centre and its air temperature; as the radial distance decreases the temperature rises (Oke, 1973, 1982). This is due to the density and morphology of built up urban centres contributing to urban and rural temperature differences (Oke, 1982, 1987). Overlaid upon this general trend is the effect of the local surroundings. This will cause local differences in air and surface temperatures and produce microclimates within a city, as shown in Figure 4. In London, temperatures may vary considerably (3-4°C) over relatively short distances (i.e. a kilometre) within urban areas, due to the different thermal properties of the land use types, as well as the varying morphology (Kolokotroni and Giridharan, 2008).

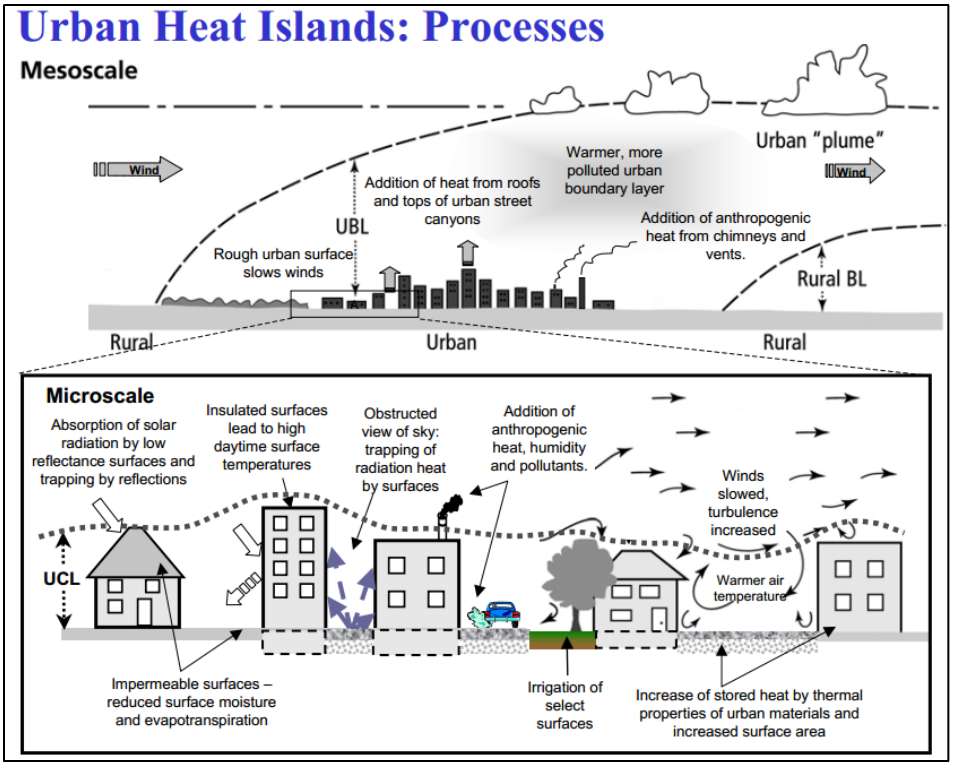

Figure 4 Physical aspects of the processes that influence the UHI (from (US EPA, 2011))

The most documented effect of urban climates is the city-scale Urban Heat Island (UHI) effect, a predominantly nocturnal phenomenon in which urban areas experience higher average air and surface temperatures than their rural surroundings (Arnfield, 2003; Oke, 1987). The difference in surface type between urban and rural surface types results in slower rates of cooling at night in urban areas (Johnson, 1985; Oke, 1982). The UHI intensity is the temperature (*T*) difference between urban and rural temperatures:

$$UHI\ Intensity = T_{urban} - T_{rural} \tag{2}$$

There are different types of UHI intensities depending on how it is measured. The surface UHI intensity is the difference in surface temperature between the city and the rural surroundings. It can be present during the day and night. The atmospheric UHI intensity is the difference in air temperature between the city and the rural surroundings. Some key features of the atmospheric UHI intensity are (Arnfield, 2003; Wilby et al., 2011):

- Decreases with increasing cloud cover – impacts rate of night time radiative cooling.
- Greatest during anticyclonic conditions – high pressure system often result in light winds and clear skies. In summer, over the British Isles this often leads to periods of fine, warm weather.
- Predominantly a summertime phenomenon – urban surfaces absorb heat and increase in temperature compared to more shaded and moist rural surfaces impacting air temperatures.
- Greatest at night – heat is absorbed and stored in urban environments and slowly released at night, elevating air temperatures, there are also lower rates of radiative cooling at night.
- City may be cooler during the day than its rural surroundings resulting in a negative intensity – instances where there is increased heat storage capacity and reduced solar radiation gain in urban surfaces compared to rural.

In temperate climates, the maximum air temperature difference is often observed soon after sunset. This is due to slow release of heat from storage from urban fabric relative to the rapid cooling of the rural area (Oke, 1982).

2.2 Climate data and design tools available to analyse the urban climate

There are a wide range of data sources and software tools that can be used to measure or model variations in the urban climate. The resources presented in this section are split by the spatial scale at which they can be applied to the urban climate. The applications and limitations of each resource are outlined. Where models are described, typical inputs and outputs are outlined.

2.2.1 City scale

To factor the city scale UHI effect into design, a number of resources are available. Air temperature based UHI analysis use weather station data, monitored data or simulated data. Continuous data sources from weather stations and models can provide detailed spatial and temporal patterns. However, there are underlying issues with each data source.

2.2.1.1 *Weather data*

2.2.1.1.1 Observed Weather data

Variables such as air temperature, humidity and wind speed have traditionally been measured from observational weather stations. In the UK, the Met Office has long term observational sites across the country. These can be accessed from the Met Office Integrated Data Archive System (MIDAS) (Met Office, 2012). The dataset comprises daily and hourly weather measurements, hourly wind parameters, maximum and minimum air temperatures, soil temperatures, sunshine duration and radiation measurements and daily, hourly and sub-hourly rain measurements, some climatology data and marine observations. Traditional Met Office sites are located in rural or semi-rural sites and they adhere to World Meteorological Organisation (WMO) standards (WMO, 2008). Using this data in the urban context has underlying issues related to the location. Figure 5 shows the distribution of Met Office weather stations that took synoptic[6] observations in May 2010, the average separation of stations in the network is approximately 40 km.

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[6] Met Office weather stations report hourly observations of weather variables known as synoptic observations.

Figure 5. Weather stations operated by the Met Office in May 2010 - UK land surface synoptic observing network
Source: (Met Office, 2010)

There are Met Office stations situated in urban areas, but any urban observational station will be impacted by the physical characteristics of the urban environment. The WMO, therefore, recommend that if an urban weather station is to represent large parts of the city, it should be located away from buildings, such as in airports and parks (Oke, 2006a). However, weather stations located in these environments have surface characteristics that are not typical of the surrounding urban areas, which can result in differences between measured variables such as wind flows. Building designers need to factor in urban climate effects through the use of urban weather stations located on buildings or in street canyons. These will be influenced by the microclimatic factors such as shading and proximity to green space and the height of the instruments. This could be useful for location specific design analysis, where microclimatic factors will influence local effects around individual streets or buildings. However, they do not represent the neighbourhood scale climate. All these issues highlight how difficult it is to obtain weather data that is reliably representative of a neighbourhood, as local characteristics vary so much in cities.

Due to the lack of Met Office data within cities and the issues with the urban stations, experimental stations can provide flexible alternative weather data. Accessible observed data exists for cities such as Birmingham and London. The HiTEMP project has set up automatic weather stations measuring temperature, precipitation, relative humidity, wind speed and direction, atmospheric pressure, and solar radiation in Birmingham (Universty of Birmingham, 2015)[7]. The London Air Quality Network has over 100 continuous monitoring sites in the majority of London's boroughs predominantly for Air Quality measurements (Kings College London, 2015) and stations have weather variables such as air temperature and wind speed. The quality of data will always be an issue with experimental stations compared to Met Office stations, which have to meet WMO standards and are regularly monitored.

To assess the performance of buildings using dynamic thermal simulation, observed weather data is synthesised into weather files. The data is used as hourly inputs for the external boundary conditions at each timestep of the model. There are different types of weather files which have been developed for different applications. A brief summary of 2 of the general approaches includes (Crawley, 1998)(U.S. Department of Energy (US-DOE), 2020)(Eames et al., 2015)(Eames, 2016):

- Typical Meteorological Year (TMY): involves creating composite years using representative months from different years.
- Actual Meteorological Years (AMY): represent hourly weather data from a single contiguous year that is not necessarily representative of a greater span of time. This approach is favoured when examining atypical or extreme years.

There are a variety of organisations that produce weather files depending on the global location required. An example of the commercial production of weather files is using the Meteonorm software (Meteotest AG, 2020). Meteonorm extrapolates hourly data from statistical data for a location. Where statistical data are not available, Meteonorm interpolates from other nearby sites. In the UK, CIBSE produces weather files for use in compliance with building regulations. As the focus of this thesis is on UK cities, the CIBSE weather files are reviewed in further detail next.

2.2.1.1.2 CIBSE Weather files for building simulation

CIBSE provide two types of hourly weather files, a Test Reference Year and a Design Summer Year (equivalent of an AMY outlined above). These are annual weather files which have the following parameters; dry bulb temperature (°C); wet bulb temperature (°C); atmospheric pressure (hPa); global solar irradiation ($W \cdot h/m^2$); diffuse solar irradiation ($W \cdot h/m^2$); cloud cover (oktas); wind speed (knots) and wind direction (Levermore and Parkinson, 2006). The Test Reference Year (TRY) is representative of 12 typical months from a 30 year dataset (1984 – 2013) and is used to assess energy consumption within buildings under typical conditions (Eames et al., 2015). It is unlikely to include extreme weather events such as heatwaves. For thermal comfort analysis such as assessing potential summertime overheating, CIBSE provides Design Summer Years (DSY). The original DSY released in 2006[8], represented the warmest observed year in the middle of the upper quartile of a

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[7] The HiTemp project aimed to set up networked weather sensors across Birmingham as an alternative to automatic weather stations used by the Met Office, to provide data at much higher spatial resolutions.

[8] Previously CIBSE had an Example Weather Year which – *sought to match the characteristics of an entire year in terms of the means and standard deviations of its monthly data to the average monthly values for many years of data* – from (Levermore and Parkinson, 2006).

30 year period, as ranked by mean temperature for the period April to September inclusive (Levermore and Parkinson, 2006).

CIBSE in collaboration with the Greater London Authority funded work to produce new DSYs to capture the UHI effect for overheating analysis in London and revise the selection methodology for the DSY (CIBSE, 2014). A new metric, the Weighted Cooling Degree Hour (WCDH) was proposed to rank warm years and is defined as (CIBSE, 2014):

$$WCDH = \sum_{all\ hours\ \Delta T > 0} \Delta T^2 \text{, } where\ \Delta T = T_{op} - T_{comf} \qquad (3)$$

where T_{comf} is the operative temperature for neutral comfort as defined in BS EN 15251 (British Standards Institution, 2007) and is related to the running mean of the outside dry-bulb temperature (Nicol et al., 2009). The WCDH is the cumulative squared difference between the predicted comfort temperature (T_{comf}) and the internal operative temperature (T_{op}) (Nicol et al., 2009). The quadratic relationship places more emphasis on more extreme departures from the comfort temperature (CIBSE, 2014).

The metric reflects the likelihood of overheating occurring when internal temperatures are higher than predicted comfort temperatures (Hugget, 2012). Initial work comparing overheating metrics showed that the WCDH predicts the level of overheating within free-running buildings better than the previous metric used to select DSYs (Hugget, 2012).

Previously DSYs for London used Heathrow weather data, which represents a semi-rural airport site. Technical Memorandum (TM) 49: Design Summer Years for London (CIBSE, 2014) outlines the methodology of selecting new sites and resulted in two new DSY summer year locations at London Weather Centre (urban) and London Gatwick (rural). Current and morphed future datasets are available for three locations for three differing years. The three DSYs available per location, represent summers with different types of hot events:

- DSY1 (1989): Moderately warm summer
- DSY2 (2003): Short, intense warm spell
- DSY3 (1976): Long, less intense warm spell

DSYs and TRYs are available for 14 locations across the United Kingdom (Belfast, Birmingham, Cardiff, Edinburgh, Glasgow, Leeds, London, Manchester, Newcastle, Norwich, Nottingham, Plymouth, Southampton and Swindon).

Future hourly weather files, based on the existing DSYs and TRYs which incorporate the UKCIP09 climate change scenarios (UKCP09, 2010), are available for the 14 sites, for three time periods (2020s (2011-2040), 2050s (2041-2070) and 2080s (2071-2100)), for the following emissions scenarios:

- 2020s – High emissions scenario – 10th, 50th, 90th percentile,
- 2050s – Medium – 10th, 50th, 90th,
- 2050s – High – 10th, 50th, 90th,
- 2080s – Low, 10th, 50th, 90th,
- 2080s – Medium – 10th, 50th, 90th,
- 2080s – High – 10th, 50th, 90th.

Current CIBSE DSY weather files for all sites other than London use observational data from Met Office stations that are normally located on the outskirts of city centres or in the rural surroundings. They will not be able to capture the difference between having a development located within the centre of city or a more rural location. There are also uncertainties with the weather stations that do have reliable data available, such as the centrally located London Weather Centre, which is influenced by microclimatic factors due to its rooftop location (CIBSE, 2014). The station is located at 25 m above street level compared to the standard 6 m height for WMO standard Met Office weather stations. As previously mentioned, it can be argued that the wind flow captured by the station does not represent street canyon conditions.

2.2.1.2 *Modelling city scale meteorology*

Observed weather data is limited to point measurements across a city and the potential limitations of the data have been outlined. Modelled data for urban areas represents an alternative source of data. The UK Met Office has two types of modelling systems in place. Climate models aim to forecast average weather conditions over a period of years due to climate change at a variety of temporal ranges in the future and operate at coarse spatial scales (Met Office, 2014, 2016). Weather forecasting models operate at finer spatial resolutions and attempt to predict meteorological conditions for the shorter temporal ranges typically from a few hours to a week.

Weather forecasting models are able to simulate the evolution of meteorological conditions over spatial scales of up to 50 – 200 km. Examples include regional meso-scale models that can be used for numerical weather prediction (NWP), such as the Met Office Unified Model (UM) (Met Office, 2014) and the Weather Research and Forecasting (WRF) Model (Skamarock and Klemp, 2008). These models can be nested or coupled to global scale models, which is how the Met Office forecasts weather for the UK (Met Office, 2016). NWP model inputs include current state of the atmosphere and inputs for land and ocean surface type. This includes features such as cloud formation, precipitation and radiative exchanges in the atmosphere and can have hydrological features. Models split the atmosphere into blocks of finite size, ranging from 20 km to 2 km across to a few hundred metres high (RMetS, 2015). For initial boundary conditions, the incoming shortwave and longwave fluxes, air temperature, specific humidity, and the wind components are set from observational data. More complex processes within these grid boxes occur at smaller scales and their effects are parameterised[9]. Idealised or averaged parameterisations include processes such as Martilli (2007) the surface energy balance (including radiation), boundary layer processes and cloud physics. Parameterisations of the urban terrain and land use allow simulation of how variations in the environment impact wind, temperature and humidity and the subsequent impact on atmospheric processes. Examples of coupled components include land-surface models, urban canopy models, chemistry models and computational fluid dynamics models (Chen et al., 2011).

To improve the accuracy of mesoscale meteorological models over urban environments, NWP prediction models can be coupled to urban energy balance schemes. Established examples include the Town Energy Balance (Masson, 2000), Building Energy Parameterisation (Martilli et al., 2002) and the Met Office Reading Urban Surface Exchange Scheme (MORUSES)(Porson et al., 2010a, 2010b). Their inputs include (Grimmond et al., 2010):

- Site parameters – morphology and material inputs,
- Atmospheric variables as boundary conditions,
- Initial thermodynamic and moisture state conditions.

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[9] Parametrisation schemes are necessary in order to properly describe the impact of these subgrid-scale mechanisms on the large-scale flow of the atmosphere. In other words, the ensemble effect of the subgrid-scale processes has to be formulated in terms of the resolved gridscale variables. Source: (ECMWF, 2016)

Many urban energy balance schemes assume 1-D bulk surfaces or 2-D single or multi-layer surfaces for building and street morphology, with varying number of input parameters for roofs, walls and roads. A review of urban energy balance schemes (Grimmond et al., 2010, 2011), found that simple schemes performed as well as more complex ones when modelling urban energy balance fluxes as defined in Equation 1. But studies have shown that multi-layer schemes improves the prediction of spatial pattern of the phenomenon such as the UHI (Chemel and Sokhi, 2012). Multi-layer models are able to estimate the urban surface energy balance, surface roughness and canopy air profiles in more detail than bulk or single layer models, but are computationally more expensive (Masson, 2006). Initial boundary conditions will use the same parameters as atmospheric NWP models, but for the atmospheric boundary layer.

Models can output a whole range of climate data at resolutions of 0.5 – 100km^2, including air temperature and wind profiles. Urban Energy Balance schemes predict the fluxes of heat, moisture and momentum due to the urban surface (Grimmond et al., 2010). This includes radiative exchanges of short and long wave radiation, sensible and latent heat fluxes, storage capacity and additional anthropogenic fluxes. Example of two urban canopy models with different levels of detail that have been coupled to the WRF model are shown in Figure 6. The BEP model can model more complex interactions compared to SLUCM (Single-layer urban canopy model).

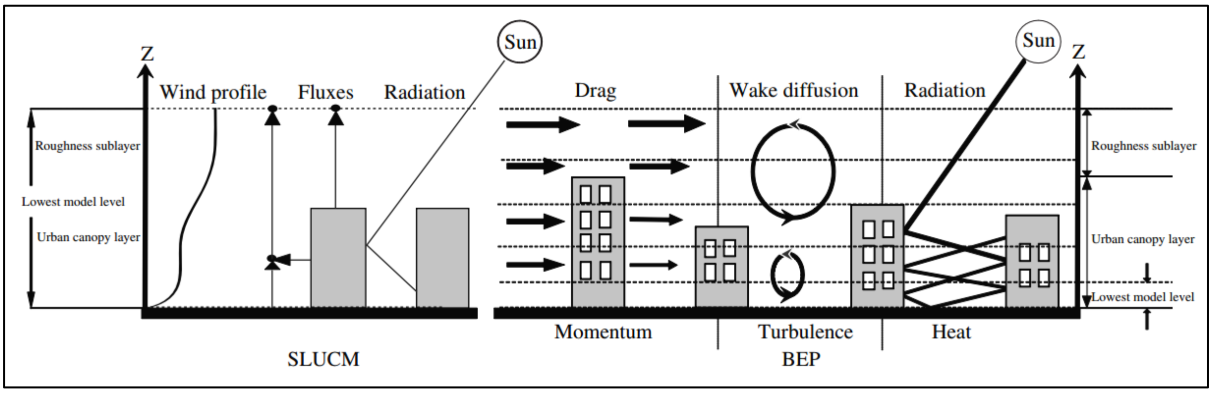

Figure 6. Schematics of two urban models that have been coupled to WRF (Chen et al., 2011), the Single-layer urban canopy model (SLUCM) (Kusaka et al., 2001) and the Building Energy Parameterisation (BEP) (Martilli et al., 2002)

Simulating urban environments using NWP models is difficult due to the heterogeneity of the urban surface. As discussed earlier, urban elements such as buildings and vegetated surfaces and the streets and neighbourhoods they form can vary at scales of less than 10m. One of the main limitations of NWP models and their urban schemes is the level of detail they are able to model aspects such as wind flow and surface temperatures (Yamada and Koike, 2011). Airflow in urban areas is complex and drag induced by buildings decreases the wind speed. Diurnal temperature variations of building and roof surfaces and the radiative exchanges between them are also not accounted for. By parameterising the wind and temperature profiles, urban energy models cannot accurately represent wind flows around buildings and streets and factors such as reflected radiation which will impact surface temperatures. Adding complexity to these urban energy balance schemes will also increase computational time. Typical NWP models have resolutions of 1km over a 100x100 grid in the horizontal and 50 grid points in the vertical. As an example, Martilli et al. (2007) estimated that to model a 10km by 10km city using a nested grid, with horizontal and vertical resolutions of 1m would take thousands of years with current computing power (Martilli, 2007).

The advantage of using modelled data is that climate data can be output at a city-wide scale on a uniform regular grid at maximum resolutions of 0.5 – 1 km^2. This is useful when analysing the city wide UHI effect as it encompasses the spatial variability of weather conditions across the city. One of the issues of stationary observational stations as reference points is how to define what an 'urban' and 'rural' sites is (Stewart, 2011). This variable spatial range allows the manner in which UHI effect varies through different transects to be analysed, rather than relying on two different observational points. This flexibility also allows specific events such as heatwaves to be modelled across a whole city and then analysed at more local scales. An example includes the WRF model being applied to West Midlands during the 2003 heatwave (Heaviside et al., 2014). The researchers used the model to estimate heat related mortality attributable to the UHI in the West Midlands during the heatwave of August 2003 (Heaviside et al., 2016).

2.2.2 Neighbourhood scale models

As discussed previously, good quality, high resolution weather data is not readily available across a city. To increase the accuracy of building simulations, more accurate microclimatic data can be used. Numerical models can be used as a powerful design tool to represent the local environment. Neighbourhood scale models are typically considered to be up to 1-2km^2 in domain size and the resolution of output data can be as fine as 0.5m. Local factors will influence energy and water exchanges and airflows between a city and the atmosphere and include the following:

- Urban morphology – street and building layout and building heights,
- Green and blue infrastructure – trees, parks and rivers,
- Types of urban surfaces and materials,
- Anthropogenic heat emissions.

Observational data from individual urban weather stations will be influenced by these local factors. Data from these stations should be analysed to see how variations in the upwind environment influence the readings.

Microclimate models will use land use variations outlined above as input data, they also require meteorological data as inputs to act as boundary conditions to initialise them. The quality of this data will have a significant influence on model outputs, which can include air temperature, humidity, horizontal and vertical wind speed, surface temperatures and heat fluxes. Urban energy balance schemes outlined previously can be used as neighbourhood scale climate models. Outlined next are two other standalone models. The differences between the two models highlight how models at this scale should be chosen depending on the type of analysis needed.

2.2.2.1 *Examples: ADMS*

The Atmospheric Dispersion Modelling System 4 Temperature and Humidity (ADMS) is a neighbourhood scale temperature and humidity model developed by Cambridge Environmental Research Consultants (CERC) as part of The LUCID Project (*The Development of a Local Urban Climate Model and its Application to the Intelligent Design of Cities*) (Mavrogianni et al., 2011) (CERC, 2010b).

The model calculates perturbations of temperature and humidity due to land use changes. The model has a domain range of 1-50km^2 and can calculate perturbations at variable resolutions. The model has been used to model the impact of land use changes to local air temperatures in the London Olympic Parkland (Hamilton et al., 2013).

ADMS is based on the meteorological pre-processing module of the standard Atmospheric Dispersion Modelling System (Carruthers et al., 1994) and the flow field and turbulence model FLOWSTAR. CERC developed the FLOWSTAR model to calculate profiles of the mean airflow and turbulence in the atmospheric boundary layer (CERC, 2013). ADMS uses hourly values of the upwind surface sensible heat flux to satisfy the surface energy balance equation, as outlined in Equation 1. The sum of the surface and latent heat fluxes is equal to the difference between the net radiation and the ground heat flux. As the local temperature depends on the sensible surface heat flux, it will be affected by local changes in the surface properties. Any changes to these surface properties will result in perturbations to the temperature and humidity profiles. Carruthers & Weng (1992) outline the theory for calculating how temperature and humidity vary with changing surface moisture, whilst the theory from Raupach et al. (1992) outlines the effect of shear stress perturbation due to changes in local surface roughness (Carruthers and Weng, 1992)(Raupach et al., 1992).

ADMS defines the upwind boundary layer profile using its estimates of the upwind heat flux terms. It then uses its estimates of the local heat flux terms to define the perturbations to the upwind boundary layer profile. ADMS estimates the heat flux terms using two methods. The upwind heat flux terms are estimated from upwind meteorological data (air temperature (°C), specific humidity (kg/kg) or relative humidity (%), wind speed (m/s) and direction (degrees) and cloud cover (oktas)) along with an estimation of the minimum Monin-Obukhov length (a parameter that represents the stability of the atmosphere and is affected by the heat production in cities) (CERC, 2010a), the height at which the meteorological data has been collected and the ratio of ground heat flux to net radiation (G/Q*). The use of G/Q* is one of the parameterisations that ADMS uses to represent the surface energy balance. The local heat flux terms are estimated by ADMS from inputs of the spatial variation of land use characteristics (albedo, surface resistance to evaporation and thermal admittance) and urban morphology (normalised building volume and surface roughness) across the domain. The normalised building volume (the total built volume within a given area, divided by that area) is calculated using the method outlined in Hamilton et al. (2008). The model does not explicitly model the geometry of buildings, rather the 3D urban morphology is represented using the normalised building volume and surface roughness.

2.2.2.2 *Examples: ENVI-met*

ENVI-met (EM) is a neighbourhood scale model which is freely accessible online, but is not open source. It is a three-dimensional non-hydrostatic model for the simulation of Surface-Plant-Air interactions inside urban environments (Bruse, 2012). An outline of the modelling modules is shown in Figure 7. It has a resolution of 0.5-10m and can scale up to neighbourhood sized grids of 2-3km^2.

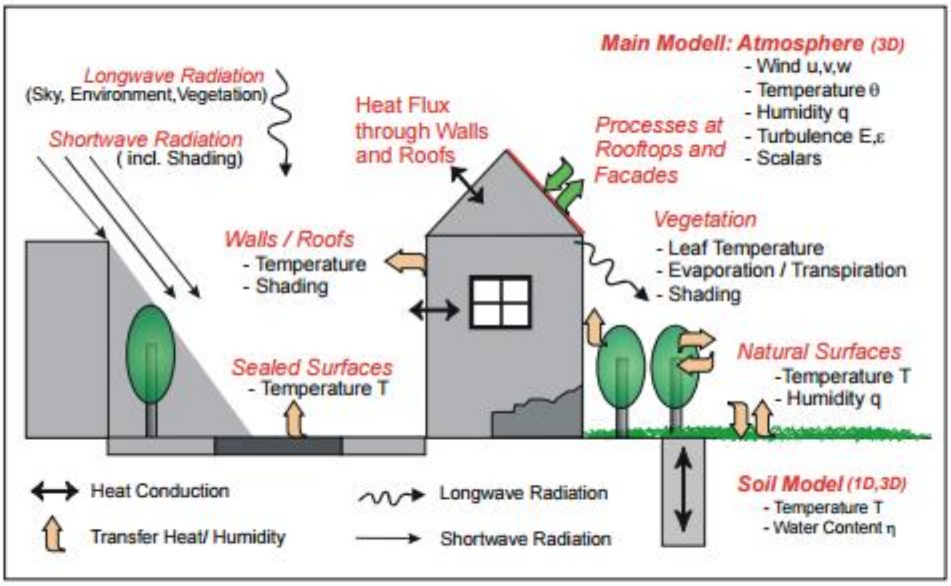

Figure 7 Overview of the different modules in ENVI-met Source: (Vankerkom et al., 2012)

Models have a typical time frame of 24-48hrs with a maximum time step of 10s. It is usually recommended that only the second day of simulations are used as the first day is used to initialise the model. For flows the 3-dimensional Navier-Stokes equations are solved with a k-ε turbulence model. Compared to CFD models, the spatial resolution is low and no boundary layer is solved at surfaces. Wall heat fluxes at building surfaces cannot be determined and correlations of convective heat transfer coefficients are used. The model can be forced by meteorological data by adjusting variables at the inflow boundaries (Huttner, 2012). Variables that can be forced in version (v) 3.1 include:

- Horizontal wind speed,
- Wind direction,
- Potential air temperature specific humidity,
- Short wave direct radiation,
- Short wave diffuse radiation,
- Incoming long wave radiation,
- Cloud cover,
- Background concentration of particles/ gases.

These variables can be forced independently from each other apart from two exceptions; cloud cover and radiation and wind speed and direction. This radiation forcing in version 3.1 results in the model having certain limitations. If shortwave radiation is forced, the cloud cover is set to zero and vice versa. For realistic simulations when forcing the shortwave radiation, values for the diffuse shortwave radiation and long wave radiation have to be forced. If no inputs for longwave radiation are forced, the model calculates the amount longwave radiation from air temperature, humidity and cloud cover. If shortwave radiation is forced and no longwave radiation inputs are forced, this will lead to inaccurate calculations, as the cloud cover is set to zero and the amount of diffuse shortwave radiation being highly dependent on the level of cloud cover (Huttner, 2012).

As EM uses CFD in its calculations, it can output results in 3-dimensions. Due to this level of detail, the model is computationally intense and hence limited to analysis over a couple of days due to calculation times. The model can calculate (Bruse, 2012):

- Shortwave and longwave radiation fluxes with respect to shading, reflection and re-radiation from building systems and the vegetation.
- Transpiration, evaporation and sensible heat flux from the vegetation into the air including full simulation of all plant physical parameters (e.g. photosynthesis rate).
- Surface and wall temperature for each grid point and wall.
- Water and heat exchange inside the soil system.
- Calculation of biometeorological parameters like Mean Radiant Temperature or Fanger's Predicted Mean Vote (PMV) – Value.
- Dispersion of inert gases and particles including sedimentation of particles at leaves and surfaces.

2.2.2.3 *Comparison of example neighbourhood scale models*

One of the major differences between the two models is that ADMS is a diagnostic model and EM is a prognostic model (Maggiotto et al., 2014). ADMS calculates boundary layer profiles using meteorological data from an upwind weather file. ADMS can therefore model longer temporal periods using weather data. EM on the other hand estimates meteorological conditions from a set of initial conditions and is limited to modelling a couple of days. The advantage of ENVI-met over

ADMS is the detail of the outputs, as EM is a 3-dimensional CFD model. ADMS is limited to outputting results in grid form at one height or at a number of fixed points of variable height.

Maggiotto et al. (2014) carried out a validation study comparing ADMS and EM to observed air temperature data for a case study in Lecce. Both models captured the diurnal cycle of air temperatures, underestimating peak day time temperatures. The authors attributed this to issues with the radiation modelling in both models. The G/Q* inputs used to parameterise the energy balance for the case study for ADMS were used from a different city (London) and underestimated Q*. EM underestimated the momentum and heat exchanges in street canyons due to surface characteristics such as albedo could have been more accurate. Both models predicted more than 80% of air temperatures within a ±1°C.

Due to the complexity of the urban climate, neighbourhood scale models that resolve radiation transfer, wind flows and vegetation interactions will always simplify the physical processes occurring using parameterisations. One major issue with the two models presented and other neighbourhood scale models is how they model the atmospheric boundary layer. This quality of the boundary conditions will rely on what upwind weather data is available or the initial conditions that are set. There are recent examples of where neighbourhood scale models have been coupled to regional climate models (De Ridder et al., 2015), improving the quality of input data.

2.2.3 Local scales

Building and street scale urban climate models operate at very detailed spatial scales. These models are able to model the airflow and radiative exchanges in street canyons and the buildings within them. Many of the more complex neighbourhood scale models will factor street canyon and building parameterisation. However, the airflow and energy balances will be simplified to reduce computational costs and increase the temporal scale of simulations. The advantage of using such detailed models is that specific scenarios can be tested, such as how a façade or building orientation will impact the immediate surrounding environment.

Microclimate models such as ENVI-met can output data to resolutions of a couple of metres. Models do exist that only simulate specific characteristics of the urban climate. A choice can be as to what the aspect of the climate needs to be factored into design. For example, radiation exchange and daylighting could be the major factors. Complex radiation models such as SOLWEIG (Lindberg et al., 2008) or Rayman (Matzarakis et al., 2007) can then be applied. If the wind environment surrounding a building is to be considered to analyse the impact on pedestrian wind comfort, then CFD models are appropriate.

Computational fluid dynamics (CFD) is a branch of fluid mechanics which employs numerical methods to solve and analyse fluid flow problems. CFD has been widely used in engineering, in urban physics CFD has been largely used to study microscale meteorological phenomena. It is possible to directly simulate specific items, such as; thermals, building wakes and large-scale turbulence, while part of the turbulence is parameterised depending on the approach.

Studies have simulated heat and mass exchanges on individual buildings and surfaces, at resolutions of 0.1 – 100m^2, with domain sizes typically ranging from 0.1 to 5km. The advantages of CFD models in urban modelling are their flexibility and detail including (Moonen et al., 2012):

- No restrictions on input geometry,
- Spatial flow-fields resolutions can be varied – areas of interest can have increased resolution by using a denser grid,
- Fluid flow, heat, moisture and pollutants can be solved simultaneously,

- Due to the high spatial resolution – heat and mass flows from urban surfaces and flow rates through building openings can be resolved.

Typical examples of how CFD can be used are for simulating flow in and around buildings, including pedestrian comfort analysis and assessment of external pollution concentrations. Using CFD models, Tsichritzis and Nikolopoulou (2019) modelled 24 case studies in London to investigate how ground level wind speed ratio[10], building height and façade area ratio[11] affected pedestrian wind comfort. The wind speed ratio and resultant pedestrian comfort were most influenced by FAR compared to average and maximum building height. The study found that uncomfortable wind conditions are more related to local morphology, such as tall buildings than ground level wind speed ratio.

Convective heat transfer coefficients (CHTC) in street canyons are impacted by the geometry of the building, the surrounding buildings and buoyancy within the canyons can impact the convective heat transfer (Allegrini et al., 2012a). For example, when wind speeds are low, the convective heat flow at building facades becomes mainly driven by buoyancy (Allegrini et al., 2012a), CFD can be used to derive more accurate CHTCs and improve the accuracy of simulations. Detailed analysis of how CFD can predict the general flow structures and the influence of buoyancy have shown that the flow within street canyons is strongly dependent on the flow at the top of the canyon (Allegrini et al., 2014).

CFD can be coupled to other models at larger and smaller scales. There are increasing number of examples of CFD being applied at the climatic meso and micro scales (Toparlar et al., 2017), including simulations of whole regions of a Tokyo (Ashie and Kono, 2011). CFD models can be coupled to NWP models, either by providing detailed sub-grid inputs into them or by using their outputs from the NWP as input boundary conditions (Schlünzen et al., 2011). At the opposite end, CFD models can be used to provide boundary conditions to building simulation models by providing pressure coefficients and heat and mass transfer coefficients. A coupled approach of a radiation model, CFD and a Building Energy Simulation model has been employed to look at energy performance of buildings with the microclimate by Allegrini et al. (2012b). The study considered both the effects of airflow around and radiation exchange between buildings.

Of all the resources discussed, one of the most useful to incorporate into the design process would be CFD. As computing power increases, there is greater potential of applying CFD to simulating climates without sacrificing on issues such as grid size. For building designers, it represents one of the most detailed and robust methods of simulation which can operate across a range of spatial scales due to the ability to vary resolutions across the input grid. One of the issues with CFD models being used to model the microclimate is validation. A review of 183 studies, found that 105 of the studies were conducted without validation, as many studies lack relevant quality measured data to validate against (Toparlar et al., 2017). As with any model, CFD studies should be properly validated to ensure reliable results using best practice guidelines (Blocken, 2015).

2.2.4 Summary

The main aim of using the resources outlined in this section is to improve the quality of analysis used in building design. The data and models available allow a designer to factor the urban climate into design. When carrying out energy use or overheating analysis, the industry standard for non-

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[10] Wind speed ratio is defined as the ratio of wind velocity at pedestrian level height to the wind velocity at the reference location, where it is not affected by buildings.

[11] Façade area ratio is total area of buildings' vertical surfaces facing the approaching wind direction divided by the total plan area.

domestic buildings is to use dynamic thermal simulation with CIBSE weather files as inputs. Overheating analysis in cities such as London now require the use of CIBSE weather files in building simulation (GLA, 2018b). The development of multiple locations for DSY files in London reliably capture the UHI effect in London. However, as has been discussed in this section there are many physical effects which these weather files do not capture. Site specific characteristics will create microclimates which could potentially impact the amount of solar radiation a building receives and the wind speed and direction.

The urban climate is complex because of these variations across a city. The reason there are no “off-the-shelf” climate models available are due to these complexities and the contextual nature of the climate. The urban climate will be impacted by the larger scale weather processes occurring that will determine temperature and wind flows across cities and then more localised physical processes in neighbourhoods and streets. Due to these complexities, the tools have spatial and temporal limitations. The more detailed a model, the higher the resolution of output data, the longer the computational time. Larger scale models sacrifice this detail by parameterising the smaller scale processes. Table 6 summarises the design tools outlined in this section.

Table 6 Summary of resources outlined, scales defined in Table 5.

Resource Type	**Spatial Scale of model or data**	**Temporal Scale of model or data**	**Resolution of data outputs**	**Output Parameters available of model or data**
CIBSE Weather files for simulation[1]	City to Local	Hourly data	Point measurements	*Dry and wet bulb temperatures, Solar radiation, Wind speed and direction*
Observed Weather data[2]	City or Local	Hourly data	Point measurements, at city scale can represent area distribution but at coarser spatial scale	Measurements vary depending on type of station, variables include: *Dry and wet bulb temperatures, Solar radiation, Wind speed and direction and Precipitation*
Numerical Weather Prediction[3]	City to Neighbourhood	Hourly data, often limited to seasonal periods	1-2km^2	Vertical and horizontal climate variables, including: *Temperature and Wind fields, Radiative exchanges and Heat fluxes*
Microclimate models[4]	Neighbourhood to local	<1 year	1 – 100m^2	Vertical and horizontal climate variables, including: *Temperature and Wind fields, Radiative exchanges and Heat fluxes*
CFD[5]	Neighbourhood to Local[7]	<2 weeks	0.1 – 100m^2	*Temperature and Wind fields*
Specialised models[6]	Neighbourhood to Local	Variable	Variable	*Radiative exchange, vegetation modelling etc.*

Examples:

1) Design Summer Year, Test Reference Year (Eames, 2015, 2016)
2) Weather station data from Met Office (2012)
3) WRF model (Chen et al., 2011)
4) Energy balance models e.g. TEB model (Masson, 2000), ENVI-met (Bruse, 2012), ADMS (Cerc, 2010b) (Carruther et al., 1994)
5) OpenFOAM (ESI, 2018)
6) RayMan (Matzarakis et al., 2009)
7) As the literature review has outlined, there are CFD models which have been applied to the city-scale, but these require massive computing power and are limited to in application due to accessibility.

2.3 Drivers of the urban climate in large UK cities

This section highlights in more detail some key drivers of the urban climate, concentrating on large UK cities. These variations will vary depending on the spatial and temporal scale considered. At the city scale, the variations in land use, type and location will impact how the UHI varies diurnally and spatially. At more local scales, the existence of green and blue infrastructure and variations in street and building density and layout will form microclimates. Evidence of how future climate scenarios impact the UHI are also presented.

Urban climate studies in the UK concentrate on the largest cities – the following sections are largely based on evidence from London, Birmingham and Manchester, but include reviews of studies from other cities such as Sheffield where available. These cities are the most populous and form the largest metropolitan areas (ONS, 2016).

2.3.1 Urban land use

Using NWP models, studies have shown that there is a correlation between urban land use fraction[12] and the UHI intensity. This can result in spatial and temporal variations in air temperatures. In London, simulated results from the Met Office Unified Model show that the UHI strength increases linearly at 0.5 K per 10% increase in urban land use fraction (Bohnenstengel et al., 2011). For larger distances downwind of the city[13], the UHI effect increases and higher values occur per percentage of urban land use fraction. As air is advected across London, it warms, and causes air temperature in downwind areas to increase. The core in the City of London, has the largest urban fraction and urban surface area develops its own UHI. With an easterly wind, the upwind side of London is slightly cooler than the downwind side and the UHI centre is situated downwind of the City. This asymmetry shows how upwind cool rural air is warmed by the city.

The geographical location of cities has an influence on the development of the UHI. In London, modelling the impact of Easterly sea breeze fronts using a WRF model shows that cool North Sea air reduce the UHI intensity upwind and displaces the UHI centre 5 – 10km to the west (Chemel and Sokhi, 2012). The thermal centre gradually shifts back to the City of London as the cooling effect is diminished. Urbanisation of London has been shown to reduce wind speeds, increase nocturnal temperatures and reduce the diurnal temperature range (Grawe et al., 2013). Large areas of cities can have homogenous characteristics such as surface roughness lengths, but in reality the surface is heterogeneous when examined at smaller scales. The reduction in wind speed observed during day and night and is due to the higher roughness of the urban landscape compared to the rural one, which enhance turbulence (Grawe et al., 2013).

In Birmingham, the use of a WRF model has shown how the UHI effect is also impacted by horizontal advection, affecting downwind air temperatures (Heaviside et al., 2014). Mean wind speeds can be reduced by 2 m/s for an urban location compared to a rural one. Downwind of the city centre, air temperatures can be 2.5 K warmer than they are upwind.

2.3.2 Anthropogenic heat emissions

Anthropogenic heat and moisture emissions are produced by energy consumption of buildings, transport and human metabolism, varying spatially and temporally across a city. Spatially, residential areas will have a more homogenous distribution of fluxes compared to more built up industrial areas. Temporally, in a temperate climate such as the UK, space heat demands will see building

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[12] The proportion of land within the modelled grid box that is urban and human made – contains buildings, roads, industry etc.

[13] Can be described as larger urban fetches – the distance upwind to the edge where the transition to a distinctly different surface type occurs (Oke, 2006b).

related heat fluxes peak in the winter and occupancy patterns will impact the diurnal distribution. An analysis of future demand for air conditioning in London has shown that the amount of energy in the form of waste heat vented may increase by 227% by 2030 (GLA, 2016c). This increase will contribute to increasing both the intensity of the overall UHI and the area where temperatures are highest.

Using estimated emissions from buildings, road traffic and human metabolism, the total average anthropogenic heat flux for Greater London was modelled to be 10.9 W/m^2 for the years 2005 – 2008 (Iamarino et al., 2012). Buildings contributed 80%, transport 15% and metabolism 5%. The heat fluxes are unevenly distributed spatially and temporally. Within the City of London borough, average heat fluxes reach 140 W/m^2 and peak at 210 W/m^2. Temporally, heat fluxes are higher in winter due to higher space heating demands in the winter. Peak winter emissions within the city can reach up to 550 W/m^2. Emissions in industrial areas peak in the late morning (11:00 – 12:00), whilst in residential areas they peak in the evening (18:00 – 19:00). Transport emissions peak during weekday rush hour periods.

During a winter period in London (December 2009), in the centre of the city, the maximum modelled anthropogenic heat emissions exceeded 400 W/m^2 in small areas, whilst at the fringes values reduced to around 60 W/m^2 (Bohnenstengel et al., 2013). These values were derived from energy-demand data for London and input into the Met Office Unified Model (Bohnenstengel et al., 2013). In late spring (May 2008), the central peak values are similar, with reduced flux at the fringes. The anthropogenic emissions altered the storage of heat, the outgoing long wave radiation and the sensible heat flux leading to an increase of winter air temperatures by up to 1.5 °C on a cloud-free day in the inner 10 km × 10 km (Bohnenstengel et al., 2013).

Across Greater Manchester, the mean heat emission has been found to be 6.12 W/m^2, with values reaching 23 W/m^2 in city centre areas and then reducing to 10 W/m^2 for non-central urbanised areas (S^{m}ith et al., 2009)[14]. The authors used a similar methodology to Iamarino et al. (2012).

The evidence from the literature shows that denser, larger cities in the UK have greater anthropogenic heat emissions.

2.3.3 Green infrastructure and vegetation

Green infrastructure in cities includes parks, gardens, street trees and green surfaces such as roofs and walls (DE Bowler et al., 2010; Kleerekoper et al., 2012). Bowler et al. (2010) carried out a systematic review of the empirical evidence of how urban green infrastructure impacts the urban environment. The review found that vegetation in the form of green spaces in urban environments tends to be cooler than the surrounding environment due to a number of reasons. Incoming solar radiation will be converted to latent heat by evapotranspiration, rather than being absorbed by building fabric. There is also a reduced surface area, increased reflectance and increased shading from trees, resulting in less absorption and storage. Due to the high sky view factors of parks, there is increased heat loss through advective cooling and longwave radiation at night. Air that is advected over this cooler surface can then be cooled. Park ‘cool islands’ are produced by the cooling effect of green spaces in cities (Spronken-Smith and Oke, 1998). Street trees can provide direct solar shading and reduce air temperatures beneath their canopies. There has been some evidence to show that certain tree species can emit Volatile Organic Compounds (VOCs) that can contribute to Ozone (O_3) production (D Bowler et al., 2010). There is evidence of short-term O_3 exposure impacting

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[14] This work was the output of the Sustainable Cities: Options for Responding to Climate cHange Impacts and Outcomes (SCORCHIO) project (SCORCHIO Project, 2010). The aim of the project was to develop tools that use the latest forecasts from UKCIP to help planners, designers, engineers and users to adapt urban areas, with a particular emphasis on heat and human comfort.

respiratory and cardiovascular systems and the increasing evidence of how it could impact long-term human health (Nuvolone et al., 2018).

The cooling effect of green spaces will be determined by the size of the space, wind speeds, the direct of prevailing wind and the orientation and configuration of the green space and the surrounding urban environment (DE Bowler et al., 2010; Chen and Wong, 2006; Doick et al., 2014; Shashua-Bar and Hoffman, 2000). During low wind speed conditions, as street temperatures increase and warm air rises, cool air from green spaces can be drawn into street canyons (Chen and Wong, 2006; Doick et al., 2014; Upmanis et al., 1998). In certain conditions, measured air temperature variations of almost 8°C have been found between parks and their surroundings (Oke, 1987).

Large green spaces can have large cooling distances up a couple of kilometres (Rovers et al., 2014). In London, measurements of summer air temperature have shown that a green space such as Hyde Park can influence the air temperatures of an adjacent street (Doick et al., 2014). The night-time cooling extent of the park ranges from 20m to 440m. In the summer, the mean temperature reduction at these distances was 1.1°C and the maximum reduction was 4°C. The cooling distance increased with increasing air temperatures and was correlated to wind speed and the amount of preceding radiation. Conditions when the UHI effect is greatest and when the cooling impact is most needed, clear sky days, with low wind speeds resulted in the furthest cooling extent. Comparing the UHI intensity at the St James Park Met Office weather station to that of the adjacent street, the intensity within the park is 45% lower than that in the street (Doick et al., 2014). This shows how using weather data which is located within a park can underestimate the UHI effect. Vegetation can directly impact human comfort through shadowing across London during summer conditions (Lindberg and Grimmond, 2011). Using the urban radiation model SOLWEIG has shown that the mean radiant temperature in urban environments can be reduced by an average of 3.1K in summer (Lindberg and Grimmond, 2011). This figure will increase with increased plan area vegetation density[15].

In Manchester, models have shown that increasing the green proportion of existing urban spaces by 10% can reduce surface temperatures by up to 2.5 K under future climate scenarios (Gill et al., 2007). Modelling of green infrastructure has been shown to impact surface and air temperatures in suburban Manchester using ENVI-met (Skelhorn et al., 2014). When vegetation in the form of trees and grass were replaced by asphalt average air temperatures rose by 2.4°C. Adding 5% extra greenspace resulted in no change in average air temperatures over the entire study area. There was also no significant correlation between tree canopy cover and the UHI intensity. Trees did reduce surface temperatures; an addition of 5% of mature trees reduced surface temperatures by 1°C. The research indicates that there is a 2.0 °C decrease in surface temperature for a 10% increase in mature trees. These results were produced using a calibrated ENVI-met model.

2.3.4 Blue infrastructure

Blue infrastructure in the form of urban water bodies such nearby oceans, lakes, rivers and small ponds can provide a cooling effects to the urban environments (Coffel et al., 2018). The air over a bodies of water can be 2 to 6°C cooler than over the surrounding urban landscape (Manteghi et al., 2015). However, when the air temperature drops below the water temperature, bodies of water can contribute to the UHI effect (Attema et al., 2015). The London Plan emphasises the need to increase the connectivity between green spaces and urban waters over the long term (GLA, 2018b). Research

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[15] Urban plan density area is the ratio of the built area projected onto the ground surface divided by the total land area under consideration.

has shown that managing the urban water balance is a key potential strategy to mitigate excessive urban heating (Henderson-Sellers et al., 2012)

Observations of wind flow over the River Thames in Central London have shown how it can impact speed and direction of wind (Wood et al., 2013). Wind speed was greatest when the direction was parallel to flow and the river channelled flow along it. The diurnal variation in wind flow was strongly affected by convection developing over the surrounding built up area. In Sheffield, measurements have shown that rivers can cool surrounding air temperatures (Hathway and Sharples, 2012). Cooling was greatest when ambient air temperatures were highest. However, the level of cooling was influenced by local built form, with higher levels of vegetation on the riverbanks resulting in greater amount of cooling. The daytime cooling effect was also greatest during the morning, but this could have been a result of low sun angles. Air inlets that were designed to be close to rivers to improve night cooling would see no additional benefit. For consecutive hot days in May, there was 2°C daytime cooling over the river and 1.5°C on the riverbank. As the water temperature increased in the summer, the cooling effect decreased. Microclimate factors such as type of riverbank, solar radiation and shading and wind speed impact the cooling effect. For open streets and squares, the cooling effect was greater 30m away from the bank compared to streets shut off from the river.

There has been evidence to show that for idealised urban areas, the cooling effect of lakes is dependent on how large they are, their distribution across a city, the distance from the lake and water temperature (Theeuwes et al., 2013). The water temperature is a crucial aspect of the cooling influence. A cool body of water will cool the surroundings, but can warm nocturnal temperatures and increase humidity. At the end of summer season, when lakes reach their highest temperatures, this will have a negative impact on summertime nocturnal thermal comfort. The influence of large bodies of water is an area that needs further investigation.

2.3.5 Local effects in street canyons

At more local scales, variations in urban morphology such as building density and height influence air and surface temperatures and wind flows resulting in microclimates. The layout and orientation of streets produce variations in neighbourhoods for spatial scales of up to 1-2km^2.

Urban microclimates will be influenced by a number of factors. In street canyons, the air and surface temperatures will be affected by radiative exchange between buildings and the wind flows (Allegrini et al., 2012b). The radiative exchange between the urban surfaces will be the sum of the short and long wave radiation and the multiple reflections they undergo. There is also less heat lost through longwave radiative cooling contributing to higher surface temperatures. The aspect ratio[16] of the street canyon will impact temperatures; narrow canyons will provide solar shelter but block longwave radiative cooling to the sky as shown in Figure 8.

There is evidence that tall buildings will absorb incoming solar radiation through multiple reflections, from using an Urban Canopy Model[17] (Marciotto et al., 2010) and a WRF model with a street canyon parameterisation (Theeuwes et al., 2014). The orientation of street canyons impacts solar exposure, the amount of trapped radiation and wind flows. Varying the albedo or greening street canyon surfaces additionally impact radiative exchange and wind flows. High albedo surfaces not only reduce surface temperatures, but also increase the reflection of radiation. The type of surface this radiation is reflected to will determine how effective albedo changes are. The surfaces receiving the

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[16] Street canyon aspect ratio is defined as the ratio of the canyon height (H) to canyon width (W), H/W.

[17] Models that parameterise urban areas, which are often coupled to meso-scale models such as WRF

radiation could absorb it and then increase street canyon temperatures. Finally, the UHI effect will vary air temperatures depending on the surrounding area and city-wide wind flows.

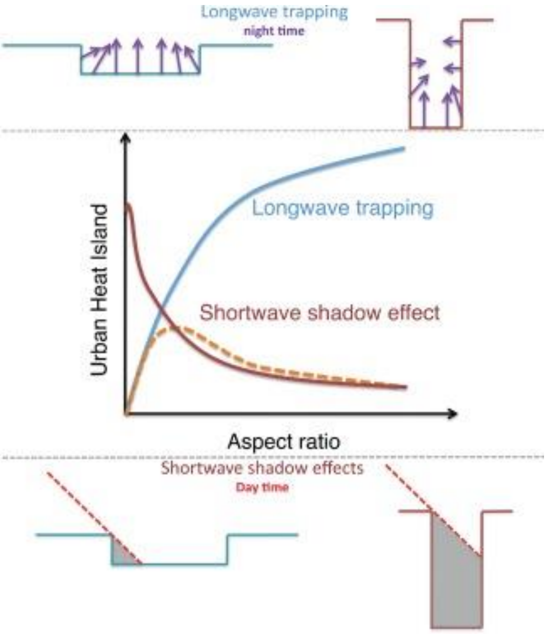

Figure 8 Effect of street canyon Source: (Theeuwes et al., 2014)

Green and low albedo "cool"[18] roofs can impact building performance through two mechanisms. Firstly, they change the heat flow through the roof. Green roofs cool the local environment by increasing the latent heat flux due to evapotranspiration from their vegetated surfaces (Kleerekoper et al., 2012). They also reduce the sensible heat flux at the roof surface, although a greater amount of net radiation is absorbed compared to cool roofs due to green roofs' added thermal mass (Takebayashi and Moriyama, 2007). Cool roofs reduce the sensible heat flux due to their higher albedo, which reduces amount of net radiation absorbed by surface. See Figure 9 for a simple schematic of some of these processes. The performance of green and cool roofs is affected by a variety of physical and environmental parameters. The type of climate particularly impacts their relative effectiveness (Santamouris, 2012). Cool roofs perform better in hotter, lower latitude climates, where solar intensity and gains are highest. Green roofs perform better in more temperate climates as their cooling ability is reliant on the level of irrigation (Ray and Glicksman, 2010).

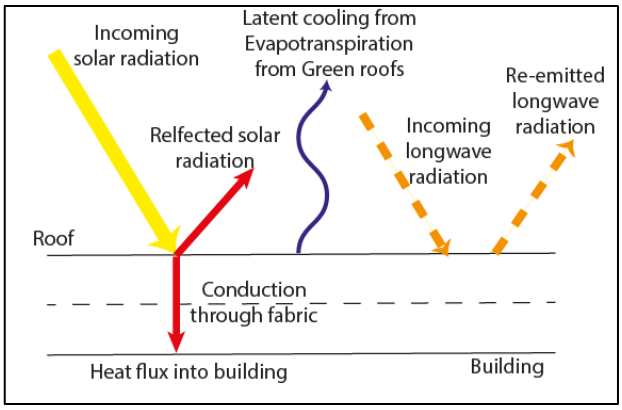

Figure 9 Examples of heat transfer in roof system. Source: (Virk et al., 2014a)

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[18] This thesis refers to low-albedo surfaces as cool roofs or walls.

In Central London, detailed measurement work has shown how air and surface temperature, wind flows and solar radiation in street canyons vary in a low and middle rise neighbourhood (Shahrestani et al., 2015). The high-rise buildings block incoming solar radiation during the day, but also reduce measured wind speeds. The orientation and sky view factors of street canyons determined the intensiveness of incoming solar radiation. Wind speeds were greatest when streets canyons were orientated parallel to wind direction. Microclimate differences between the streets included tree-lined streets being the coolest and the sky view factor impacting diurnal differences between streets. Low sky-view factor streets were coolest during the morning and warmest at night.

Sky view factor (SVF) has been shown to be directly correlated to density in cities such as London and Paris (Chatzipoulka et al., 2018). The differences between the two cities impact the relationship of SVF to urban form. Paris is a planned European city with urban areas and form with high degrees of order, compactness and uniformity. London's urban area and form has a high degree of heterogeneity (Chatzipoulka et al., 2016). Built form density in London increases vertically and horizontally. In Paris, density increases are predominantly horizontal. The result of these differences is that increases in density in Paris result in lower SVF compared to those in London with similar density (Chatzipoulka et al., 2018). The SVF is influenced by the amount of the open space surrounding buildings (Chatzipoulka et al., 2016).

Measured data in Manchester has shown how the aspect ratio of street canyons determines how large the UHI effect is (Levermore and Cheung, 2012). The maximum UHI effect rapidly increases for low canyon aspect ratios. However, the influence of the surrounding urban environment still contributes to the UHI effect even when the canyon disappears as sky view factors tend towards 1. The contribution of the street canyon effect to the UHI effect is less the overall contribution of the urban sprawl (Levermore and Cheung, 2012).

2.4 Urban Heat Islands in UK cities

This section outlines how the UHI varies in some of the largest UK cities. Both air and surface UHI intensities are presented for some cities. The source data presented varies with each city, some use observed data, others modelled and remotely sensed data. The focus of the thesis is on UK cities and as has been outlined previously in Section 1, Section 2.1 and Section 2.3 – the UHI effect is most prevalent in the largest cities and the negative impacts of urban warming are also most likely in the largest cities.

2.4.1 London

London's UHI was first observed by Howard (1833) and then more extensive measurements were carried out by Chandler (1965) using Stephenson screens. Chandler's (1965) measurements recorded a 1.6 K UHI intensity for central London. More recent extensive observed data exist for the years 1999 and 2000, which used a large array of stations measuring hourly data at a slightly higher level of 6 m (Graves et al., 2001; Watkins, 2002). Modelled data from the Met Office Unified Model also exists for the summer of 2006 (Bohnenstengel et al., 2011; Porson et al., 2010a; Porson et al., 2010b), with screen level temperatures available at 1.5 m, at a resolution of 1 km^2 over a 100 km × 100 km grid.

The average UHI intensity for mean summer (June to August) air temperatures were found to be 2.5 K for observed data (Watkins et al., 2002). The thermal centre of the urban heat island was found to be in the City of London, but also shifted with wind direction by several kilometres (Graves et al., 2001). During the heatwave of August 2003, the UHI intensity reached highs of 9 K during the night (GLA, 2006). The summer heat island intensity reaches a maximum of 8 K for the observed data (Watkins, 2002) and 9.5 K for the modelled data (Bohnenstengel et al., 2011).

2.4.2 Birmingham

The first documented UHI in Birmingham compared the nocturnal air temperatures at Edgbaston (urban site) and Elmdon (rural site) for the period 1965 – 74 (Unwin, 1980). The peak nocturnal UHI intensity observed was 1.34 K (Unwin, 1980). This was followed by work that used a 20 km thermographic transect across Birmingham to measure the UHI intensity, measuring a maximum of 4.5 K (Johnson, 1985). Both measurements found that the UHI intensity was most pronounced during anticyclonic conditions (Johnson, 1985; Unwin, 1980), which produce clear skies, low wind speeds and dry weather such as those experienced in heatwaves (Wilby et al. 2011). More recently, remotely sensed MODIS (Moderate Resolution Imaging Spectroradiometer) Land Surface Temperature satellite data has been used to calculate Birmingham's UHI effect (Tomlinson et al., 2012). The analysis sampled data from June to August from 2003 to 2009 and sorted the data according to atmospheric stability. The highest UHI intensities reached up to 5 K during the most stable atmospheric conditions and up to 7 K in a heatwave period in July 2006. Modelled data for the summer 2003 heatwave period for Birmingham found an average UHI intensity of 3 K and a maximum of 7 K (Heaviside et al., 2014).

2.4.3 Manchester

In Manchester, the UHI intensity has been calculated using observed air temperatures in Greater Manchester for 2010 (Cheung, 2011; Levermore and Cheung, 2012). The urban observations were from Piccadilly Gardens located in central Manchester, whilst the rural observations were from a Met Office Station in Woodford. The maximum UHI intensity reached up to 8K in summer, usually occurring at night. Intensities greater than 8K can occur during winter nights, but these are very rare. High intensities, of greater than 6K, are more frequent during summer nights. The mean summer UHI intensity was 2-3 K. Thermal transects were used to measure the air and surface temperatures in Manchester for the summers of 2007 and 2008 (Smith et al., 2011). The maximum nocturnal UHI intensity was observed to be 5K and the surface temperatures exceeded 10 K in some instances.

An UHI analysis of Manchester Met Office weather data compared Manchester Hulme to Manchester Ringway for 1996-2011 (Levermore et al., 2015). The UHI intensity was found to increase with lower wind speeds and low cloud cover and has been steadily increasing over the 15-year period analysed at a rate of 0.024°C per annum. In a century the increase would therefore be around 2.5°C, which is similar to the lowest estimates of climate change (UKCP09, 2010). Other work has shown how low sky view factors result in the lowest UHI intensities (Levermore and Cheung, 2012)

2.4.4 Glasgow

The UHI in Glasgow has been derived from analysis of historic weather data (Emmanuel and Krüger, 2012). The average summer nocturnal UHI intensity was 1.4°C. It should be noted that the urban weather station at Glasgow City Airport is located away from the city centre. The temperature differences between weather station sites was defined by Local Climate Zones (LCZ)[19] (Stewart and Oke, 2012) for 2010. Local differences between sites have more of an impact on air temperatures than distance from the city centre:

- Urban warming occurred in the more built up areas,
- The diurnal range of the urbanised location was smaller than the rural location,
- Land cover characteristic defined by LCZ appeared to have an influence on local climate.

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[19] The LCZ system comprises 17 zone types at the local scale (102 to 104 m). Each type is unique in its combination of surface structure, cover, and human activity.

2.4.5 Impact of climate change on the UHI

Due to increasing urbanisation and projected climate change scenarios such as those presented by the current UK Climate Projections (UKCP09) (UKCP09, 2010), urban warming and its potential adverse implications will be exacerbated. UKCP09 projections suggest that by the 2050s, London's summers will be 1.1 – 5.2°C warmer under medium emissions scenario (UKCP09, 2010). However, there is no strong evidence that UHI intensities will increase for cities such as London. As outlined in Section 2.3.2, this could be impacted by added waste heat resulting from increased uptake and use of air conditioning systems (GLA, 2016c).

Technical Memorandum 49 analysed how the UHI effect in London varied over a 50 year period using Met Office observational data London Gatwick (rural) and London Weather Centre (urban) (CIBSE, 2014). The analysis from TM49 found that there was a slight correlation between the occurrences of high peak UHI intensities being more frequent during a warm spell (defined by Weighted Cooling Degree Hour). However, there is a much weaker correlation between average UHI intensities occurring during warm spells such as heatwaves. This is in agreement with other analysis of Met Office data (Wilby et al., 2011).

Land Surface Temperatures taken over a decade (1996 to 2006) were used to analyse the temporal differences in the daytime UHI effect (Holderness et al., 2012). Monthly averages of the UHI intensity derived from images were able to differentiate between heatwave events in London. Individual images were not able to represent typical or extreme climatic conditions or trends due to local and diurnal effects and the daytime UHI intensity did not differ significantly between the years analysed.

There has been some evidence predicting that warmer projected climates will also see an increase in the UHI intensity due to the increasing frequency of heatwave events. Climate projections Chicago and Paris show that the frequency and intensity of heat waves will increase in the future (Meehl and Tebaldi, 2004) and are likely to be exacerbated by the UHI effect. If there is an increase in the number of anticyclonic events in London which can result in heatwave periods, this could lead to more intense UHIs (Wilby et al., 2011). The projected annual average temperature increase for London that would be attributed to the UHI is around 2°C under the UKCIP02 Medium – Low Emissions scenarios (UKCP02, 2002) (Wilby, 2003).

Future climate models have shown that for a doubling of atmospheric CO_2, there is a modelled increase of 0.9 K in night time temperatures in urban areas in London due to climate change (McCarthy et al., 2010). The same model showed an increase of 0.6 K for additional 60 W/m^2 of anthropogenic heat emissions. Other modelled estimates predict the UHI in London to change by 0.1 K or less by the 2050s, having minimal impact on the climate projections (McCarthy et al., 2012). Projected climate change will result in a greater increase of hot nights for cities compared to their rural areas.

2.5 Impacts on building performance

The section outlines how urban climates impact building performance, in terms of the comfort and health of the occupants and the building energy use.

2.5.1 Impact on comfort and health

UHIs will tend to reduce exposure to winter cold but increase exposure to summer heat. Summertime overheating due to increasingly warmer climates is seen as a global threat to health and wellbeing (Patz et al., 2005), the UHI effect will only exacerbate any future heat stress. The impact of ambient temperatures on health and comfort varies across the globe due to how well the population is habituated to the conditions and the appropriateness of the housing stock (WHO, 2009).

The 2003 UK heat wave resulted in an increase of 17% of heat-related deaths in Southern England, resulting in 2139 excess deaths in England and Wales with the highest incidence of excess deaths occurring in London where deaths in those over the age of 75 increased by 59% (Kovats et al., 2006) (Johnson et al., 2005). When maximum daily temperatures (rather than average daily temperatures) rise above a threshold, mortality rates increased sharply. In London, that threshold was found to be 24.7°C (Armstrong et al., 2010), Table 7 shows the regional variations. It should be noted that the values were calculated by considering regional climate variations; the impact of London's climate was calculated separately to the South East of the UK.

Table 7 Distribution of summer daily maximum temperature and deaths attributable to heat per region, adapted from (Armstrong et al., 2010)

		Deaths attributable to heat	
Region	**Threshold temperature**	**%**	**No**
North East	20.9	0.3	398
North West	21.7	0.6	2067
Yorkshire & Humberside	22.2	0.8	1820
Wales	21.6	0.8	1191
West Midlands	23	1.1	2587
East Midlands	23	1.2	2179
South West	22.3	0.9	1986
South East	23.5	1.2	4062
East	23.9	1.1	2568
London	24.7	2	5124
Total		1	23982

London has been found to incur the highest heat-related mortality rates in the UK during periods of hot weather (Hajat et al., 2007), with those aged 65 or more years most at risk. Heat effects and consequent heat stress in urban areas are more severe than rural ones (Hajat et al., 2007). In winter, there is some evidence that the UHI in London acts to reduce cold-related mortality (Milojevic et al., 2011, 2016), but the study was limited by the availability of winter temperature data. Other studies have shown that vulnerability to cold is greater in rural populations, where cold effects were slightly stronger in more deprived areas (Hajat et al., 2007). Increased temperatures can also result in increased ground level ozone production and associated health impacts and contribute to a number of non-fatal health and comfort problems such as heat cramps, exhaustion and non-fatal heat stroke (PHE, 2015; US EPA, 2011).

Health, wellbeing and productivity in buildings are influenced by the climatic and cultural differences due to design and the working environments (World GBC, 2014). A report by the World Building Council (2014) found that the indoor air quality, thermal comfort and amount of daylighting are environmental factors that will impact workplace productivity. The report highlights research that has investigated the relationship between thermal comfort and work place performance, two studies found a reduction in work place performance in temperatures of 30°C (Lan et al., 2011) (Wargocki, 2006) (World GBC, 2014). This is in agreement with other review papers that have analysed the relationship between indoor environmental quality, thermal comfort and occupant well-being in offices (Al Horr, Arif, Katafygiotou, et al., 2016; Al Horr, Arif, Kaushik, et al., 2016).

There has been evidence from modelling studies to show that the level of overheating in buildings across London varies depending on the local physical characteristics of the location and the type of building. Buildings located closer to the centre of London have an increased number of occupied hours for which the internal temperature was above 28 °C (Demanuele et al., 2012). Building characteristics such as the geometry and fabric have a greater impact on overheating than the location of a building within London’s UHI (Oikonomou et al., 2012). These modelling studies used outputs from the London Site Specific Air Temperature (LSSAT) model (Kolokotroni et al., 2009), which was developed as part of the LUCID project (Mavrogianni et al., 2011).

Built form and land use correlations have been mapped to land surface temperatures within London (Mavrogianni et al., 2009). The results showed that there is a stronger correlation between dwelling building height and heat-related mortality, than environmental variables such built density, green coverage and surface temperature (Mavrogianni et al., 2009). Modelling of medium to high-rise flats have shown that they are at greater risk of overheating than low-rise flats in social housing (Mavrogianni et al., 2015). The age and type of social housing will also have an impact on overheating levels (Mavrogianni et al., 2015). Increasing ventilation levels could be increasingly difficult in a warming climate and also lead to increased exposure to outdoor pollutants.

In other UK cities, such as Birmingham, the risk factor of people vulnerable to heat risk has been linked to their location within the city (Tomlinson et al., 2011). The UHI magnitude, calculated from remote sensing results, was correlated to the potential exposure of vulnerable people for a night in July 2006, vulnerable people in the middle of the city, where the UHI magnitude is highest, were most exposed to heat risk. Urban households in Manchester are also impacted by UHI effects (Lee and Levermore, 2013). For an observed UHI of 5K, there can be a 3K increase in night-time internal temperatures between an urban and rural site.

Across the UK, the variation in climate will have an impact on natural ventilation design. The same dwellings could have a higher risk of overheating within London compared to other UK cities using different DSY weather files (Taylor et al., 2014). Individual building archetypes do not have the same levels of risk in each city, emphasising the need for regional weather data. The impact of design interventions such as insulation varies depending on climate type (Peacock et al., 2010). Insulation in Edinburgh could reduce overheating levels, whilst increasing them in London.

2.5.2 Impact on energy

In a warming climate, buildings will be at risk of overheating and new and existing buildings will need to be adapted to minimise the need for additional cooling (CIBSE, 2005b; Holmes and Hacker, 2007). UHIs can result in higher cooling loads and lower heating loads depending on the climate and the location of a development within a city. London’s UHI results in a decrease in Heating Degree Days of 360 whilst increasing the Cooling Degree Days by 41 (calculated using base temperatures of 18.3°C) (Davies et al., 2008). Even in cooler UK climates such as Edinburgh, the UHI effect impacts energy use. More urbanised and centrally located sites have lower calculated heating degree days and higher cooling degree days (Emmanuel and Krüger, 2012). However, it has been suggested that due to the high heating demand in Scottish cities, the UHI effect in cities like Glasgow can be used to enhance local energy savings (Emmanuel and Krüger, 2012).

The higher external temperatures caused by the UHI effect has been shown to impact the energy use and heating and cooling strategies depending on the location of a building within London. Modelling using the outputs of the LSSAT model as shown that heating loads will increase and cooling loads will decrease as the location of an office building moves away from the centre of the city (Kolokotroni et al., 2012). Other studies using LSSAT results have shown that cooling ventilation strategies such as passive night time cooling will be less effective in an urban location to a rural one (Kolokotroni et al., 2006). The impact of location on annual energy will be dependent on relative location within the UHI and local differences. As an example, modelling of a conditioned office resulted in cooling loads increasing by 25% and annual heating loads decreasing by 22% for an urban located building compared to rural located one (Kolokotroni et al., 2007). All these studies place an emphasis on the importance of using more localised weather files in order to factor in the location dependent microclimatic conditions for each site chosen.

Increased air temperatures due to projected climate change, could result in a need to reconsider the current design of HVAC cooling loads (Watkins and Levermore, 2010). Modelling a HVAC unit in a single zone office room has shown that for a 1°C increase in external temperatures there was a 10% increase in cooling load, a 14% increase needed in chiller power and the fan distribution needed to be increased by 30-50%.

At more local scales, the urban form and density created by different configurations of buildings and neighbourhoods can impact building energy use in cities such as London. The formation of street canyons will impact radiation exchange and wind flows. Street orientation, overshadowing from adjacent buildings and radiation from opposite facades will impact energy use. The impacts vary depending on whether the building is naturally ventilated or conditioned and on building type. Urban areas generally have lower wind speeds and higher temperatures due to the UHI effect and also increased noise and pollution and, therefore, natural ventilation strategies have to be carefully considered. Various modelling studies have investigated how the surroundings of a building affect its energy consumption. The methods include using Digital Elevation Models (Ratti et al., 2005) (Steemers, 2003) coupled to an LT energy analysis model (Baker and Steemers, 2000); an analytical microclimate model for predicting air temperature (Shashua-Bar et al., 2006), correlating measured data of how wind and temperature vary in urban environments to rural environments (Ghiaus et al., 2006), experimental measurements of the potential of ventilation in urban environments (Geros et al., 2005), radiation modelling of street canyons (Strømann-Andersen and Sattrup, 2011), analysing the influence of street width, street direction and roof shape on solar gains on building surfaces using TRNSYS dynamic thermal simulation model (TRNSYS, 2010) which has a 3D radiation (van Esch et al., 2012), (Allegrini et al., 2012b). Aspects of design that will impact energy use from these studies include:

- The proportion of the building envelope exposed to the urban environment will impact its energy use by affecting the heat losses.
- This will differ for different building types. For dwellings, increasing building density beneficially reduces heat losses, but also reduces solar and daylight availability.
- Naturally ventilated shallow plan[20] office buildings will use less energy for cooling, but ventilation strategies will be impacted by lower wind speeds, noise and air pollution.
- This limitation can be addressed by mechanically ventilating the street facing zone (mixed-mode).
- Increasing building depths can result in increased energy use for offices – deep plan air-conditioned buildings can use up to twice as much energy as mixed-mode buildings.
- Improving the urban microclimate can lead to reduced air-conditioning usage in buildings,
- The impact of HVAC systems efficiency and occupant behaviour can impact consumption to a greater extent than the effect of urban geometry.

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[20] The effectiveness of natural ventilation in deeper plan offices is subject to the design of ventilation pathways (CIBSE, 2005a).

- Radiative exchange between buildings within a street and lower wind speeds can result in higher façade surface temperatures.
- Shading of facades will not only impact radiation balance, but energy use due to artificial lighting requirements.

The impact of street canyons on total energy consumption, compared to unobstructed sites has been shown to range up to +30% for offices and +19% for housing (Strømann-Andersen and Sattrup, 2011). Detailed analysis of coupled CFD and building simulation software has shown that the density of buildings in urban neighbourhoods has been shown to reduce HVAC CoP values by 17% compared to rural values (Gracik et al., 2015). The degradation of performance is related to the influence of roof top warming and the location of the HVAC unit. Other microclimatic influences which will impact energy use include locating a building in close proximity to a park. In Hong Kong, proximity to a park has been shown to reduce cooling loads by up to 9% (Chen and Wong, 2006).

2.6 Design strategies in urban climates

Adapting buildings to urban climates will be dependent on the size of development, its location within a city and the local environment. As has been outlined in previous sections, in temperate and cold climates, the UHI effect has positive effects in the winter resulting in lower heating demand. It is in the summer where the warming effect of the climate can result in overheating and increased usage of cooling. It has been suggested for some time that the net effect of adaptation strategies to both buildings and their surrounding environment is the most effective mechanism at mitigating UHI effects (Taha et al., 1988). Climate adaptation can be seen as the net effect of small local measures (Rovers et al., 2014), reducing heat gains into a building whilst optimising the urban environment. This section splits the evidence of the effectiveness of design strategies into varying spatial scales.

2.6.1 City-wide strategies

With the potential for higher occurrence of hot events and projected climate change, the aim of city-wide strategies is to minimise the impact of urban warming for developments of all sizes. City-wide variations in surface vegetation and changes in albedo of surfaces will impact air and surface temperatures. These strategies rely on altering an urban surface to one that will absorb less incoming solar radiation through shading or albedo changes or cool through evapotranspiration. The theory is that the net effect of these strategies will lead to a cooling effect across a city.

2.6.1.1 *Effect of greening strategies*

These strategies include increasing the proportion of urban greening such as parks or planting trees that provide shading and the adoption of green roofs. A combination of citywide strategies has been stressed in cities such as New York, where maximising the amount of vegetation through a combination of tree planting and green roofs was modelled to be more effective than changing the albedo of surfaces. Less built up areas of the city saw reductions of 1.1°C during times of peak cooling loads (Rosenzweig et al., 2006, 2009). In Tokyo, greening the sides of buildings and reducing anthropogenic heat from air-conditioning reduced modelled daily mean, spatially averaged, near-ground, summer air temperatures by 0.7°C and 0.5°C respectively across the city, resulting in less cooling energy use (Kikegawa et al., 2006). Adding green space to high density areas has been shown to reduce future surface temperatures in Manchester, whilst removing green spaces increased surface temperatures (Gill et al., 2007).

Wide spread adoption of green roofs has been found to reduce daytime air temperatures by a maximum of 3°C in Chicago (Smith and Roebber, 2011). In Toronto, modelling has shown that retrofitting 50% of roofs with vegetation would result in the entire city cooling by 0.1-0.8°C, and if irrigated; the cooling could increase to 2°C (Liu and Bass, 2005). In the Baltimore-Washington area during a heatwave period, the maximum surface reduction modelled using a NWP model was 0.6 °C for green roofs and 0.8 °C for cool roofs (Li et al., 2014). Near surface temperatures were reduced by a maximum by 0.1 °C and 0.2 °C for green and cool roofs respectively.

2.6.1.2 *Effect of strategies that vary the albedo of building and street surfaces*

A survey of measured surface temperatures of conventional roofs found that they are 31-47°C hotter than overlying air whilst cool roofs stay within only 6-11°C warmer in a variety of Canadian and American cities (US EPA, 2011) . City-wide modelling of cool roofs in Athens reduced daytime ambient air temperatures by up to a maximum of 2°C and reduced the UHI intensity by 1-2 K (Synnefa et al., 2008), when 85% of 0.45 km^2 modelled grids had their albedo modified. Changing the surface albedo of urban street canyons using retro reflective films has been shown to lead to decreases in surface temperatures and mitigation of the UHI effect (Bonamente et al., 2013; Rossi et al., 2014). There is also evidence that increasing the albedo of roofs and pavements in various American cities can lead to a maximum reduction in daytime summer air temperatures of 0.5 °C (Millstein and Menon, 2011).

2.6.2 Neighbourhood and building scale strategies

The previous section outlined how the net effect of city-wide strategies could reduce air temperatures across the city. Strategies at lower spatial scales will aim to impact the local microclimate of a neighbourhood and subsequently impact the performance of a building. Technical Memorandum 36 contains a range of case studies analysing the impact of building design adaptations in a warming climate (CIBSE, 2005b), the studies highlighted that low-energy, sustainable designs can be achieved using the following principles (Holmes and Hacker, 2007):

- switch off – reduce solar and internal gains,
- spread out – use thermal mass to attenuate peak gains,
- blow away – properly designed ventilation systems,
- cool – when peak gains cannot be mitigated by natural ventilation, use additional cooling.

The strategies that relate most directly to the urban climate are “switch off” and “blow away”. These strategies can be defined in terms of direct and indirect effects:

- Direct effect – will impact the heat transfer into a building through altering the fabric or services of the building itself and reducing gains into the building,
- Indirect effect – will impact the performance of a building by adapting the local climate and impacting local air and surface temperatures, radiative exchange and wind flows.

The effect of some of the strategies at the neighbourhood and building level are outlined next.

2.6.2.1 *Effect of neighbourhood scale strategies*

For London, there is evidence that the most crucial factors that affect outdoor temperatures at the neighbourhood scale are changes to albedo for all climate conditions, building thermal mass during clear sky conditions and street aspect ratio during cloudy conditions (Kolokotroni & Giridharan 2008). Using ENVI-met modelling for a case study in London, vegetation and high albedo materials have also been found to have the capacity to mitigate the UHI effect (O’Malley et al., 2014). However, the study found that optimising building orientation and layout and the subsequent impact on solar radiation penetration and wind patterns were more effective.

The impact of vegetation and high albedo surfaces on street canyon temperatures and wind flows are highly complex. Modelling studies testing how the addition of these strategies will impact temperatures within a street canyon have found that (Alexandri and Jones, 2008; Ali-Toudert and Mayer, 2006, 2007, Shashua-Bar et al., 2004, 2006)(Shashua-Bar and Hoffman, 2003):

- Wind flows are reduced when perpendicular to street canyon orientation,
- High aspect ratios will reduce canyon air temperatures,
- The balance between shading due to aspect ratio and decreased loss of longwave radiation to sky is complex,
- Shading or overhangs reduce street canyon temperatures,
- Tree shading reduces air and surface temperatures with canyons but also impact air flow within them,
- Impact of vegetated surfaces depends on climatic conditions,
- Impact of roof strategies on street canyons is less than impact of façade strategies,
- Both green and cool surface changes can mitigate the UHI effect at local scales.

The optimal urban street formation in a temperate high latitude climate has been found to be (van Esch et al., 2012):

- Orientated east-west,
- An absolute width of at least 20 m,
- Deciduous trees placed on the north side of east-west orientated streets to provide shading,
- Trees placed on east side of street on north-south running orientated streets.

Street canyon formations and surrounding buildings impact the convective heat transfer at a buildings surface. Allegrini et al. (2012a) found that the space cooling demands for a building in a street canyon differ up to a factor of 1.8 depending on which convective heat transfer coefficients correlations were used (Allegrini et al., 2012a). The geometry of the building, the presence of neighbouring buildings and buoyancy within the street canyon are found to be the most influential factors for convective heat transfer at the building surface. Evaporative cooling also impacts the convective heat loss at building surfaces (Saneinejad et al., 2011). Surface temperatures can be reduced through evaporative cooling, but the rate is impacted by the height of wall and the wind flow. Wall sections higher up in street canyons on the leeward side dry quicker and are cooled quicker to the distribution of convective heat loss.

Recent experimental research for Manchester estimates a cooling effect of 1.06 °C at 300 mm above an intensive green roof, with a maximum summer night time cooling of 1.58 °C (Speak et al., 2013). There is limited evidence that this cooling effect impacts street canyon air temperatures. However, in addition to thermal effects, green roofs are known to decrease storm water runoff and hence reduce urban flooding, increase biodiversity, filter various air and water pollutants and sequester carbon dioxide (Getter et al., 2009; Getter and Rowe, 2006; Rowe, 2011). HVAC units can also contribute to increasing UHI effects through anthropogenic heat emissions (Tremeac et al., 2012). Sensible heat output by the units contributed linearly to increases in street air temperatures in Paris. This varied depending on the location of the area within the city. The units contributed to air temperature changes of up to 2.5°C in street canyons for certain scenarios.

2.6.2.2 *Effect of building scale strategies*

Traditional passive adaptations to a building such as increased thermal mass, lower glazing ratios, increased shading and optimised infiltration and day air change rates have been shown to be more effective at reducing cooling loads in rural locations compared to urban ones in London (Kolokotroni et al., 2006). Due to the increased air temperatures in the urban environment, passive measures such as night time ventilation were less effective than in the rural location. Design adaptations in dwellings in the UK have been ranked according to how they impact overheating and energy usage (Porritt et al., 2012). The effectiveness of interventions depended on the occupancy pattern of inhabitants and the number of exposed facades. Elderly occupants occupied different rooms during the day compared to working families and end of terrace dwellings had more exposed facades. The interventions found to be most effective were high albedo paint, external wall insulation, night-time purge cooling and reducing solar gains through internal and external shading. The effectiveness of intervention was related to the orientation of facades and differed by room type.

Modelling studies have shown that green roofs can reduce overheating in naturally ventilated buildings (Jaffal et al., 2012; Niachou et al., 2001; Parizotto and Lamberts, 2011; Zinzi and Agnoli, 2012). Green roofs can reduce the annual energy use in buildings, but the magnitude of the savings is dependent on the amount of existing insulation, irrigation levels and climate (Castleton et al., 2010; Jaffal et al., 2012; Niachou et al., 2001; Sailor et al., 2012). Cool roofs are effective at reducing summertime cooling demand in buildings (Jo et al., 2010; Kolokotroni et al., 2013; Levinson and Akbari, 2010; Synnefa et al., 2007) and summertime overheating (Kolokotroni et al., 2013; Romeo and Zinzi, 2011; Synnefa et al., 2007). Kolokotroni et al. (2011) modelled the impact of cool roofs in an office in London and found that retrofitting them onto on office resulted in winter energy penalty and summer energy saving, with an annual reduction in energy use.

2.7 Evaluation of current design guidance

Section 1.1.3 outlined the recent policy response by the GLA, but design guidance on urban design and buildings is limited. Publications have highlighted the importance of considering the microclimate in design (DETR, 2000), in urban planning (Littlefair, 2000) and the impact of London's UHI on cooling demands (Graves et al., 2001), but much work has been carried out since they were published. Standard such as BREEAM Communities (C) (BRE, 2012), USA based LEED Neighbourhood (ND) (USGBC, 2009) and the Japan based CASBEE (JSBC and JaGBC, 2015) assess the quality of a development in terms of its impact on the surrounding environment. Developments are ranked using a rating system. Factors that will impact the rank include; impact to microclimate considerations, such as thermal comfort and wind speeds, UHI mitigation, effective land use strategies and resource usage. However, the standards are limited in their use of quantitative assessment of the design strategies.

All neighbourhood sustainability assessments schemes aim to not only the environmental but also the economic and social impacts of developments (Sharifi and Murayama, 2013, 2014) (Komeily and Srinivasan, 2015; Reith and Orova, 2015). Compared to LEED ND and BREEAM C, CASBEE UD has more criteria relating to the impact environmental impact on the local climate. It covers aspects such as the positioning of heat exhaust; ecosystem networks, wind resilience, provision of excessive space for the potential future expansion of facilities, consideration for building cladding materials, mitigation of sunlight obstruction (Sharifi and Murayama, 2014). These and other certification schemes share similarities in their assessment criteria, however due to the subjective nature of sustainability they often assign different weighting to different criteria (Komeily and Srinivasan, 2015). The number of indexes that are mandatory also differs from scheme to scheme. They often lack assessment of the regional context of the developments and lack focus of the cross-scale relationships in urban environments. This could be solved by embedding the neighbourhood development in the context of the wider urban development plan of a city. Their uptake is varied due as their voluntary status and current market appeal, it can be argued that they should be made mandatory for new developments (Sharifi and Murayama, 2014). Finally, there is concern that developers will try to achieve the greatest points with the lowest cost and that ratings do not take into consideration future changes to the neighbourhood (Sharifi and Murayama, 2013).

Recently the International WELL Building Institute has been piloting the WELL Community Standard, which assesses projects on a variety of environmental criteria such as air and water quality, light pollution, thermal comfort and acoustics (IWBI, 2019). The thermal comfort criteria include credits for extreme weather warnings for communities, urban heat island mitigation, external solar shading and inclusion of urban vegetation and water bodies within the design.

2.8 Summary

This chapter reviewed the current knowledge on the physical basis of urban climates, the tools and data available to measure and model them, how they vary across cities at different spatial scales, their impact on building performance and design strategies available. A summary of the chapter is outlined next.

To factor in urban climate phenomena into the design of buildings and their services, there are a wide variety of climate data and software modelling tools available. In the UK, high quality, long time series of observed data are usually available from rural or semi-rural Met Office weather stations. Measurements from urban weather stations are limited in availability and are impacted by the local microclimate. Weather files produced by CIBSE from observed data have been produced for an urban location within London, but these still limited as they represent point sources of data. Urban weather stations exist in cities other than London and there is potential for new weather file locations.

Models that output climate data provide an alternative to observed weather data. However, their spatial and temporal limitations have to be understood to apply them effectively. The urban climate is complex and no model is able to resolve all the physical processes that exist. A city-scale NWP model is useful for analysing how the UHI effect varies across a city. Modelled data at the city-scale exists for London and there is potential for new analysis of the characteristics of the UHI effect. Microclimate models are useful for analysing design adaptations such as green roofs or land-use changes within a neighbourhood. Previously, the LUCID project provided a few case studies that used data from climate models to analyse how they directly impact building performance.

At the largest scale, models can be used to analyse how location within a city and the characteristics of its urban land use can influence air temperatures upwind and downwind. This can result in variations in the spatial pattern of the UHI. Neighbourhood scale models have simulated the effects of green infrastructure in the form of green spaces, rivers and trees and how they cool the urban environment. At the lowest spatial scales, models can simulate street canyons and how the radiative exchange between surfaces and shadowing dominate how air temperatures vary.

The UHI intensity has been measured and modelled in major cities in the UK. The maximum intensity in 3 of the UK’s major cities peaks at 8 K, whilst higher intensities are rare. There is evidence that the frequency of summer heatwaves could increase in the future, the negative impacts of warming would be exacerbated by the UHI effect.

Summertime overheating has previously resulted in increased mortality rates in London and is seen as a threat to public health. Overheating in buildings is linked both to the location of a development within a city’s UHI and differences in building characteristics and the local environment. The availability of climate data from models and weather files in London have implications for overheating analysis. Energy use in buildings is also linked to both to local variations in the urban climate and the overall location within the UHI.

The advantages of using climate models are their variable temporal and spatial resolution. The impact of current and future land use changes in the form of new developments and neighbourhood scale adaptation strategies, such as green infrastructure, can be analysed at variable resolutions.

Design strategies for adapting developments and their surroundings to the urban climate can be split into different spatial scales. At the city-scale, strategies include greening in the form of parks and trees and changing the albedo of building and streets. Neighbourhood scale strategies can be split into direct and indirect passive effects. Direct strategies only affect heat gains into the building through varying aspects of the building envelope. Indirect strategies use adaptations that affect the local climate, such as optimising street width and shading from trees.

There is currently a lack of design guidance for industry practitioners on the effects of urban climates, how to model and measure these effects and the potential design strategies that affect both building performance and the local microclimate. As the literature review has highlighted, the urban climate is inherently complex, with effects that differ depending on the spatial and temporal scale and there are a wide range of tools with which to quantify these effects. The aim of this thesis and as outlined in by the research questions in Chapter 1 is to provide further guidance and evidence of integrating climate data from varying spatial and temporal scales and sources into building design. The research is presented in a series of case studies that present methods to achieve these aims. The next chapter investigates how a new source of climate data from a city-scale climate model can be used to provide new in-depth analysis the UHI effect in London.

Research Outputs

3 Using city-scale modelled climate data to provide a spatial and temporal analysis of the Urban Heat Island effect in London

3.1 Introduction

The aim of this chapter is to demonstrate how new and existing sources of climate data can be analysed to provide a more in-depth understanding of the spatial and temporal variation of the UHI effect in London. This analysis can then be factored into building design by providing additional useful data and guidance that can be used by practitioners in their designs.

3.2 Review of available climate data sources in London

The review in Chapter 2 found that for London, the UHI intensity has previously been evaluated using Stevenson screens (Chandler, 1965) Met Office meteorological data is limited as there are only a certain number of synoptic weather stations across the whole of London, all of which do not have reliable records. CIBSE TM49 (2014) outlines a summary of the availability of historical weather station data in London and the location of the weather stations, see Figure 10, Figure 11 and Figure 12.

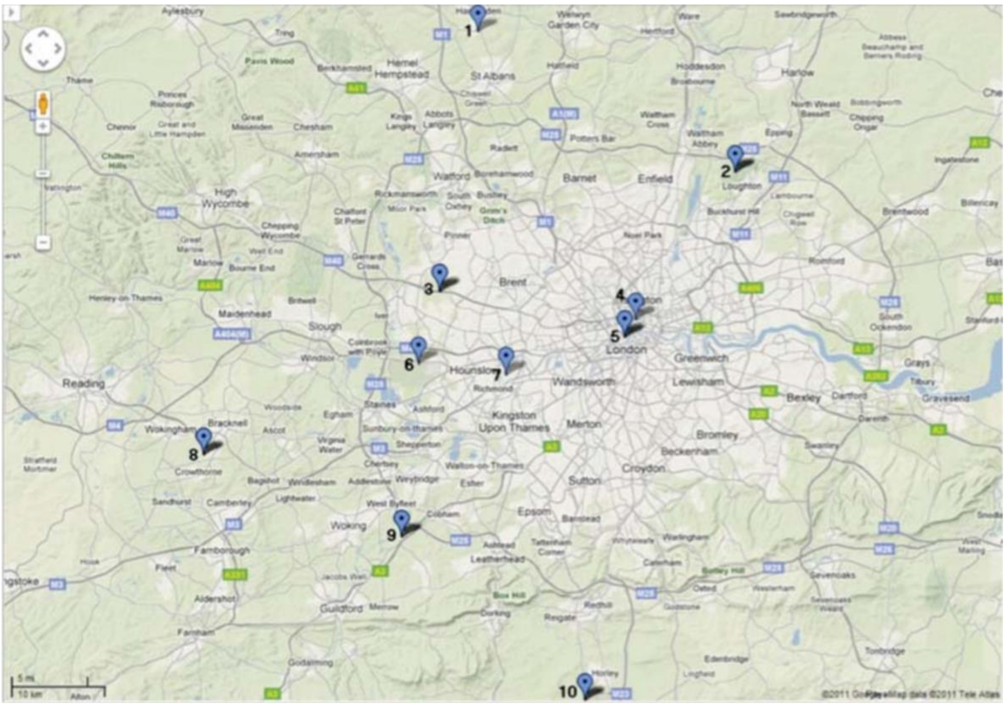


Figure 10 Met Office weather stations in London – (1) Rothamstead, (2) High Beach Essex, (3) Northolt, (4) London Weather Centre, (5) London, St James' Park, (6) London Heathrow, (7) Kew Gardens, (8) Beaufort Park, (9) Wisley, (10) Gatwick Airport. Source: CIBSE (2014).

As discussed previously in Chapter 2 and shown in the Figures above, the limitation of using Met Office weather station data is that it represents point measurements and the temperature data availability varies between sites. To quantify and analyse the UHI effect in London using more recent data would only be feasible from using Wisley (WSY) or Northolt (NTH) as a rural reference point and St James Park (SJP) or London Weather Centre (LWC) as an urban reference point. There are also uncertainties with the weather stations that do have reliable data available, for example LWC is located on a roof (CIBSE, 2014) and SJP is located in the middle of a park.

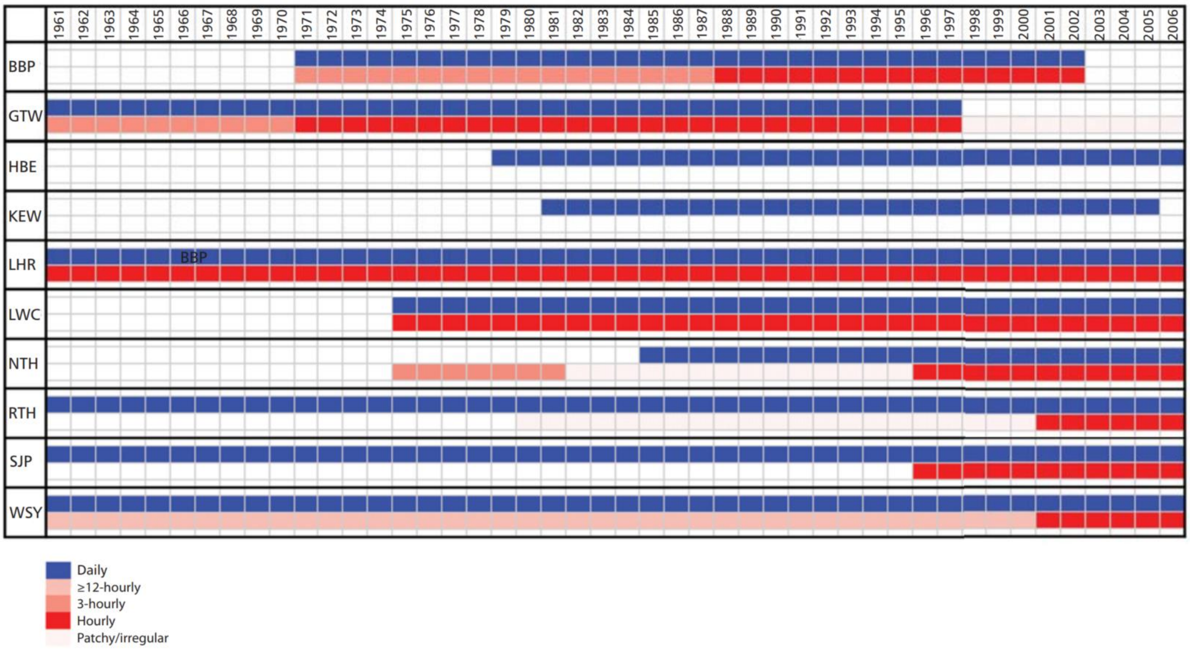


Figure 11 Data availability of Met Office weather stations in London as outlined in CIBSE TM49 - (RTH) Rothamstead, (HBE) High Beach Essex, (NTH) Northolt, (LWC) London Weather Centre, (SJP) London, St James' Park, (LHR) London Heathrow, (KEW) Kew Gardens, (BBP) Beaufort Park, (WSY) Wisley, (LGW) Gatwick Airport. Source: from CIBSE (2014)

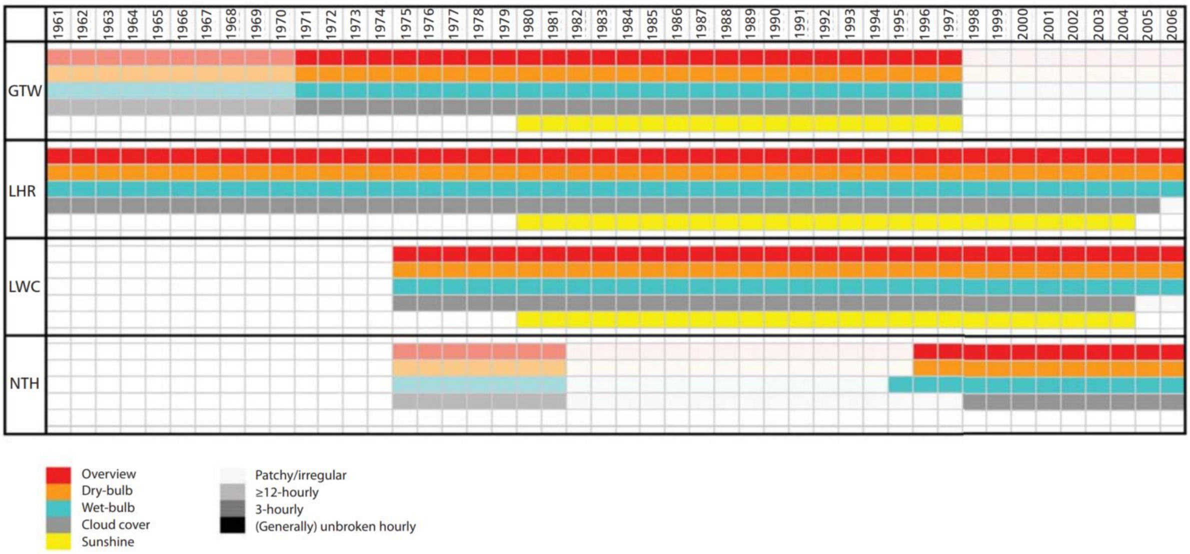


Figure 12 Further breakdown of Met Office weather station sites that have appropriate temperature data as outlined in CIBSE TM49 – (NTH) Northolt, (LWC) London Weather Centre, (LHR) London Heathrow, (LGW) Gatwick Airport. Source: CIBSE (2014)

As outlined in Section 2.2, CIBSE uses data from the Met Office weather stations to synthesise weather files for use in building simulation through its DSY and TRY files. The introduction of additional DSYs weather files in London for a variety of locations does allow practitioners to capture the UHI effect. Previously the weather files were limited to using London Heathrow, but the addition of the Gatwick and London Weather Centre allows climatic conditions to be factored into building design depending on the spatial location of their building. These files still face the same limitations as all weather station data, they are limited to point sources.

There are other sources of observational weather data available across the city (Watkins et al., 2002). This observed data were from an array of sensors set up by Brunel University and the Building Research Establishment (BRE) from August and September 1999 and July to September 2000 and was the most spatially extensive available for London to date. The observed data used sensors which recorded air temperatures and were placed at a height of 6 m, which is higher than standard Met Office sensors. The data collected using the arrays were used in previous design guidance for building designers. *Cooling Buildings in London* (Graves et al., 2001), a BRE publication presented various analyses of how the microclimate varied in London using the data. This was followed by an analysis of how summertime cooling is impacted by the UHI effect (Graves et al., 2001). The data was used in the London Site Specific Air Temperature (LSSAT) model (Kolokotroni et al., 2009) and used in multiple studies to assess thermal comfort and energy use, see Chapter 2. These studies showed how the nocturnal cooling strategy and energy use of a building are impacted by its location within the city due to the UHI effect. Figure 13 shows the locations of the observed data used in the model.

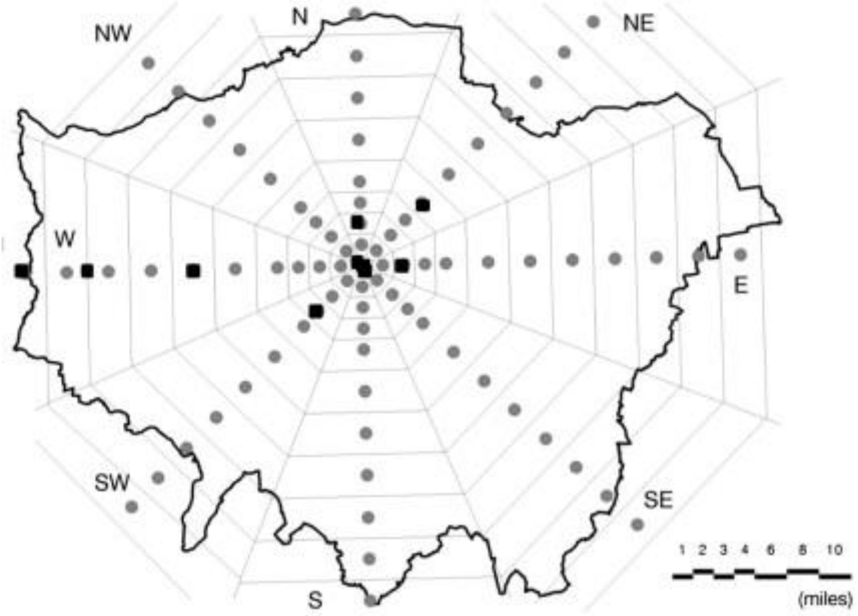


Figure 13 Observation locations used to produce the LSSAT model, grey represents data from 1999/2000 and black 2008. Source: (Kolokotroni et al., 2010)

The data was also included the UHI section of the previously published CIBSE Guide A: Environmental Design (CIBSE, 2006), which included the following:

- A frequency distribution of UHI intensities for summer 2000, where the highest nocturnal intensities quoted are 6 – 7 K for less than 2% of observed period.
- Diurnal variation of intensities (up to 8 K) across one whole summer.
- Plots showing spatial distribution of the UHI at day and night in relation to wind speed for both calm and windy conditions.
- UHI adjustments at three radii to be added onto Sol-air temperatures quoted earlier in the chapter for use in manual calculations. These adjustments were produced with Heathrow as a rural reference point. They were relatively low intensities due to Heathrow having its own UHI compared to surrounding rural area. The greatest adjustment is less than 3 K.

The limitations with using this data to analyse the UHI effect in London is that it only represents certain spatial transects within London. The observed years 1999 and 2000 were also not particularly warm years, there is some evidence from analysis in CIBSE TM49 that more extreme intensities occur in summers with warmer heatwave events (CIBSE, 2014). If more extreme intensities occur in warmer years, then night-time cooling strategies and sizing of HVAC units would be under-designed in accordance with the current guidance. This could lead to negative implications for the health and comfort of a building's occupants. However, the use of more extreme events could also lead to unneeded extra cost through over-design.

The only accessible modelled data available at the city-scale for London is from the Met Office Unified model, which uses the MORUSES parameterisation (Bohnenstengel et al., 2011). The modelled data exists for a warmer year 2006 exists (Bohnenstengel et al., 2011). The major advantage of using the validated modelled data is that the spatial resolution of outputs allows urban and rural reference points to be specified across the whole of London at a variety of transects, as it covers 100km^2 and has an output resolution of 1 km^2. The model has been validated against screen-level air temperatures and showed agreement to within 1 – 2 K (Bohnenstengel et al., 2011). The data was the output of the LUCID project and is only available for 2006 (Mavrogianni et al., 2011). The reason for the limitation of accessible data is the model is run on the Met Office Unified model, which is used for weather and climate predictions. The lowest available resolution of the standard Unified Model has an output resolution of 1.5 km grid boxes. The use of the MORUSES parameterisation and to output results at a lower resolution of 1 km grid boxes to the normal Unified Model outputs was only possible through additional funding.

Other regional climate models such as WRF have been applied to London (Chemel and Sokhi, 2012), but the data is not accessible.

3.3 Objectives

The availability of accessible city-scale climate data allowed an analysis of the spatial and temporal variation of the UHI effect in London. There were also existing observed datasets that have been analysed to provide climate data sources and guidance to practitioners. The work in this chapter aimed to answer the research questions of how new and existing forms of climate data can be used to provide more in-depth analysis of the UHI effect in London and how these can then be factored into building design. This chapter has the following objectives:

- Analyse how modelled city scale climate data for London be used to quantify the Urban Heat Island effect.
- Provide a methodology of how outputs from a city-scale climate model can be analysed and then inform building design, including an analysis of the spatial variation of the UHI using this data.

The work in the chapter is therefore split into two parts, the first used the new modelled climate data to analyse the spatial and temporal effect of UHI. Secondly, the modelled data and observed data are compared through an analysis of the frequency of extreme UHI intensities with the aim of providing a more in-depth understanding of how the UHI effect can impact building design.

The work in this chapter was included in the update of CIBSE Guide A (2015). The initial discussion of the update and comparison of the two datasets was published in a conference paper and presented at the CIBSE Technical Symposium:

Virk (2013) Developing and expanding current CIBSE design guidance on urban climates. In: CIBSE Technical Symposium, Liverpool John Moores University, Liverpool, UK, 11-12 April 2013.

3.4 Methodology

3.4.1 Data availability and processing

The climate data for air temperatures is available in the following formats:

- Modelled data – May to August 2006, data is a 100 by 100 grid, each cell representing 1 km by 1 km.
- Observed data – July to September 2000, point measurements at a variety of locations,

The access to the modelled data was discussed previously. The observed data was provided by Richard Watkins, full details of the data are discussed previously and were the output a research project at Brunel University and the Building Research Establishment (Watkins, 2002).

3.4.2 Spatially varying diurnal UHI intensity using modelled data

To analyse the UHI intensity of the modelled data, the following methodology was applied to the gridded dataset:

- The initial central urban reference point of the grid is placed at Bank Station and is an average of a 3km by 3km grid.
- Two fixed "rural" reference points were used:
    - Semi-urban reference point: located at a grid box where Heathrow is,
    - Rural reference points: Average of two reference points to the Southeast and Southwest of London (roughly at Wisley, which is a Met Office weather station).
- The urban reference point is then varied using three radial distances from the central point. The average of the temperatures in each of these areas represents the urban reference point as shown in Figure 14.

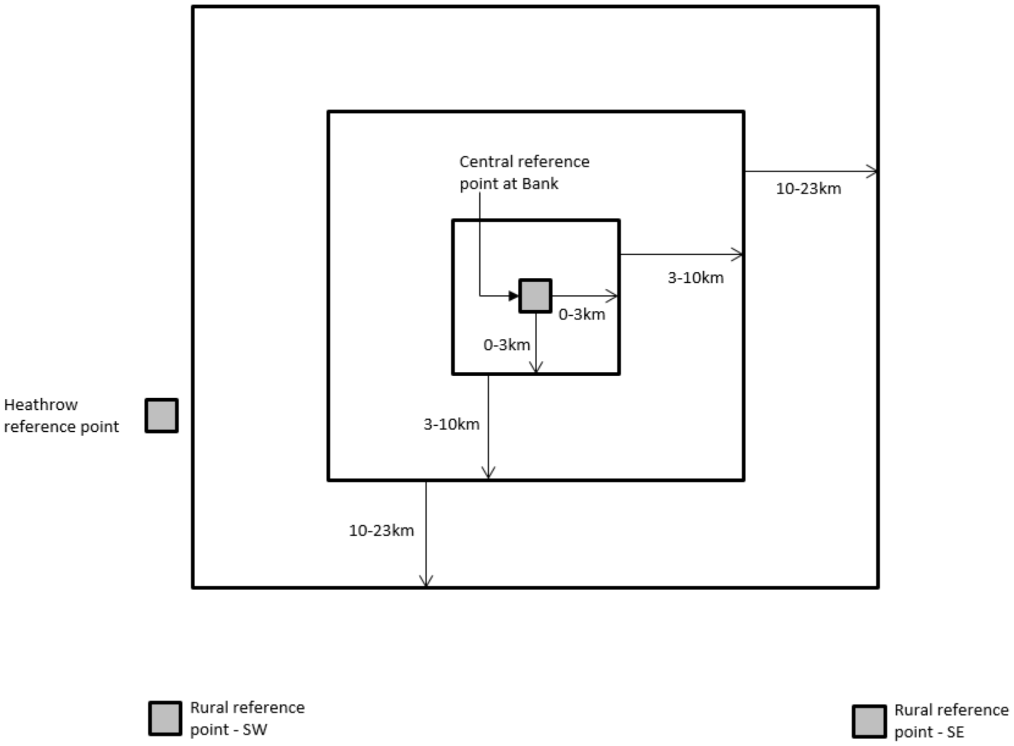


Figure 14 Schematic of radial distances from the central reference area used to work out UHI intensities and profiles

These radial distances represent 0 – 3 km, 3 – 10 km and 10 – 23 km from the initial area centred at Bank Station. The UHI intensity is calculated as the difference between this average and the rural reference point. A mean diurnal UHI profile is calculated by repeating this procedure for each hour of the day for the period May to August 2006. The location of the modelled reference points are shown on a map of London in Figure 15.

Figure 15 Location of observed and modelled reference points used to produce frequency distributions

3.4.3 Frequency of extreme of UHI intensities of modelled and observed data

To compare the frequency of extreme events in the modelled data with the observed data, frequency distributions of the summer UHI intensities were produced. This follows the methodology of how the observed data had previously been presented in CIBSE Guide A (2006).

The location of the observed and modelled reference points are shown in Figure 16. The observed data used single reference points for each location:

- Urban reference point: The British Museum,
- Rural reference point: Langley Park (directly west of London).

The modelled data used reference points representing a 3 km x 3km average for each location:

- Urban reference point: Bank Station,
- Rural reference points: Average of two reference points to the Southeast and Southwest of London (roughly at Wisley, which is a Met Office weather station).

The final distributions average the intensities for the South Eastern and South Western reference points for the modelled data as recommended by the model developer.

3.5 Results

3.5.1 Diurnal UHI profiles

The diurnal profiles are a useful measure of the UHI intensity as they show how the spatial distribution of the UHI effect and its strength develops over the course of a day. The choice of rural and urban reference points impacts the profiles significantly.

3.5.1.1 *Rural reference point: Heathrow*

Figure 16 shows the diurnal profile with Heathrow as a reference point for modelled data. The maximum UHI intensity reaches 2.6 K, which is similar to the 2 K average found using the observed data (Watkins et al., 2002). As the annular urban reference point moves away from the centre, the nocturnal intensities decrease. During the day from 07:00 to 16:00, the rural site is warmer than the city. This is evidence of a ‘cool island’ developing, which has been observed in other large cities (Spronken-Smith and Oke, 1998). The urban surface absorbs a greater amount of energy during the day compared to the rural surface due to a greater surface area and their properties. This absorbed heat is then released back into the atmosphere at night, increasing urban air temperatures.

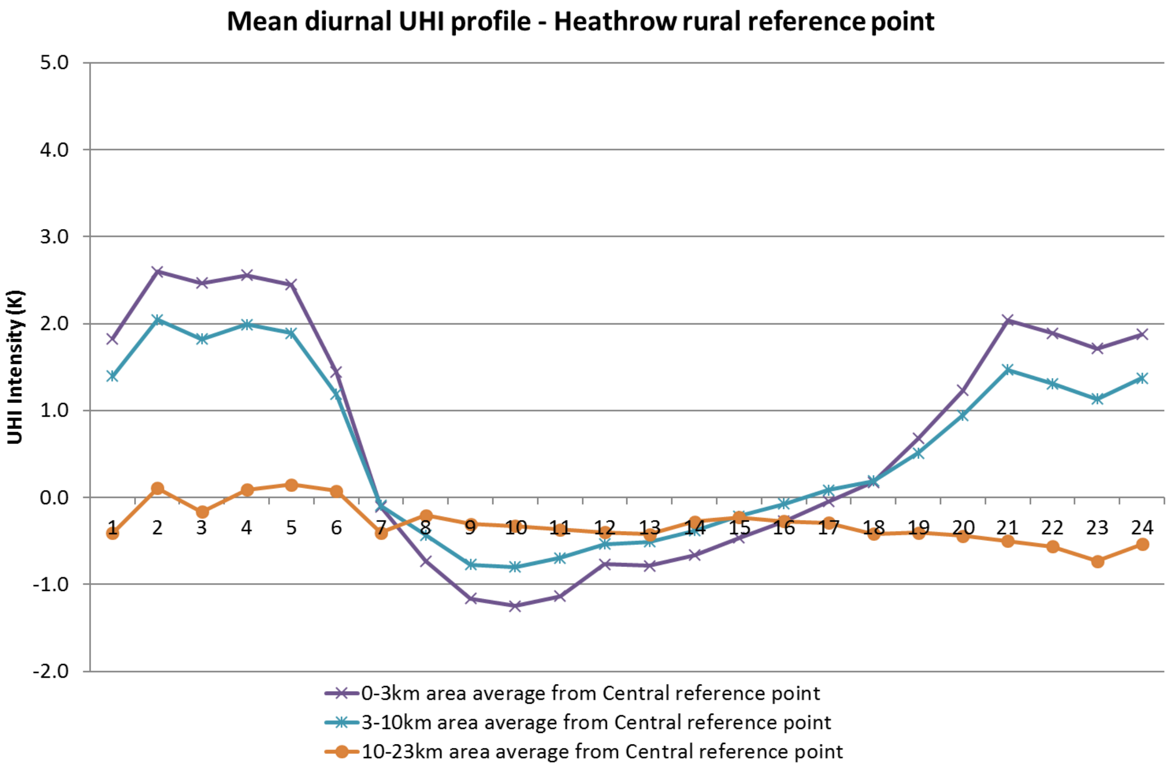


Figure 16 Mean diurnal UHI profile (compared to Heathrow) for annular regions centred on Bank Station using modelled data for summer period.

Heathrow is approximately 25 km away from Bank Station. Heathrow is not representative of a rural site for two reasons. The first is that it is located in a semi-urban location relative to the centre of London. Secondly, being an airport the site features buildings and impervious surfaces more similar to an urban site. This results in Heathrow developing its own UHI compared to the surrounding area. This is evident in Figure 16 in the 10 – 23 km diurnal profile. The UHI intensities are negative for 20 hours of the day, meaning that Heathrow is warmer than that area.

3.5.1.2 *Rural reference point: Langley Park*

Figure 17 shows the mean diurnal UHI intensity with using the average of two rural reference points, SW and SE of London. The maximum UHI intensity is 5 K, which is almost double that compared to using Heathrow as a rural reference point. All annular regions have positive nocturnal UHI intensities compared to Figure 16. The maximum intensities are also higher per annular region.

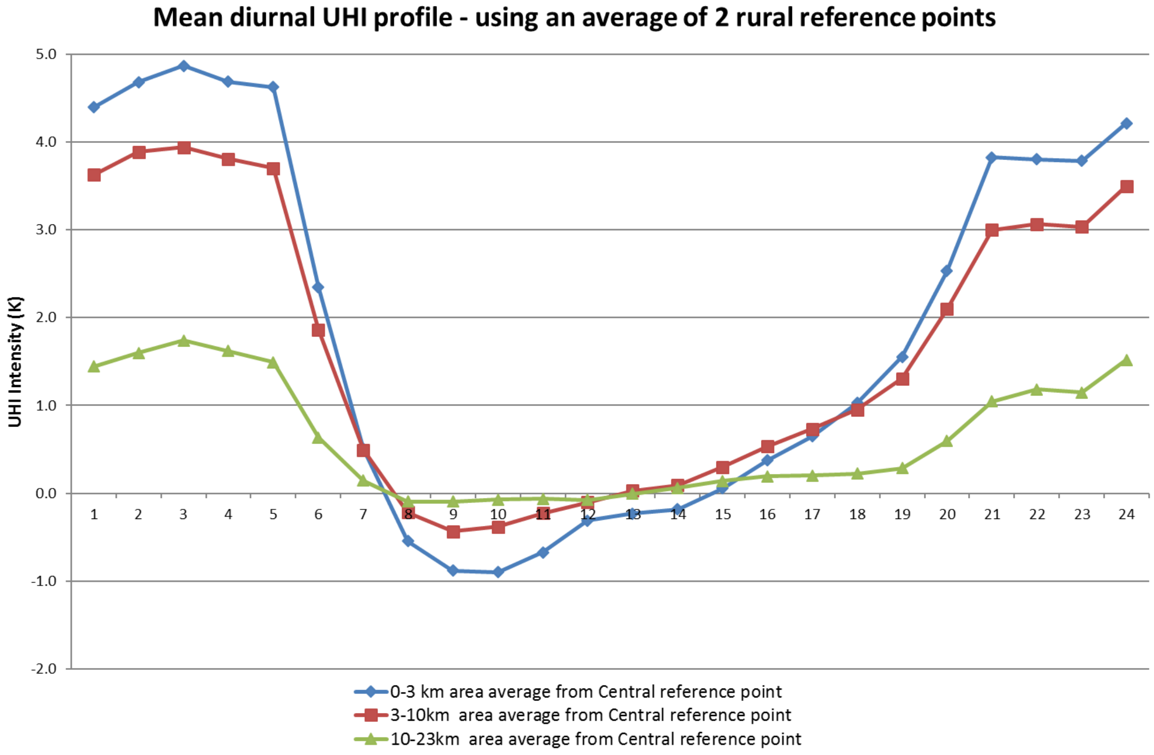


Figure 17 Diurnal UHI profile (compared to an average of 2 rural reference points) for annular regions centred on Bank Station using modelled data for summer period.

After 05:00, which would be when the sun rises, there is a sharp drop in intensities as with Figure 16 due to the heating of the rural surface. The 'cool island' phenomenon is evident from the two other central urban regions. However, for the 10 – 23 km region, there is no difference between the daytime urban and rural intensities. The intensities start becoming positive after 16:00 as with Figure 16.

3.5.2 Frequency Distributions

The results for both sets of data cannot be directly compared, as they use different reference points and represent different years. The aim instead was simply to investigate whether there are any significant variations in intensities between the data, which could highlight the need to quote higher intensities in CIBSE guidance. Figure 18 and Figure 19 show the results comparing the intensities produced from the average of the Southeast and Southwest reference points for modelled data and their average compared to the observed intensities, split by day and night.

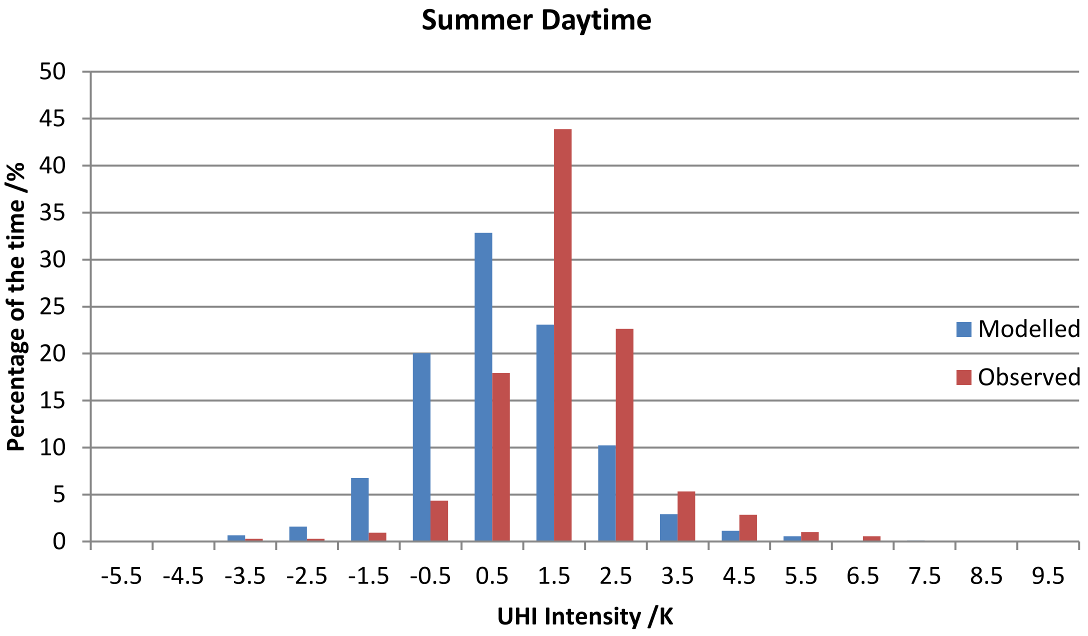


Figure 18 Summer daytime frequency distributions of UHI intensities for observed and modelled data

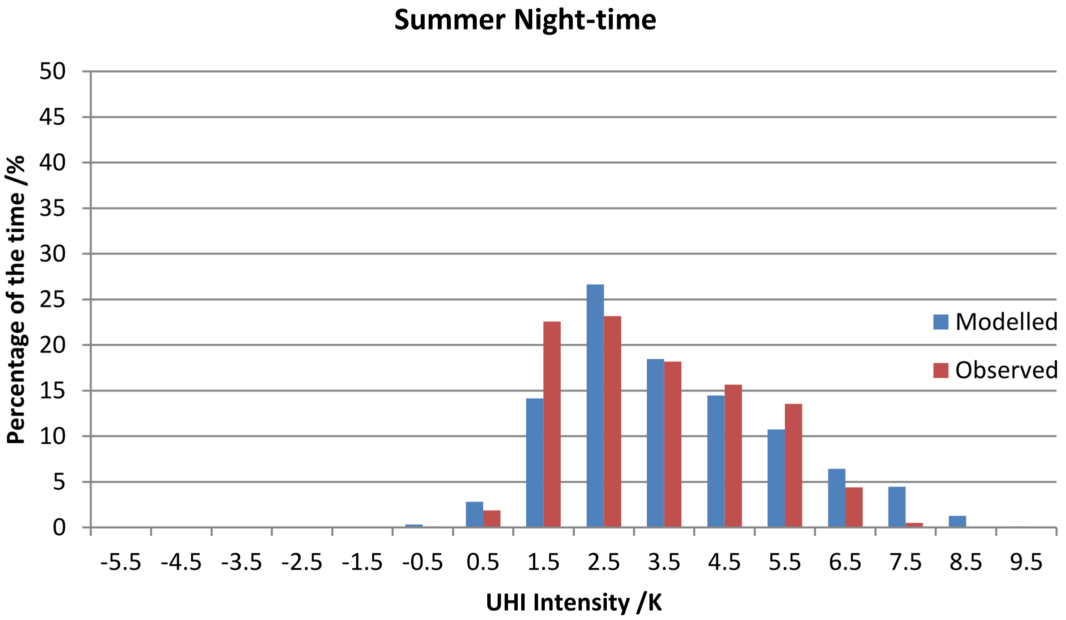


Figure 19 Summer night-time frequency distributions of UHI intensities for observed and modelled data

The differences between the data are as:

- Daytime intensities are rarely above 2.5 K for both sets of data.
- Between 2.5 K and 5.5 K, night-time observed and modelled frequencies are fairly similar.
- The highest night-time observed intensity is 7.5 K, at which frequency of modelled intensities are 3% higher.
- The modelled data does produce intensities up to 8.5 K and 9.5 K, but these are very rare at less than 1.5% of the time.
- Intensities above 5.5 K are 5% more frequent than in the modelled data than the observed.

The frequency distribution above shows that the occurrence of extreme intensities of above 6 – 7K in both sets of data are rare. High UHI intensities are likely to occur in specific conditions; clear skies, low wind speeds and dry weather (Wilby et al., 2011). The results could have been influenced by both the location of the reference point and the differences between the summer heat events between the two datasets. Even with a more rural reference point, the warmer year (2006) does not necessarily result in higher UHI intensities being produced. Although these results represent only one summer period for modelled data, the trends are consistent with further, more exhaustive evidence reported in CIBSE TM49 (CIBSE, 2014).

3.6 Conclusions

3.6.1 Summary of the methodologies used and their results

The work in this chapter used city-scale modelled data to provide an analysis of the spatial and temporal variation in London's UHI. A methodology was developed to analyse the gridded data, by both varying the urban reference point and varying the "rural" references points. Varying the urban reference point showed that the UHI intensity is highest at night and at the centre of the city. Varying the "rural" reference point showed that Heathrow's semi-urban built environment impacts the UHI intensity.

This analysis of the modelled and observed data compared the frequency of occurrence of UHI intensities for the two different sources, following the methodology in CIBSE Guide A (2006). The UHI intensities during a relatively warm simulated year appeared not to vary significantly as compared with observed data relating to a cooler year. These results were similar to the UHI intensity analysis in CIBSE TM49 (CIBSE, 2014).

3.6.2 How can these findings help building designers?

The balance between designing building services to cope with rare extreme climatic events and the extra cost involved in overdesigning is a difficult one to address appropriately. The use of modelled data to show how the UHI intensity varies spatially for London highlighted a few features of the UHI effect and the advantages of using modelled data:

- Radial distance from the centre of the city can be used as an accurate measure of the overall difference between urban and rural air temperatures.
- The choice of reference point has a significant impact on the estimated intensity.

This is true in any city and the gridded output of the model allowed different reference points to be investigated. This is advantageous compared to Met Office weather station data, where long series of data are limited to a select few sites. The limitation of the modelled data is that due to the complexity and availability of the MORUSES model, it was only able to produce data for a summer from one year.

The work in this chapter provides answers to the first and second research questions. The city-scale modelled data was analysed through a developed methodology to provide a more in-depth analysis of the UHI effect in London. The analysis in this chapter can be factored into the building design process through the use of UHI intensities at the early design stages. These data are an indicator of how the location of their buildings will influence nocturnal cooling strategies. The frequency distributions are useful representations how high the UHI intensity can reach. Using the charts, designers can judge that extreme intensities are rare and factoring them into their design could lead to overdesign. However, for robust and more extensive analysis of how the UHI can be factored into design – other forms of analysis should be used. The introduction of additional DSYs in London for a variety of locations within the UHI will allow practitioners to more usefully model the climatic conditions depending on the spatial location of their building within London. The next Chapter analyses whether observed data for Birmingham and Manchester from Met Office weather stations can be used to create new urban DSYs.

4 Urban Heat Island analysis of Met Office weather station data for Birmingham and Manchester for the creation of new CIBSE weather files

4.1 Introduction

The aim of this Chapter is use existing observed climate data to provide more in-depth analysis of the UHI effect in two UK cities; Birmingham and Manchester. This UHI analysis can then be used to assess the appropriateness of additional weather file locations for the creation of 'urban' DSYs for the two cities. The weather files would provide additional tools to building designers to factor in the UHI effect into their design.

The previous Chapter outlined an UHI analysis of city-scale modelled and observed climate data for London. The analysis shows that the location of the chosen reference point significantly impacted the UHI intensity. As outlined in the literature review in Section 2.5, the location of a development within a city can consequently have an impact on building performance in terms overheating risk.

In the UK, overheating risk within buildings is assessed using methodologies such as CIBSE TM52 (2013) and CIBSE TM59 (2017). These assessment methodologies model overheating risk in buildings using CIBSE Design Summer Year (DSY) weather files. As outlined in Section 2.2, DSYs are available for 14 locations and are synthesised from observations from Met Office weather stations (CIBSE Guide A, 2015). As outlined in the review of weather data in Section 2.2, apart from London, the current DSYs are based on observed weather data in rural locations. The work described in CIBSE TM49 reviewed and revised the process used to create DSYs in London (CIBSE, 2014). The work proposed a new method of selecting warm years for assessing overheating risk of buildings at design stage and also analysed how the UHI could be taken into account in London, leading to the creation of DSYs for three new locations. The rural location of most CIBSE weather files could affect overheating analysis within cities, TM49 highlighted this for London. The review of climate data sources in Section 3.2 for London also showed how TM49 assessed the appropriateness of weather station for the creation of new DSYs.

There are a limited number of weather stations in the towns and cities that the 13 CIBSE DSYs are located in (apart from London). A review of the availability of Met Office weather stations from the MIDAS database (Met Office, 2012) in terms of their location and the availability of hourly weather data showed that two cities have appropriate weather stations located in more urban environments – Birmingham and Manchester. These cities are also the most populous and form the largest metropolitan areas (ONS, 2016) and were therefore chosen for the focus of this research.

4.2 Review of available climate data sources that quantify the UHI effect in Birmingham and Manchester

4.2.1 Birmingham

The UHI was first documented in Birmingham by Unwin (1980), who compared weather station data in Birmingham. He compared the nocturnal air temperatures at Edgbaston (urban site) and Elmdon (rural site) for the period 1965 – 74. The maximum UHI intensity observed was 10 K, with an average of 0.27 K and a mean night time maximum of 1.02 K. Johnson (1985) used a 20 km thermographic transect across Birmingham to measure the UHI intensity, measuring a maximum of 4.5K. Both Johnson (1985) and Unwin (1980) found that the UHI intensity was most pronounced during anticyclonic conditions, which produce clear skies, low wind speeds and dry weather such as those experienced in heatwaves (Wilby et al. 2011). More recently, remote sensed MODIS (Moderate

Resolution Imaging Spectroradiometer) Land Surface Temperature satellite data has been used to calculate Birmingham's UHI effect (Tomlinson et al., 2012). The analysis sampled data from June to August from 2003 to 2009 and sorted the data according to atmospheric stability. The highest UHI intensities reached up to 5 K during the most stable atmospheric conditions and up to 7K in a heatwave period in July 2006.

4.2.2 Manchester

In Manchester, observed air temperatures in Greater Manchester for 2010 have quantified the UHI intensity (Cheung, 2011; Levermore and Cheung, 2012). The urban observations were from Piccadilly Gardens located in central Manchester, whilst the rural observations were from a Met Office Station in Woodford. The maximum UHI intensity reached up to 8 K in summer, usually occurring at night. Intensities greater than 8 K can occur during winter nights, but these are very rare. High intensities, of greater than 6 K, are more frequent during summer nights. The mean summer UHI intensity was 2-3 K. Smith et al.(2011) used thermal transects to measure the air and surface temperatures in Manchester for the summers of 2007 and 2008. The maximum nocturnal UHI intensity was observed to be 5 K and the surface temperatures exceeded 10K in some instances.

From the evidence in the literature, significant UHIs have been observed and modelled in both cities.

4.3 Objectives

This work in this Chapter aimed to provide an answer to the second research question by providing an in-depth analysis of the UHI effect in Birmingham and Manchester, using existing observed climate data from more centrally located weather stations within these cities. The UHI analysis of these sites can then provide evidence that a new 'urban' DSY could be appropriate for each city. This analysis aimed to answer the first research question as these weather files would then allow practitioners to factor in the urban climate into building design. To achieve these aims, this Chapter has the following objectives:

- Analyse how observed climate data for Birmingham and Manchester can be used to quantify the Urban Heat Island effect.
- Using the quantified UHI effect from the analysis, assess if observed data from urban weather stations in Birmingham and Manchester can be used to create new weather urban weather files.

The work starts by assessing the availability of weather station data within both cities. This is followed by an analysis that quantifies the Urban Heat Island effect. This analysis is then used to assess if the urban weather station data can be reliably synthesised to produce CIBSE weather files.

The work in this chapter was published in a conference paper and presented at the CIBSE Technical Symposium:

Virk G et al. (2015) Urban Heat Island analysis of Birmingham and Manchester for the creation of new Design Summer Years, CIBSE Technical Symposium. In: CIBSE Technical Symposium, London, UK 16-17 April 2015.

4.4 Methodology

4.4.1 Met Office weather station data availability

The Met Office provided the raw data for all stations located around the 13 sites with hourly air temperature data, which are also available for research purposes from the Met Office Integrated Data Archive System (MIDAS) database (Met Office, 2012).

The coordinates, elevation and distance from city centre of all the weather stations available in both cities are shown in Table 8. As can be seen in Table 8, all these weather stations are both located more than 10 km from the city centre. Figure 20 and Figure 21 show the locations of the weather stations on a map.

Table 8 Coordinates and elevation of weather stations for Manchester and Birmingham

	Latitude (°)	**Longitude (°)**	**Altitude (m)**	**Distance to city centre (km)**	**Start Date**	**End Date**
Birmingham EDGBASTON	52:48N	01:93W	160	2.3	1997	2011
Birmingham WINTERBOURNE	52:46N	01:93W	130	3.0	2002	2011
Birmingham ELMDON	52.452N	-1.741E	96	11.2	1984	1997
Birmingham COLESHILL	52.48N	-1.689E	96	14.3	1998	2013
Manchester HULME LIBRARY	53:47N	02:25W	33	1.5	1997	2011
Manchester RINGWAY	53.356N	-2.279E	69	16.8	1984	2003
Manchester WOODFORD	53.339N	-2.153E	88	13.6	2004	2011

The current location of DSY weather files and the year they are selected from are as follows:

- Birmingham:
  - DSY1 – 1989 – Elmdon
  - DSY2 – 1995 – Elmdon
  - DSY3 – 2006 – Coleshill
- Manchester:
  - DSY1 – 1997 – Ringway
  - DSY2 – 1995 – Ringway
  - DSY3 – 1990 – Ringway

The DSY selection methodology is outlined in further detail in Section 2.2 and are outlined in CIBSE TM49 (2014) and Eames (2016). Both of these cities have weather stations that are located closer to their respective city centres, which have an extensive run of hourly weather data, which are summarised next.

4.4.1.1 *Birmingham weather data*

Birmingham has two urban weather stations with an extensive run of recent temperature data, at Winterbourne and Edgbaston as shown in Figure 20. The rural weather stations used to create the current DSY are Elmdon, which is located next to an airport and Coleshill. For the purpose of the analysis, the UHI evaluation for Birmingham used two urban weather stations and compared them to Coleshill. Elmdon was not included in the analysis due to the limited number of years available.

Figure 20 Location of Birmingham weather stations

4.4.1.2 *Manchester weather data*

Manchester has one urban weather station with extensive temperature data, located at Hulme Library as shown in Figure 21. The two rural weather stations are Ringway, which is located near to Manchester International Airport, and Woodford, which is located next to a smaller airfield.

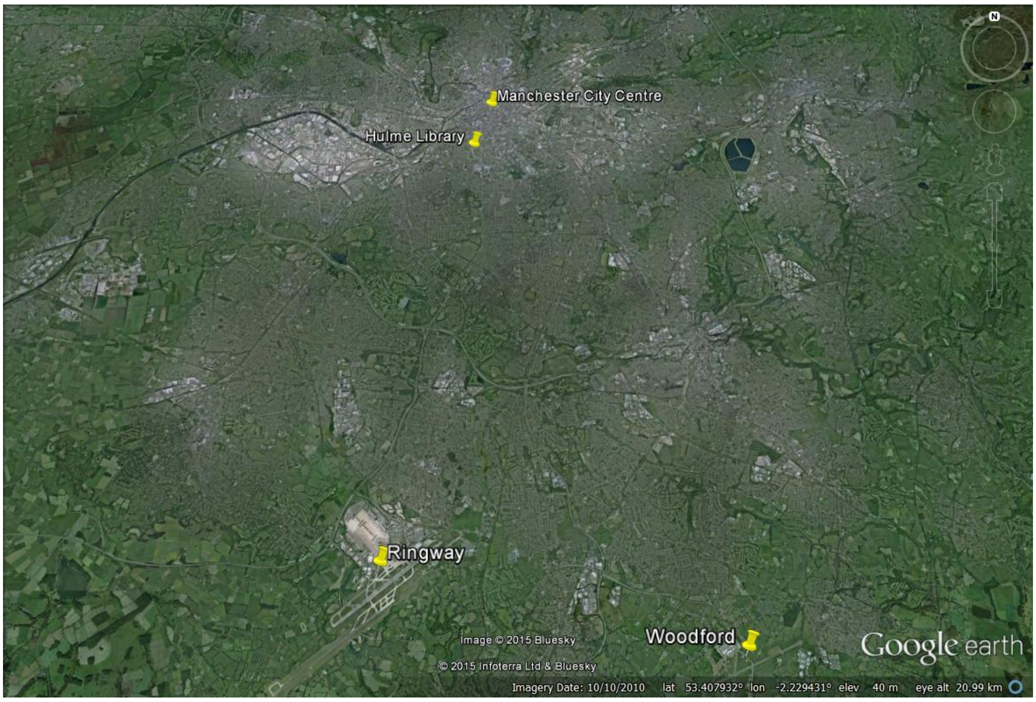


Figure 21 Location of Manchester weather stations

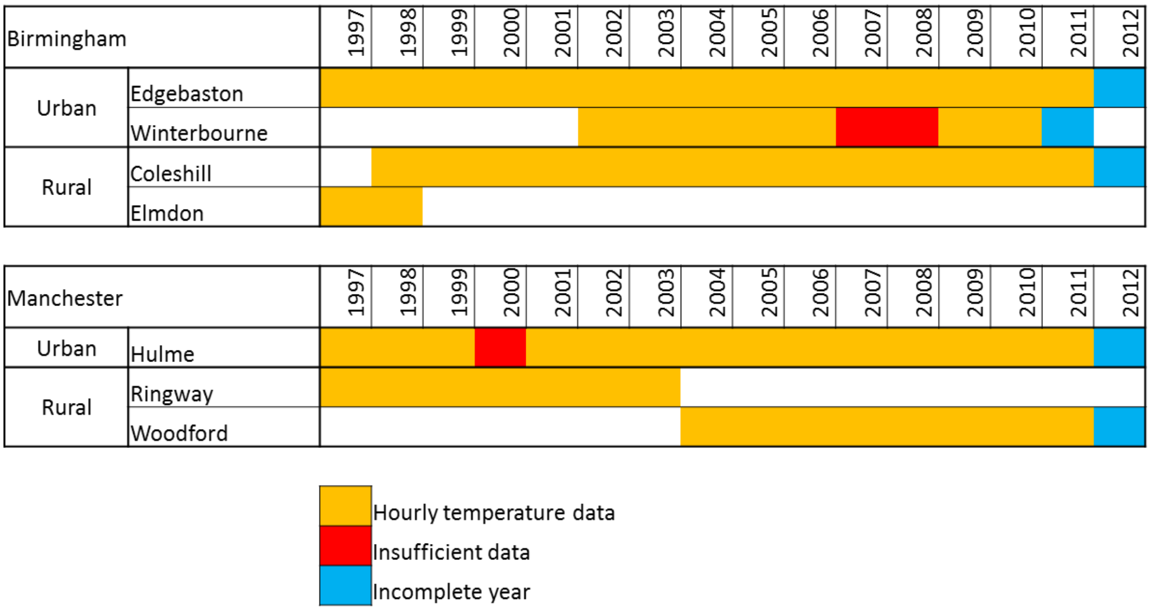
4.4.2 Data processing

Previous work on analysing weather statistics and for the selection of DSY weather files followed the following methodology (CIBSE, 2015; Eames, 2016):

- Where weather station data was limited, the nearest suitable station was used to complete the time series.
- When data is limited at the chosen weather station, an appropriate replacement site was found near to the original at a similar spatial distribution relative to the other sites.

The work in this Chapter aimed to calculate the UHI intensity using different rural and urban reference points. Using the results of the UHI analysis, the appropriateness of the weather station locations can then be assessed. If they are deemed appropriate, then new DSY weather files could be produced.

Figure 22 shows the data availability of the selected sites. The first year for each site is the first complete year of hourly temperature data. Any years with insufficient data, where multiple months of the data is missing, were excluded from the analysis.



Birmingham		1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Urban	Edgebaston	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦
	Winterbourne						🟨	🟨	🟨	🟨	🟨	🟥	🟥	🟨	🟨	🟦	
Rural	Coleshill		🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦
	Elmdon	🟨	🟨														

Manchester		1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Urban	Hulme	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦
Rural	Ringway	🟨	🟨	🟨	🟨	🟨	🟨	🟨									
	Woodford								🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦

🟨 Hourly temperature data
🟥 Insufficient data
🟦 Incomplete year

Figure 22 Data availability for weather stations chosen

There were still missing temperature data from the MIDAS datasets which were interpolated using the following methodology, outlined in Eames (2016) and using algorithms from previous work (Eames et al., 2011; Levermore and Parkinson, 2006):

1. Periods of data which are unlikely to contain a daily minima or maxima are flagged for interpolation.
2. During the flagged periods, missing daily extrema are interpolated using valid points either side.
3. Hours at which these extrema occur are linearly interpolated.
4. All other missing data are interpolated along with the generated minima and maxima using a spline algorithm.

4.4.3 Data analysis methodology

For both cities, the longest run of data available is 14 years for Edgbaston and Hulme, which could be extended up to 16 years if 2012 and 2013 are available. The data are analysed in the following ways; the summer period used is May to September:

Weather statistics

The daily minimum temperature (*Tmin*) and daily maximum temperature (*Tmax*) are averaged for the whole seasonal dataset for each location for the summer period (May to September) of each year. The maximum and minimum temperatures of each location are also presented.

UHI intensity and mean diurnal UHI intensity:

The reference points used to calculate the UHI intensity for each location are varied depending on city due the data limitations outlined above are as follows:

- Birmingham
    - Rural reference point – Coleshill (1998 to 2011),
    - Urban reference point – Winterbourne (2002 to 2011)[21] and Edgbaston (1998 to 2011),
- Manchester
    - Rural reference point – Ringway (1997 to 2011) and Woodford (1998 to 2011)
    - Urban reference point – Hulme (1997 to 2011) [22]

The UHI intensity is calculated by first subtracting the concurrent hourly rural temperature from the urban location and then averaging for each hour, the data is presented as:

- The frequency of occurrence of UHI intensities for the whole summer period for the whole available dataset are presented.
- The above is repeated for each location for two notable heatwave periods, August 2003 and July 2006 for each city.

The analysis is repeated for the heatwave periods as if a new DSY weather file were to be produced, the selection methodology outlined in CIBSE TM49 (2014) and in Eames (2016) will choose DSYs dependent on the type of historical heatwave event. The years 2003 and 2006 were notable historical national heatwave events (Eames, 2016).

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[21] Some years are excluded from Winterbourne due to limited data, see Figure 22.

[22] Some years are excluded from Hulme due to limited data, see Figure 22.

4.5 Results

4.5.1 Birmingham

Table 9 shows the temperature analysis for the summer period for the Birmingham weather stations. The daily mean *Tmin* shows the differences between the urban and rural stations. Winterbourne and Edgbaston are more than 1°C warmer at night (*Tmin*) compared to the Coleshill. However, when the mean diurnal UHI intensity is plotted as shown in Figure 23, there is a difference between the two urban sites.

Table 9 Birmingham summer air temperature analysis for whole dataset

	Mean (°C)			Min (°C)	Max (°C)
Station	Tmean	Tmin	Tmax	Tmin	Tmax
Winterbourne	14.8	10.4	19.1	-0.9	33.6
Edgbaston	14.87	11.5	18.6	2.7	33.5
Coleshill	10.55	9.2	19.1	-0.7	34.1

Edgbaston has a standard UHI profile, where the night time temperatures are higher than the rural location, the mean diurnal intensity does not exceed 0.8 K and there is an urban 'cool island' during hours of daylight. This could be due to the extra thermal capacitance of the urban surfaces, absorbing incoming solar radiation to a greater extent than at a rural location and subsequently lowering near surface air temperatures.

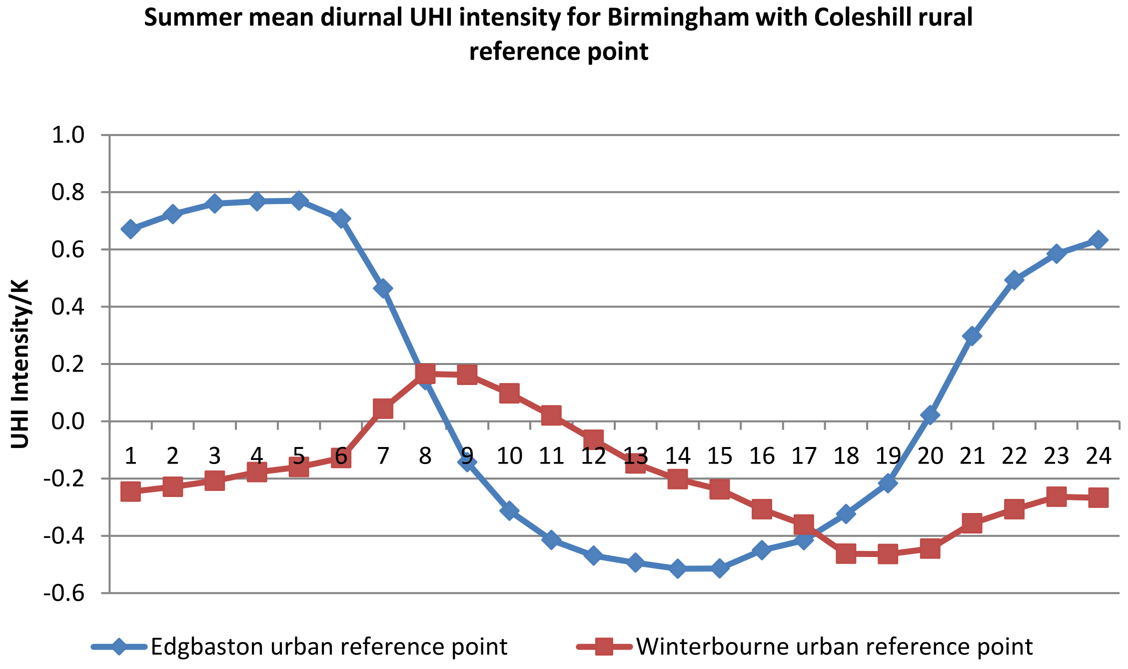

Figure 23 Mean diurnal UHI Intensity for summer for whole Birmingham dataset

The Winterbourne diurnal profile shows that on average there is not a large variation in temperatures compared to Coleshill. The mean UHI intensity does not increase above ±0.5 K. The station is located within the Winterbourne Botanical Gardens and the park-based location results in lower air temperatures compared to Edgbaston. The difference between the two stations is further highlighted in the frequency of occurrence of UHI intensities plots as shown in Figure 24 and Figure

25. Typical UHI intensities frequency distributions between urban and rural locations will be mostly positive. When Winterbourne is used the urban site, for almost 10% of the time at night, it is cooler than the rural Coleshill – which is not typical of an urban site.

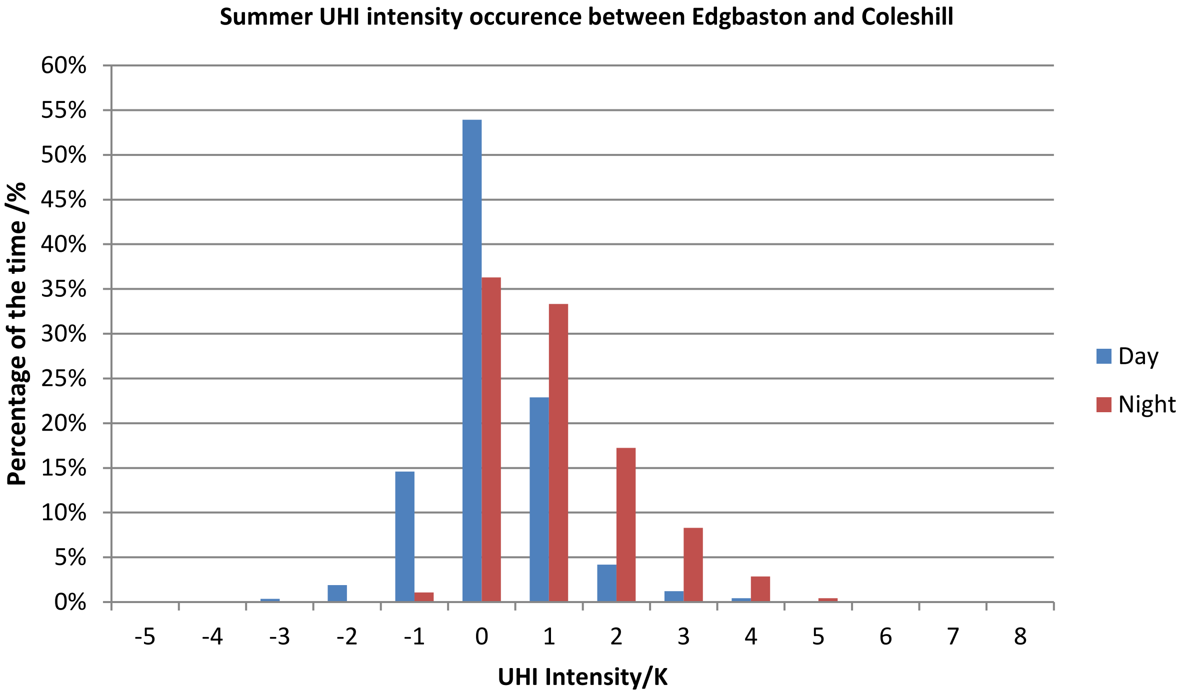

Figure 24 Frequency of occurrence of UHI intensities with Edgbaston as urban reference point

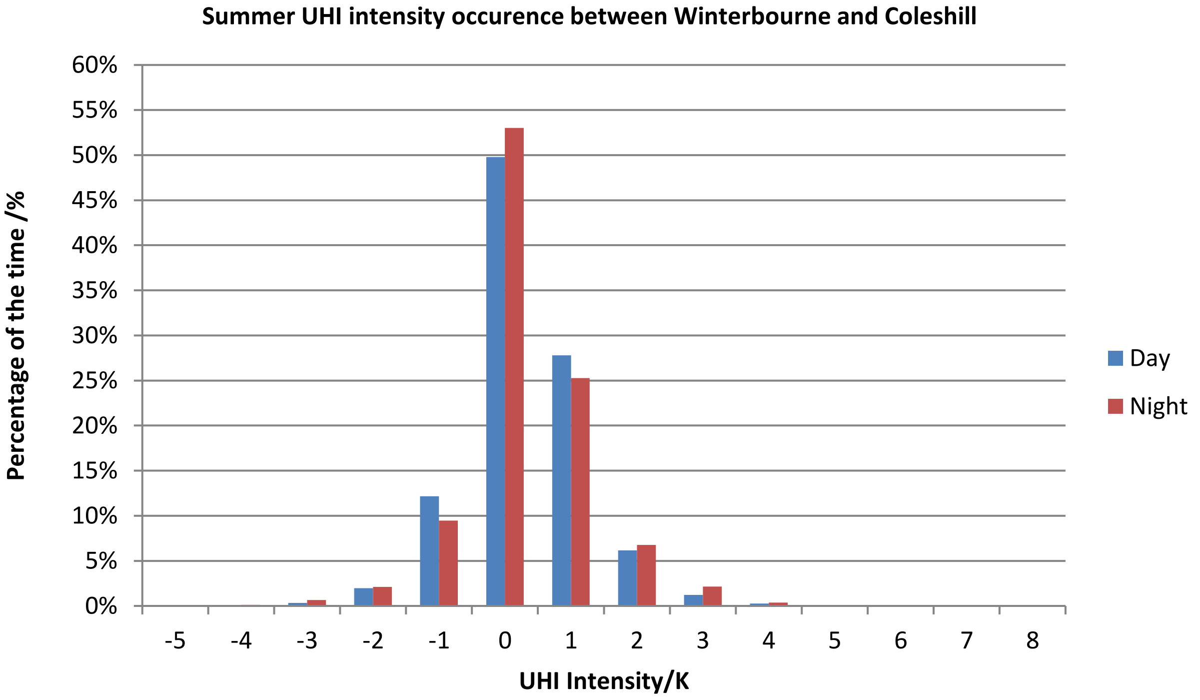

Figure 25 Frequency of occurrence of UHI intensities with Winterbourne as urban reference point

When Edgbaston is the urban reference point, the frequency of daytime intensities at 2 K is more than double that compared to Winterbourne. At night, the Edgbaston frequency distribution has a greater skew towards higher intensities. Both reference points rarely have UHI intensities of above 2 K, with the frequency of occurrence of any higher intensities being less than 10% of the time. The results clearly show a difference between the two urban sites. One explanation for this could be their proximity to the city centre. However, Winterbourne has been shown to be an inappropriate station to use data from. This is due to it being located within an urban park as evidenced by the analysis. Images and the mapped locations of the of Edgbaston and Winterbourne weather stations are shown in Figure 26, Figure 27, Figure 28 and Figure 29.

Figure 26 Edgbaston measuring equipment located at a suburban location – non-standard Met Office station © Crown copyright 2015 Met Office

Figure 27 Edgbaston measuring equipment located at a suburban location – Source: Google maps.

Figure 28 Winterbourne measuring equipment, located in a park – non-standard Met Office station © Crown copyright 2015 Met Office

Figure 29 Winterbourne park and the surroundings – Source: Google maps.

Both sites are non-standard Met Office sites, they do not meet the criteria set out by the World Meteorological Organisation (Oke, 2006a) due to their semi-urban location. Both images show evidence of some of the microclimatic factors that could impact measurements, such as rooftop location (Edgbaston) and amount of green space (both sites).

4.5.1.1 *Birmingham Heatwave Period*

Due to the issues with the data from Winterbourne, only data from Edgbaston was used when analysing the two heatwave periods – August 2003 and July 2006. The results in the previous analysis show that Winterbourne would not be an appropriate location for an urban weather station as it has the observations are impacted by the surrounding microclimate and can be discounted from further in-depth UHI analysis.

Table 10 Birmingham air temperature analysis for two heatwave periods

	Mean (°C)			Min (°C)	Max (°C)
Station	Tmean	Tmin	Tmax	Tmin	Tmax
Edgbaston Aug 2003	18.3	14.4	22.8	8.5	33.2
Coleshill Aug 2003	18.1	12.9	23.5	5.9	34.1
Edgbaston Jul 2006	20.3	15.5	25.4	10.7	33.5
Coleshill Jul 2006	20.0	14.1	26.0	7.5	34.1

As shown in Table 10, the mean *Tmin* is fairly similar compared to the whole seasonal dataset. However, when the mean diurnal UHI intensity is plotted in Figure 30, there is an increase in the night-time temperature differences. The mean night time intensities did not increase above 0.8 K for the seasonal dataset, but now the maximum intensity varies between 1-1.5 K.

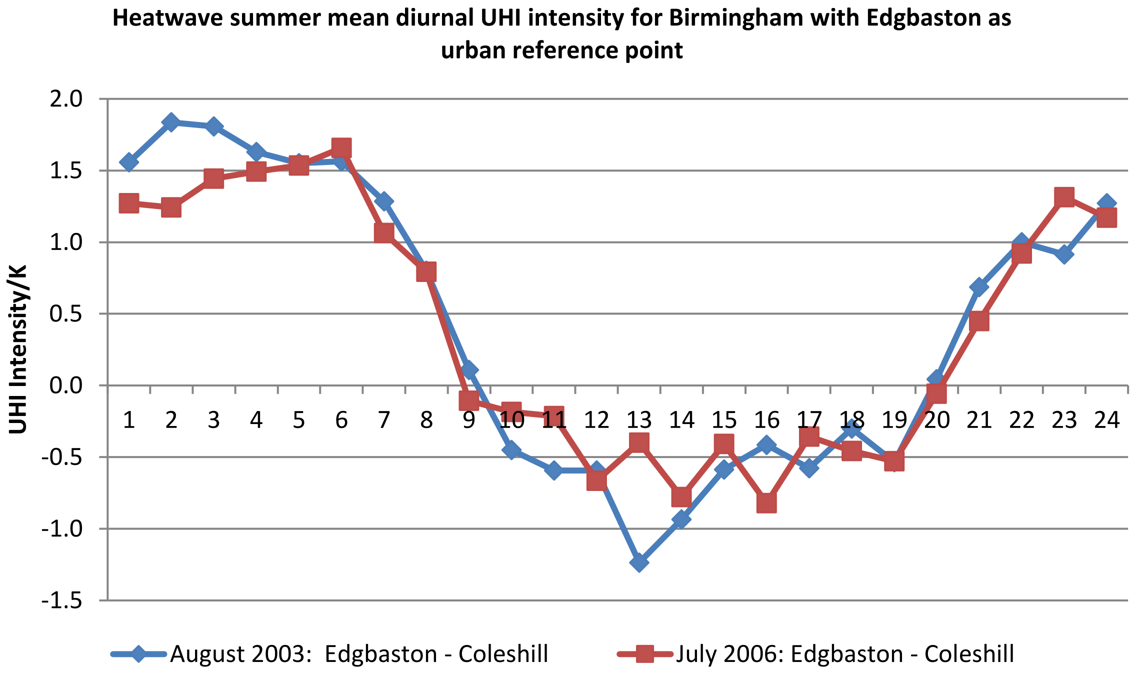

Figure 30 Mean diurnal UHI Intensity for two heatwave periods for Edgbaston compared to Coleshill

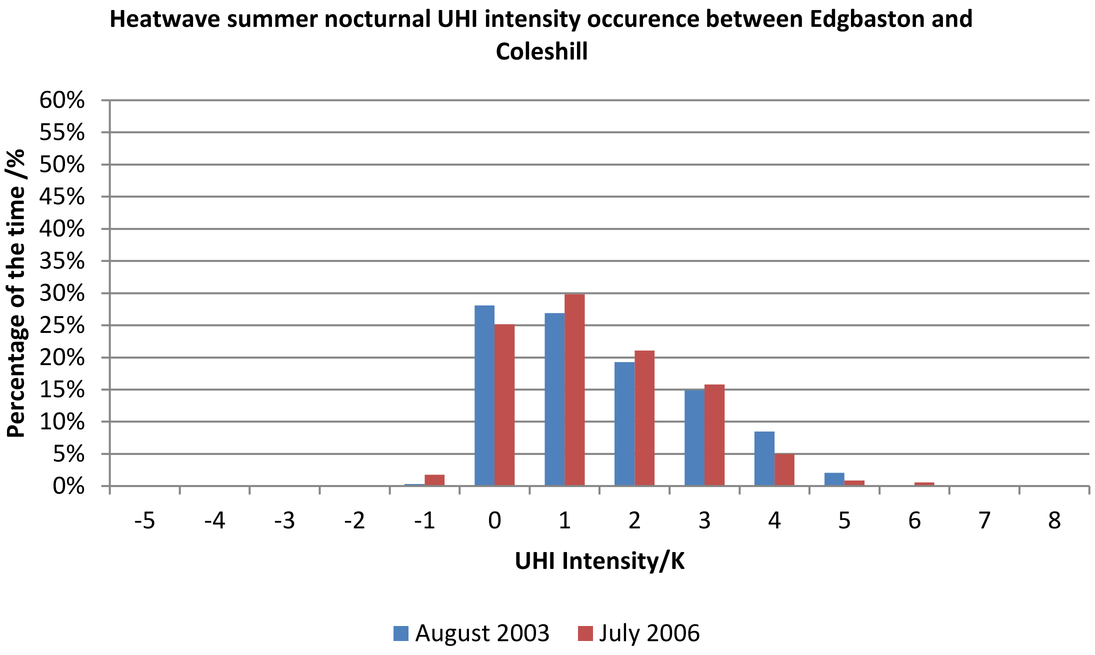

Figure 31 Frequency of occurrence of night-time UHI intensities for two heatwave periods for Birmingham Edgbaston compared to Coleshill

The night-time frequency distribution also shows how UHI intensities of greater than 2 K are now more frequent, as shown in Figure 31. There is not a significant difference between the two heatwave periods for Birmingham.

4.5.2 Manchester

The temperature analysis for the Manchester weather stations is shown in Table 11. For Manchester, the differences between the two rural reference point results in varied temperatures compared to Hulme. The difference between the mean *Tmin* for Woodford compared to Hulme is greater than when compared to Ringway. The reason for this could be that Ringway is located near a large airport and this influences the night time temperatures compared to Woodford, which is in a more rural location next to an airfield.

Table 11 Manchester summer air temperature analysis for whole dataset

	Mean (°C)					Min (°C)	Max (°C)
Station	Tmean	Tmin	Variance	Tmax	Variance	Tmin	Tmax
Hulme	15.4	12.2	8.1	18.8	13.2	2.8	32.1
Woodford	14.3	10.1	10.8	18.2	12.2	-1.7	30.7
Ringway	14.8	11.2	8.7	18.5	13.4	0.0	31.5

The difference between the rural stations is also evidenced when the mean diurnal UHI intensity is plotted in Figure 32. The night-time UHI intensities are higher when Woodford is the reference point compared to Ringway. On average, the Woodford intensities reach up to 1.8 K compared to 1 K for Ringway.

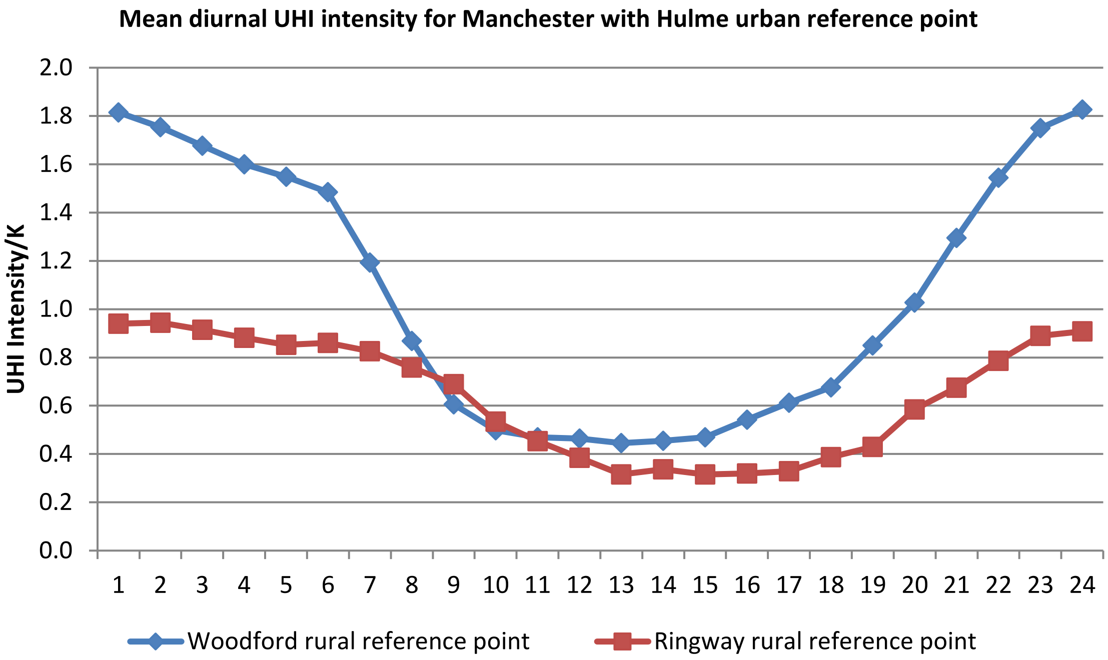

Figure 32 Mean diurnal UHI Intensity for summer for whole Manchester dataset

As shown in Figure 33 and Figure 34, Manchester Hulme is located on a rooftop in a suburban location. As with the urban Birmingham sites, it is a non-standard WMO site and wind profiles will be influenced by its rooftop location.

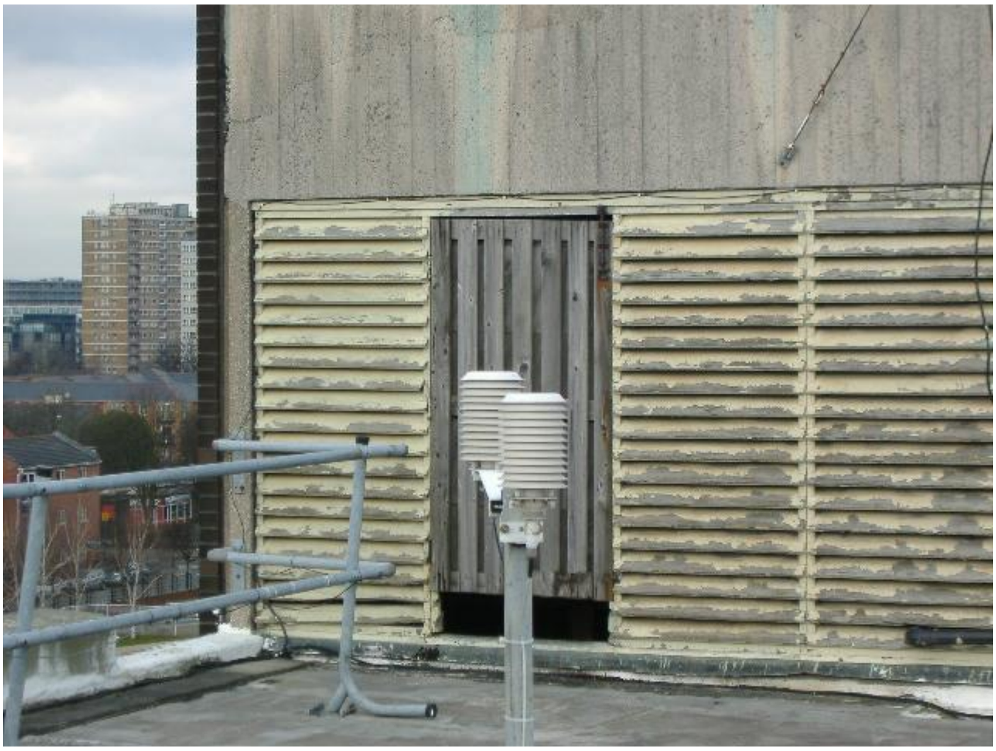

Figure 33 Hulme measuring equipment, rooftop location – non-standard Met Office station © Crown copyright 2015 Met Office

Figure 34 Hulme measuring equipment location – Source: Google maps.

Compared to Birmingham, Manchester does not show evidence of an urban “cool island”, as daytime intensities are positive. This could be explained by the local microclimates around the two rural sites. They are both located near to runways, which are likely to be tarmac-like surfaces. These surfaces will absorb more incoming solar radiation compared to a more rural weather station, such as Coleshill. This would prevent an urban “cool island” forming and resulting in negative UHI intensities.

The difference between the rural stations is further highlighted in Figure 35 and Figure 36. The frequency of night-time intensities above 2 K is greater when Woodford is the rural station compared to Ringway. The intensities rarely reach above 3 K at Ringway.

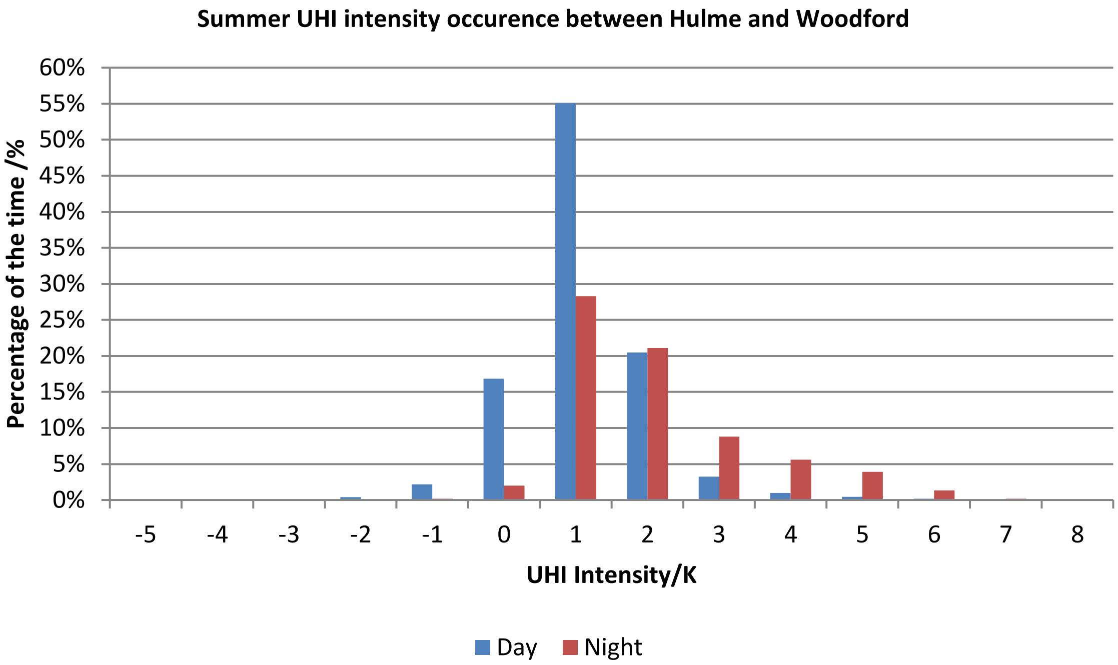

Figure 35 Frequency of occurrence of UHI intensities with Woodford as rural reference point

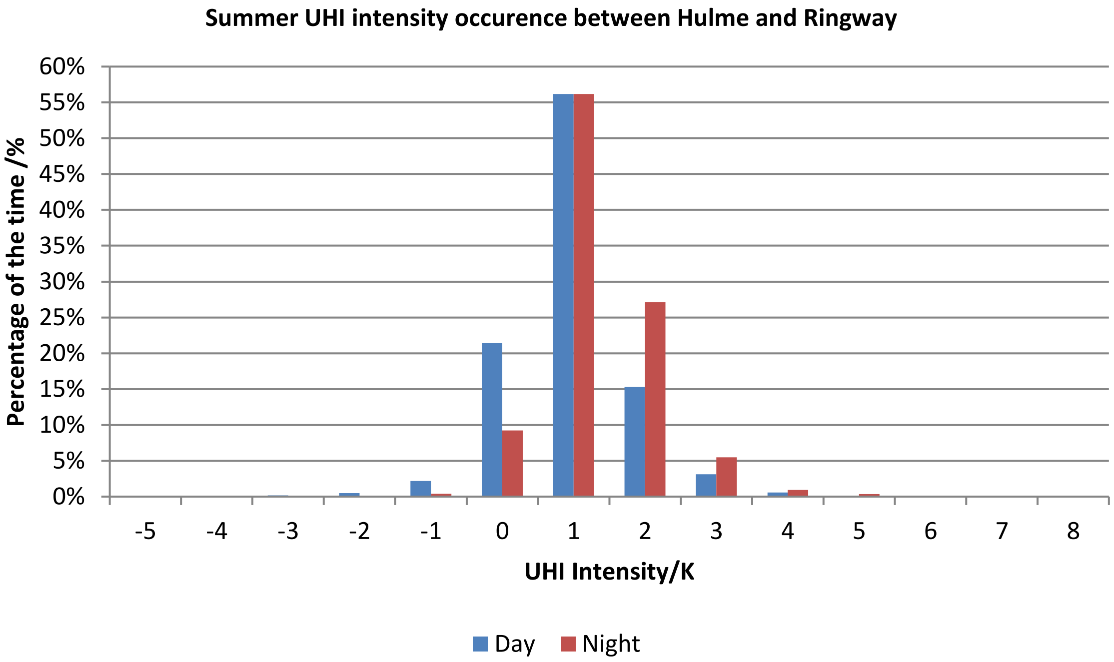

Figure 36 Frequency of occurrence of UHI intensities with Ringway as rural reference point

4.5.2.1 *Manchester Heatwave Period*

Due to the data availability as shown in Figure 22, when comparing the heatwave periods, Ringway is the rural reference point in 2003 and Woodford is the reference point for 2006. The temperature analysis for these periods is shown in Table 12. The difference in mean *Tmin* is the same as the overall seasonal dataset when comparing Hulme to Ringway in August 2003. However, in July 2006, the difference in *Tmin* is 1°C higher than the overall seasonal dataset when comparing Hulme to Woodford.

Table 12 Manchester air temperature analysis for two heatwave periods

	Mean (°C)			Min (°C)	Max (°C)
Station	Tmean	Tmin	Tmax	Tmin	Tmax
Hulme Aug 2003	18.3	14.7	22.2	7.3	32.1
Ringway Aug 2003	17.5	13.6	21.7	6.0	31.5
Hulme July 2006	20.8	16.3	25.4	12.0	31.2
Woodford July 2006	19.4	13.4	24.9	8.0	30.7

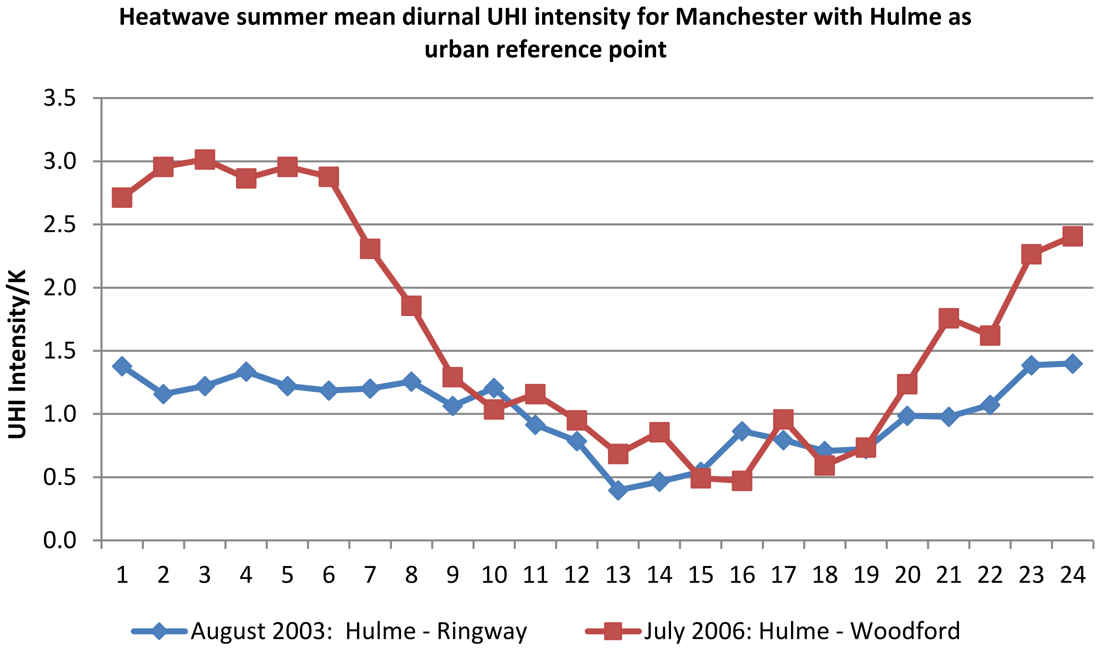

Figure 37. Mean diurnal UHI Intensity for two heatwave periods – rural reference point is varied

The mean diurnal UHI intensity plot for these two periods again highlight how the rural stations differ from one another, as shown in Figure 37. The plot for July 2006 when Ringway is the rural reference point does not differ that much compared to the Ringway plot for the overall seasonal dataset in Figure 37. However, there is a difference in the Woodford plot during the heatwave period as the mean diurnal intensity reaches 2.5 K.

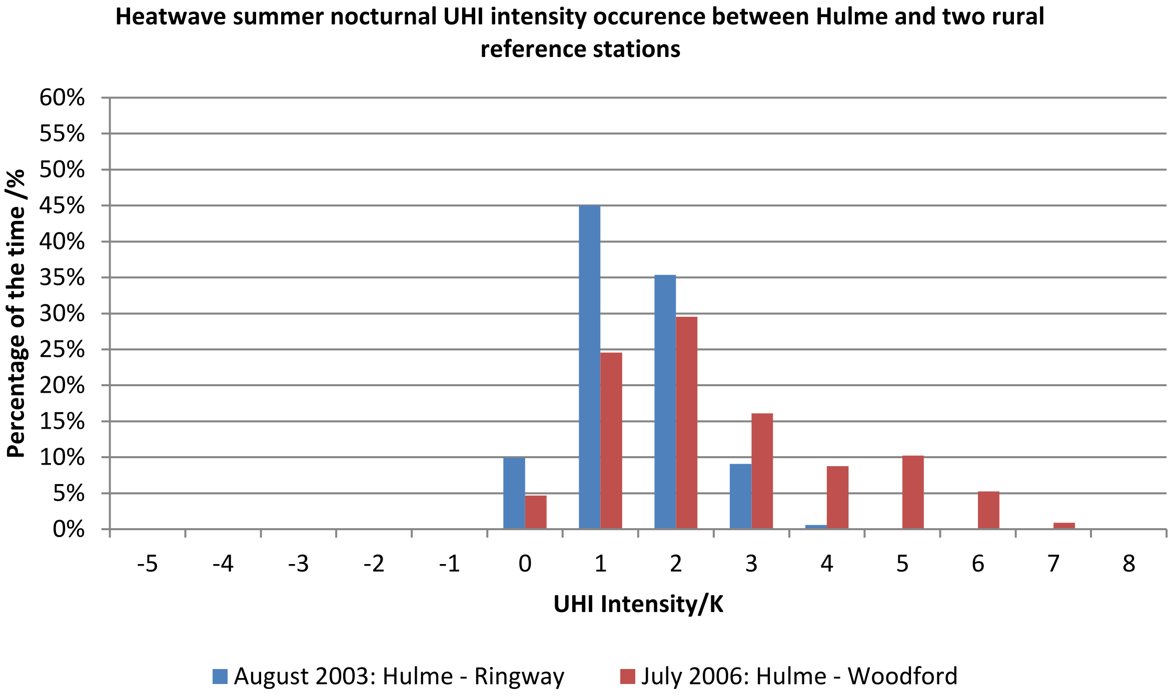

Figure 38. Frequency of occurrence for night-time heatwave period for Manchester

During the two heatwave periods, the frequency of UHI intensities higher than 2 K is only higher in July 2006, with Woodford as a rural reference point as shown in Figure 38. The frequency distribution of July 2006 is skewed towards the higher frequencies, with intensities of 3-6 K all occurring for more than 5% of the time.

4.6 Conclusions

4.6.1 Summary of the methodologies used and their results

The work in this Chapter analysed the UHI effect in Birmingham and Manchester using observed data from the MIDAS dataset. The urban reference points in the analysis were non-standard Met Office weather stations located closer to the city centre of each city. The UHI intensity was calculated from using historical weather station data and the rural and urban reference points were varied according to data availability.

The aim of the chapter was also to assess whether the potential weather station sites for Birmingham and Manchester have high enough UHI intensities to justify a new ‘urban’ DSY. The literature review in Section 2.4, highlighted that there is plenty of existing evidence that both cities can have high UHI intensities of up to 7 – 8 K maximum intensities. The results from the Met Office weather stations do show evidence of similar mean maximum intensities of 7 – 8 K for Manchester and 5 – 6 K for Birmingham for all years in the dataset. As outlined in the previous Chapter 3, the location of either rural or urban reference points is a crucial factor in any UHI analysis, as local factors impact the weather data.

When analysing the whole seasonal dataset for Birmingham, UHI intensities above 2 K are rare. When two heatwave periods are selected, there is an increase in higher frequencies of high intensities. For Manchester, intensities above 2 K are also rare, occurring less than 10% of the time. However, in July 2006, with Woodford as a rural reference point, there is a noticeable increase in the frequency of higher intensities.

4.6.2 How can these findings help building designers?

The analysis in this Chapter investigated whether the meteorological data available for Birmingham and Manchester would justify the production of a new urban Design Summer Year (DSY) for the city. Modelled and observed data can be used to analyse the UHI effect in cities as shown in the analysis in the previous Chapter. This work aimed to answer the second research question as the analysis of the existing weather data confirmed that the UHI intensity within both cities is significant. The analysis included an assessment of the suitability of the urban weather station sites for producing a new CIBSE DSY weather file. This analysis aimed to answer the first research question, as any new weather files used in building simulation would capture the UHI effect, which could be used to analyse the overheating risk in a building throughout the year.

One of the issues with both cities is that the stations available are not located in the centre of either city and are non-standard Met Office stations. London Weather Centre has a core urban location, although it is located on a rooftop. Manchester Hulme is located 1.5 km outside the city centre and is also located on a rooftop. Birmingham Edgbaston is also located outside the city centre and Birmingham Winterbourne is an inappropriate station to use data from as it is located within an urban park as evidenced by the analysis. Images of the weather stations show evidence of some of the microclimatic factors that could impact measurements, such as rooftop location and amount of green space. This is one of the main issues with weather stations located within cities. The height at which the stations are placed will be impacted by alterations to wind profiles. In terms of rural stations, Ringway being located near a larger airport and more centrally than Woodford and this could impact how high the UHI intensity.

The advantage of having a new ‘urban’ DSY is that it gives designers the option of using a more centrally located weather station for either Birmingham or Manchester and allows them to make a judgement as to how it will affect their design. The current DSY files potentially underpredict the performance of buildings in terms of overheating. The production of a new ‘urban’ DSY would depend on a number of factors, which are discussed next.

The quality and quantity of temperature data available to produce a new weather file needs to be assessed. As with the London Weather Centre Met Office station which was analysed in TM49 (CIBSE 2014), Hulme and Edgbaston are both non-standard sites as they do not conform to WMO standards.

The hourly temperature data available for each site is also limited to 14 to 16 years. London Weather Centre and London Gatwick have almost 30 years of continuous temperature data, which means that appropriate hot events (for DSYs) and average months (for TRYs) can be selected. The other issue is whether crucial variables such as wet bulb temperature, cloud cover and sunshine exist for these stations or whether they can be sourced from nearby sites. For London weather files, when there have been missing variables from weather stations, weather files have been synthesised with data from other nearby locations. This methodology could be repeated for Manchester and Birmingham after reviewing what data was available.

Due to the limited number of Met Office stations available for each city, any new ‘urban’ DSY that used the stations outlined in this Chapter would not be truly urban. They would represent a semi-urban location, with warmer air temperatures observed at each location. The issue of a how much baseline data is available to carry out the TM49 methodology to select new ‘urban’ DSYs is a limitation. The next stage of producing any new ‘urban’ DSY is to analyse what other weather data is available to construct a new weather file, which would include using data from other sites for other variables. Future work should include testing any potential weather files to see how the annual energy balance and overheating levels are impacted. As outlined in Section 2.2, new DSY locations have been produced and the next chapter used a case study to test the new London DSYs.

5 Using the new CIBSE Design Summer Years to assess overheating and adaptation strategies in an existing office in London and the effect of the urban heat island on design

5.1 Introduction

The aim of this chapter is to test the CIBSE Design Summer Year (DSY) weather files using a case study in London that represents an existing office. This research project coincided with the public release of new DSY weather files for London. These files represent new sources of climate data from existing observed weather station data that can be factored into building design through the use of dynamic thermal simulation software. This chapter aimed to analyse the new weather files to assess how differences within the weather files capture the UHI effect in London and then apply them to an existing case study building. The case study also allowed the effect of simple retrofitted design adaptation strategies to be tested.

The work in Chapter 3 showed how the UHI intensity in London varies depending on the radial distance of the reference point from the centre of the city. Building designers in the UK use DSY weather files to assess overheating risk in cities, however these weather files are located in rural locations. Chapter 4 analysed the appropriateness of potential new “urban” weather file locations for Birmingham and Manchester in terms of key climate variables. As both cities have an UHI, the current weather stations used to create the DSY weather files are potentially underpredicting the night-time temperatures as they do not capture the UHI effect.

As outlined in Section 1.1, summertime overheating is increasingly being recognised as a major design issue in the sustainable development of buildings (CCC, 2018; House of Commons, 2018)(DEFRA, 2012; GLA, 2011; PHE, 2015). For London, studies have shown that on average the closer a building is located to the centre, the higher the level of overheating (Demanuele et al., 2012; Kolokotroni et al., 2006, 2007; Oikonomou et al., 2012), but there is still much variation due to site specific microclimatic factors. Previous work has shown that it may be difficult to mitigate overheating within existing free running buildings without the use of adaptation measures such as (Holmes and Hacker, 2007; Jentsch et al., 2008):

- External solar shading,
- Use of thermal mass,
- Ventilation strategies such as night cooling.

The literature review in Section 2.3 and 2.6 also highlighted the use of low-albedo surfaces as design adaptations that can mitigate overheating. There is need for increased use of passive design solutions in order to reduce the energy use of buildings to meet future emissions targets. As passive natural ventilation strategies interact with the external environment to cool a building, designers need appropriate tools and data in order to ensure appropriate solutions. There is also a need to ensure any retrofitted design adaptations such as additional insulation and improved glazing to meet current regulatory standards do not exacerbate the risk of overheating within free running buildings.

When the new London DSYs were released, there was a need to analyse the differences between the weather files in terms of similar key climate variables which impact internal temperatures and apply them to a case study to understand if these differences do impact building performance in terms of overheating risk and retrofitted design adaptations.

5.2 CIBSE Overheating Criteria

CIBSE Guide A provided guidance to assess summertime overheating for free-running buildings. Guide A recommended a criterion where operative temperatures should not exceed 28°C for 1% of occupied hours (CIBSE, 2006). This will be referred to as the "Old Criteria" in this chapter. Following a review by the CIBSE Overheating Taskforce, the new overheating criteria use the adaptive approach to thermal comfort. Technical Memorandum 52 (CIBSE, 2013b) outlines the new criteria which are based on BS EN 15251 (British Standards Institution, 2007). The recommendations of the Taskforce and the resulting criteria for naturally ventilated buildings are outlined below.

The adaptive equation for comfort used in BS EN 15251 relates the indoor comfort temperature to the outdoor air temperature and is defined as

$$T_{comf} = 0.33T_{rm} + 18.8°\mathrm{C}$$

where T_{comf} is the internal comfort temperature and T_{rm} is the exponentially weighted running mean of the daily-mean outdoor air temperature as outlined in CIBSE Guide A (CIBSE, 2006). The new guidance suggests acceptable temperature ranges in relation to T_{comf}, as shown in Table 13. These categories define the maximum allowable difference between the operative temperature and T_{comf} for the building being simulated.

Table 13 Suggested categories defined by acceptable temperature ranges of deviations from Tcomf. Source: (CIBSE, 2013b)**.**

Category	Explanation	Suggested acceptable range (°C)
I	High level of expectation only used for spaces occupied by very sensitive and fragile persons	± 2
II	Normal expectation (for new buildings and renovations)	± 3
III	A moderate expectation (used for existing buildings)	± 4
IV	Values outside the criteria for the above categories (only acceptable for a limited periods)	> 4

The guidance recommends that new and renovated buildings should be designed to fall within category 2 limits for naturally ventilated buildings. The maximum acceptable temperature T_{max} for these buildings is consequently defined as

$$T_{max} = 0.33T_{rm} + 21.8°\mathrm{C}$$

Using this maximum temperature threshold, all the new criteria are based on the following temperature difference

$$\Delta T = T_{op} - T_{max} \quad (°\mathrm{C})$$

where T_{op} is the internal operative temperature and T_{max} is the upper limit of the acceptable comfort temperature. Using ΔT the criteria directly quoted from the guide (CIBSE, 2013b) are as follows;

- Criterion 1 - Hours of Exceedance (H_e): The number of hours (H_e) that ΔT is greater than or equal to one degree (K) during the period May to September inclusive shall not be more than 3% of occupied hours.
- Criterion 2 – Daily Weighted Exceedance (W_e): To allow for the severity of overheating the weighted exceedance (W_e) shall be less than or equal to 6 in any one day, where

  $$W_e = (\Sigma h_e) \times WF = (h_{e0} \times 0) + (h_{e1} \times 1) + (h_{e2} \times 2) + (h_{e3} \times 3)$$

  where WF is the weighting factor and is equal to 0 when $\Delta T = 0$.

- Criterion 3 - Upper Limit Temperature (T_{upp}): To set an absolute maximum value for the indoor operative temperature the value of ΔT shall not exceed 4K.

Criterion 1 assesses the frequency of overheating within the building, calculating how often the operative temperature exceeds the ±3 K above T_{comf}, which is the limit defined as $T_{max.}$ Criterion 2 assesses the severity of repeated overheating. Finally, criterion 3 assesses whether the maximum comfort temperature has been exceeded for any period where there is excessive overheating. If a building fails two of the criteria for occupied hours, it is classed as overheating. As outlined above in order to calculate whether the building is overheating, only the operative temperature and outdoor running mean are needed from the simulations.

5.3 Climate data used in overheating assessments in London

As outlined in more detail in Section 2.2, the CIBSE Design Summer Year (DSY) is the industry standard for assessing overheating when using the TM52 and TM49 overheating assessment methodologies (CIBSE, 2013b, 2014). Previously, the DSY represented the warmest past year available in the middle of the upper quartile as ranked by mean temperature. The existing DSY file for London was available for LHR for 1989. TM49 reviewed and revised the process used to select DSYs (CIBSE, 2014). The TM assessed how warm years were chosen and also analysed how the UHI could be taken into account in London. The new DSYs are available for three locations London Weather Centre (LWC), London Heathrow (H) and London Gatwick (Gat) for the following baseline years which represent summers with different heatwave events:

- 1976 – a relatively intense persistent warm spell,
- 1989 – a moderately warm summer,
- 2003 – a single intense warm spell.

The weather files represent an urban (LWC), semi-urban (H) and rural (Gat) location, see Figure 10 for a map with the locations of the weather files. As has been outlined in Section 2.2 and in Section 3.1, the output of CIBSE TM49 means that a practitioner now has a choice as to which is the most appropriate weather file, dependent on location and overheating risk (CIBSE, 2014). TM49 recommends that all three of these years are used in the design process in order to investigate the sensitivity of the design to different weather conditions such as heatwave events (CIBSE, 2014). The UKCP09 Climate Projections predict that summer mean temperatures will increase by 2.7°C by the 2050s (central estimate) in London (UKCP09, 2010). The new DSYs are also available for UKCP09 probabilistic future climate projections for the 2020s, 2050s and 2080s (UKCP09, 2010). With the use of future weather files, the future resilience and overheating risk of developments can also be simulated.

5.4 Future CIBSE weather files

To estimate future building performance in terms of overheating risk using a DSY or energy use a TRY weather file, weather files need to be produced for future climate scenarios. As outlined in Section 2.2, CIBSE weather files are available for UKCP09 climate projections (UKCP09, 2010) for three time periods (2020s (2011-2040), 2050s (2041-2070) and 2080s (2071-2100)), for the following emissions scenarios:

- 2020s – High emissions scenario – 10th, 50th, 90th percentile,
- 2050s – Medium – 10th, 50th, 90th,
- 2050s – High – 10th, 50th, 90th,
- 2080s – Low, 10th, 50th, 90th,
- 2080s – Medium – 10th, 50th, 90th,
- 2080s – High – 10th, 50th, 90th.

The weather files are produced using a "morphing" methodology originally outlined in CIBSE TM36 and in Belcher, Hacker and Powell (Belcher et al., 2005; CIBSE, 2005b). The methodology modifies each weather variable in the current files to the selected future climate scenarios through the following mathematical operations:

1. an absolute change or shift of the current hourly weather variable,
2. a stretch of the current hourly variable for relative projections,
3. a combination of both shifting and scaling to reflect future climate projections.

The methodology allows the future weather files to be meteorologically consistent with current weather files and preserves the location specific differences in the weather files. There has been criticism the methodology does not allow for extreme anomalies in the projections (Jentsch et al., 2008) and that limiting weather files to a selection of a single climate model and a single emission scenario does not allow for the variability in future climate projections (Eames et al., 2012). Alternative methods of creating future files include the Weather Generator (Sustainable Energy Research Group, n.d.), the methodology of which is outlined in Jentsch (2008).

CIBSE limited the number of future climate scenarios was to keep the number of files to a manageable size (CIBSE, 2014). The weather generator outputs represent statistically credible representations of what may occur in the future. As the morphing methodology "shifts" and "stretches" the observed data from the original DSY baseline. This allows comparable performance of current and future simulations compared to the using files produced by the weather generator.

The work in this chapter aims to test weather files which are used in overheating assessment in the UK and therefore does not test other available future weather files.

5.5 Objectives

Building designers have a challenge to reduce carbon emissions and also ensure that their buildings do not overheat in the summers. There is also a need to understand the effect of retrofitted passive design solutions, including night-time ventilation strategies that aim to reduce overheating. The work in this chapter aimed to answer the first research question by testing new sources of climate data by factoring them into design process through building performance modelling. The work also aimed to answer the second and third research questions by initially analysing the weather variables within the DSY weather files. The weather files are then used to model the impact of location and choice of baseline year of a DSY on levels of overheating before and after an office is retrofitted with additional insulation and improved glazing to meet current regulatory standards. To achieve these aims, this Chapter has the following objectives:

- Analyse how CIBSE weather files be used to quantify the impacts of the Urban Heat Island effect on overheating within an office.
- Provide an analysis of the differences in climate variables between weather files and how this captures the UHI effect in London. The effect of these differences can then be tested on an example building model.
- Assess the effect of simple climate adaptation design strategies such as insulation, low-albedo roofs and shading in both a current and future climate scenario.

The chapter starts with the analysis of the differences between weather variables between the weather files and how these differences capture London's UHI. This is similar methodology as was used in Chapter 4. This is followed by the building performance case study, which tests both current and future CIBSE DSY weather files.

The work in this chapter was published in a paper in the Building Services Engineering Research and Technology journal:

Virk G et al. (2015) Using the new CIBSE design summer years to assess overheating in London: Effect of the urban heat island on design. Building Services Engineering Research and Technology.

5.6 Urban Heat Island analysis of baseline weather file locations

The new CIBSE DSYs were developed so that designers could incorporate the effects of London's UHI into overheating assessment. This section analyses differences in climate variables between the locations to understand how the UHI could potentially impact the overheating assessment. Figure 39 shows the frequency distributions of the UHI intensities for the 3 new baseline DSYs for the summer period May to September. The central reference point has been varied from London Weather Centre (LWC) to Heathrow (LHR), whilst Gatwick (Gat) is used as the rural reference point.

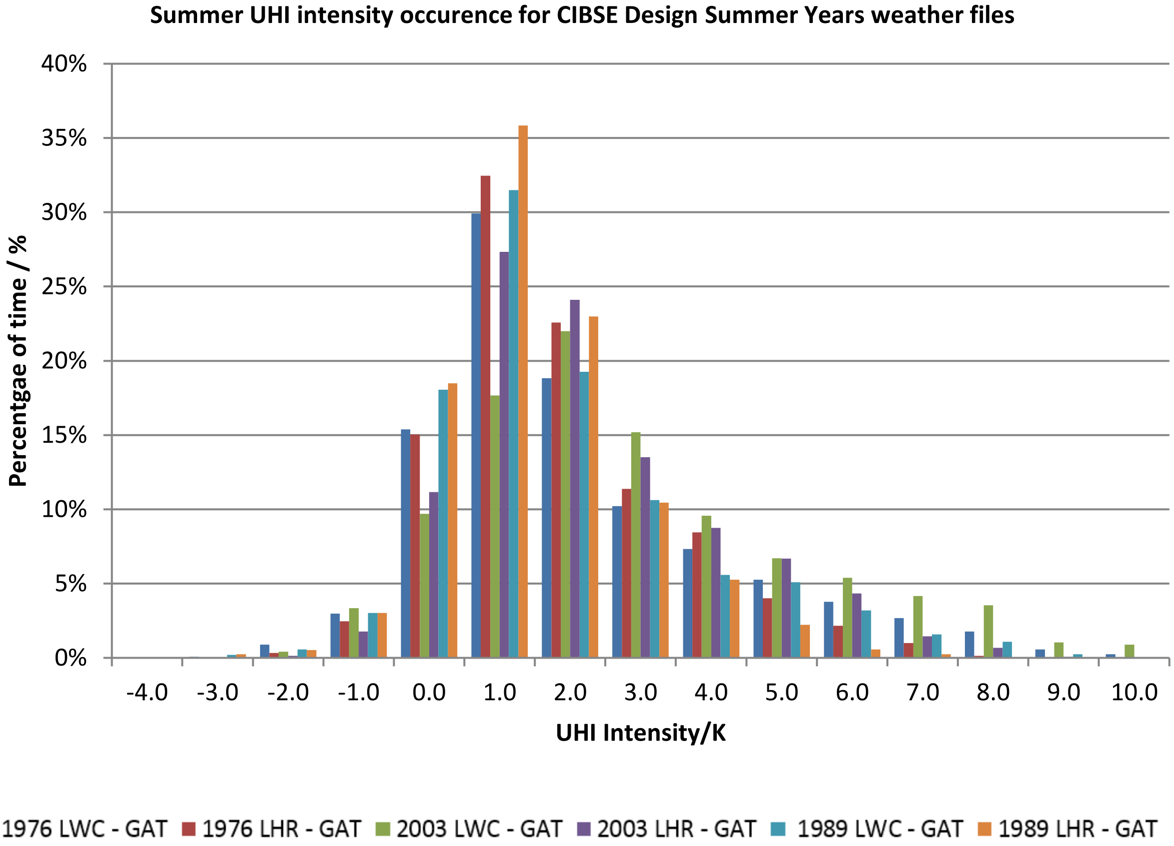

Figure 39 Summer frequency distributions of occurrence of UHI intensities for observed DSY for 2 urban reference points; London Weather Centre and Heathrow and 3 different baseline years

As expected of a more centrally located weather station, the frequency of higher intensities of 5 K and above are more frequent at LWC than at Heathrow for each year. When comparing the three years, it is evident that the baseline years with longer and more intense summer heatwave events 1976 and 2003, have more frequent extreme UHI intensities in excess of 5 K. For both years, the intensity can reach up to 9 K. In the summer of 2003, the coolest Gatwick temperatures were recorded, which is evident in the increased frequency of very high intensities. For 2003 and 1976, there is also a greater frequency of intensities above 4 K compared to 1989.

Table 14 shows the temperature characteristics of each of the baseline years for each location for the summer period May to September.

Table 14 Temperature characteristics of each location and baseline year for May to September

	Mean (°C)			Min (°C)	Max (°C)
Weather File	Tmean	Tmin	Tmax	Tmin	Tmax
LWC 76	17.8	8.7	29.9	7.8	34.3
H 76	17.5	7.7	29.4	5.5	34.0
Gat 76	16.2	5.2	28.4	2.0	33.4
LWC 03	18.1	8.2	31.6	6.5	37.4
H 03	17.4	6.4	31.1	4.2	37.2
Gat 03	15.7	3.0	29.3	-0.2	36.0
LWC 89	17.9	8.5	28.1	6.9	32.2
H 89	17.5	7.8	28.2	4.8	33.4
Gat 89	16.5	5.7	27.8	2.5	33.4

Table 14 also shows that the peak summer temperatures Tmax, are higher in 2003 and 1976 compared to 1989. The difference between peak daytime temperatures between the sites for each year is not greater than 2°C. When comparing the mean wind speeds for each location and year in Table 14, wind speeds generally increase from rural to urban location. Heathrow 1989 is the only year when Gatwick has higher wind speeds than LWC or Heathrow. In 1976 and 1989, wind speeds at LWC are 1m/s higher than Heathrow and Gatwick. Part of the explanation for the higher wind speeds at LWC are due to its rooftop location, whilst the other two sites are WMO standard Met Office land surface synoptic stations. High UHI intensities are likely to occur in specific conditions; clear skies, low wind speeds and dry weather such as those experienced in heatwaves and anticyclonic conditions (Wilby et al., 2011). The influence of wind speed on city-scale UHI effect cannot be explained by comparing the mean wind speeds for each location and year. But the microclimatic effects experienced at each location could have an impact on ventilation strategies and consequently impact levels of overheating.

Table 15 Mean wind speed for the baseline DSYs for May to September

Weather File	Mean Wind Speed m/s
LWC 76	4.8
H 76	3.8
Gat 76	3.5
LWC 03	3.6
H 03	4.0
Gat 03	2.5
LWC 89	4.1
H 89	2.8
Gat 89	3.0

There is a more significant difference between the sites is at night, where the mean and maximum Tmin are for Heathrow and Gatwick are all lower than LWC. This will be caused by a multitude of factors that contribute to the city-scale UHI effect. LWC and Heathrow are situated in denser urban environments, with comparable lack of vegetation and decreased sky view factors due to urban form. This leads to greater thermal capacity and less evapotranspiration and a consequent increase in excess heat due to lower heat advection (Oke, 1987).

The 1989 baseline year, which has been the traditional DSY in use for London since 2006, is clearly cooler than the other two baseline years. However, the differences in using the 1976 and 2003 baseline years in the design process will be more complex. These differences will be dependent on the sensitivity of the building design to external temperatures and the type of occupant profile and ventilation strategy used. If a building is reliant on night time cooling or is occupied at night, the magnitude of UHI intensity will have a greater impact on the design and the differences between the weather files will be more relevant due to the differences in night time (Tmin) temperatures and microclimatic effects such as wind speeds. Following this analysis, the case study should be designed to test a building where the internal conditions are going to be correlated to the external temperatures and which is naturally ventilated.

5.7 Building performance case study: Methodology

5.7.1 Modelling methodology: Building model

The case study building was modelled to represent one floor of a naturally ventilated open plan office, with construction typical of an existing London office. The building was modelled using the dynamic thermal simulation software EnergyPlus version 8.1 (U.S. Department of Energy (US-DOE), 2016), the software has been extensively validated, as outlined in Appendix A. The base model is a 15 m by 30 m office building with 4m ceiling height, orientated North to South, see Figure 40 for 3D model of the office. The deep plan size and orientation were chosen as they suit natural ventilation strategies (CIBSE, 2005a). The North and South facades have 50% glazing ratio, with 60% opening ratio. The East and West facades have no glazing. The glazing ratios and orientation were chosen as they are representative of a building that would be suited to natural ventilation strategies. For this study the surrounding morphology has not been modelled. Buildings in highly dense urban areas such as central London may receive less solar gains due to overshadowing from adjacent buildings.

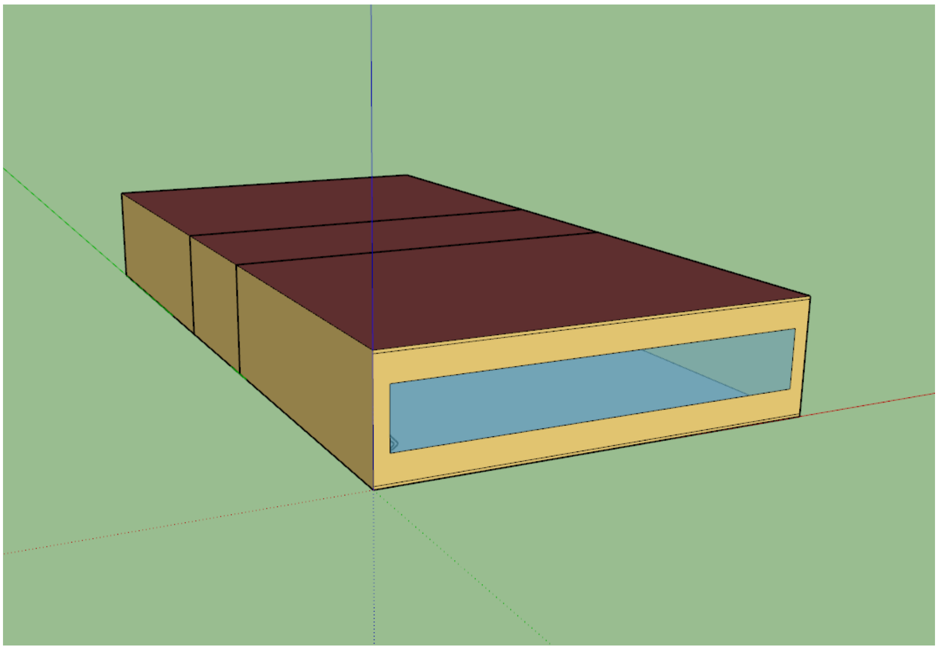

Figure 40 3D model of case study building.

5.7.1.1 *Construction*

Two base case constructions were modelled. The first is a poorly insulated open plan office with single glazing with internal high reflectivity blinds similar to the 1960s naturally ventilated case study presented in TM36 (CIBSE, 2005b). The second model represents a feasible retrofit that meets 2013 Part L requirements (DCLG, 2013). This retrofit model has better insulated fabric and double-glazed windows with a low emissivity coating on the inner pane, again with internal high reflectivity blinds. Only the top floor of a single story of the office building was modelled as it is assumed that the heat gains and overheating risk for an existing open plan office would be greatest in the exposed top floor. The construction details are outlined in Table 16.

Table 16 Building construction with U-Values for the base and retrofitted models

	U Value (W/m^{2}K)	
Element	Basecase	Retrofit
Roof	1.45	0.25
Wall	1.74	0.33
Window	5.89 - Single Glazing (SHGC: 0.86)	1.78 - Double Glazing (SHGC: 0.65)

5.7.1.2 *Occupancy and internal gains*

The office is fully occupied from 09:00 to 17:00 during the week. Internal gains were taken from CIBSE Guide A and TM36 for offices (CIBSE, 2005b, 2006). The sensible heat emission is 80 W/person, with an occupancy density of 10 m^2/person. The lighting load is 12 W/m^2 and the equipment load is 15 W/m^2.

5.7.1.3 *Infiltration and natural ventilation*

To model natural ventilation in EnergyPlus, the 'Air Flow Network' model was used (Gu, 2007). The model incorporates infiltration through permeable exposed facades and exchange with the outdoor environment through opening of windows and outdoor wind pressure coefficients. The East and West facades were presumed to be unexposed to wind and sunshine, representing surfaces that are shared with other buildings. These surfaces are treated as adiabatic and there is no airflow between them. The model used a permeability value for an existing "leaky" building of 20 m^3/(m^2·h) at 50 Pa (CIBSE, 2006), which is kept constant in all models. Window opening was determined by the internal temperature. During occupied hours, windows are opened when the internal temperatures exceeded a setpoint of 22°C. This is towards the lower end of comfort temperature recommended for offices, representing the worst-case scenario for ventilation strategy. The retrofit model is ventilated at night time (22:00 – 06:00) to represent night purging, with a night ventilation setpoint of 14°C internal temperature.

5.7.1.4 *Additional retrofit strategies*

The effectiveness of two additional retrofit strategies and the impact of orientation were also modelled. The retrofit model was varied to include low albedo, cool walls and roofs and external shading. Cool walls and roofs were modelled by increasing the albedo from 0.1 to 0.7, which has been found to be optimal for offices in London in previous studies (Kolokotroni et al., 2013). The orientation of the models was varied by orientating the building facades exposed to solar gains from North to South to East to West. External shading was modelled by adding 1 m overhangs and fins to the South facing window and the both East and West windows when the model orientation is varied from South facing. Installing overhangs in a centrally located office would be limited by space and planning restrictions. Deeper overhangs, which would provide greater amounts of solar shading, were therefore not modelled.

5.7.2 Overheating Criteria

The operative temperature (Top) was output from the EnergyPlus modelling for the period May to September. The outdoor running mean is calculated from the dry bulb temperature. The level of overheating within the office was assessed using the CIBSE overheating criteria as outlined in TM52

(CIBSE, 2013b). The three overheating criteria are determined by the difference between the operative temperature and the running mean of the dry bulb, see Section 5.2 for details. A building needs to pass two of the criteria to pass the overheating assessment. The results in this chapter are presented as an exceedance of the threshold of the three criteria as a percentage of occupied hours. The case study uses Category 2 limits for naturally ventilated buildings to assess the level of overheating, which is recommended by the guidance for renovated buildings. The Old CIBSE overheating criteria as outlined in Section 5.2 are also presented as a comparison to the adaptive criteria in the initial Baseline modelling, see next section for details of all modelling scenarios.

5.7.3 Weather Files

Nine baseline years DSYs weather files were modelled; London Weather Centre (LWC), London Heathrow (H) and London Gatwick (Gat) for three years each; 1976, 1989 and 2003. The additional adaptation and orientation scenarios were then modelled using the 2003 baseline year for all three locations. Only one baseline year was chosen as the main aim was to investigate how the UHI effect would impact the effectiveness of the adaptation strategies. The overheating risk for a future climate scenario ("morphed" on the 2003 baseline year (CIBSE, 2009)) for all locations was also modelled. The future climate period modelled is the 2050s for a medium emissions scenario (90th percentile). All the modelled variations are as follows:

- **Baseline** – Baseline current weather files used for all locations – 9 weather files:
    - Base model – poor insulation and no night ventilation
    - Retrofit model – improved insulation and glazing, with a night ventilation
- **Adaptation strategies** – 2003 Baseline current year used for all locations – 3 weather files:
    - Retrofit model
    - Cool retrofit
    - Shaded retrofit
    - Combined retrofit
    - Orientated (EW) retrofit
    - Orientated (EW) cool retrofit
    - Orientated (EW) shaded retrofit
    - Orientated (EW) combined retrofit
- **Future scenarios** – 2050s Medium Emissions scenario "morphed" on 2003 baseline for all locations – 3 weather files:
    - Retrofit model
    - Cool retrofit
    - Shaded retrofit
    - Combined retrofit
    - Orientated (EW) retrofit
    - Orientated (EW) cool retrofit
    - Orientated (EW) shaded retrofit
    - Orientated (EW) combined retrofit

5.8 Results

The results section is split into three sections as outlined above – Baseline years, Adaptation Strategies and Future Scenarios.

5.8.1 Baseline years

To investigate how the new DSYs impact overheating, both the differences between the baseline year chosen and the location are analysed. The results from the uninsulated base model are shown in Figure 41. All locations for each baseline year fail the overheating assessment, as they exceed two of the criteria. The choice of baseline year has a greater impact on the level of overheating than the choice of location. The 1989 baseline year has the lowest mean maximum temperature as shown in Table 14 shows the temperature characteristics of each of the baseline years for each location for the summer period May to September. Table 14 compared to 2003 and 1976. Using the 1989 DSY, the building overheats for the lowest percentage of occupied hours and fails two of the criteria for less than 5% of occupied hours. For the other two years, Criterion 1 is exceeded for over 25% of occupied hours and Criterion 3 is exceeded for at least 10% of hours. There is not a strong indication that overheating is impacted by the UHI effect. Gatwick has similar levels of overheating as London Weather Centre (LWC) for 1976 and 2003.

Figure 42 shows the level of overheating for the retrofitted building, which is night cooled. Insulating the building and changing the ventilation strategy are shown to be effective strategies for reducing overheating under the current climate. The choice of baseline year still determines the severity of overheating as with the base building. Only LWC 1989 and Gatwick 1989 do not exceed all three overheating criteria, with Heathrow exceeding Criteria 1 by 3% and 2 by 1% of occupied hours. For the baseline year 2003, although Criterion 1 is exceeded for a greater number of hours, the building only fails for 1% of hours for all three locations. This is the same for 1976, with Heathrow failing by 2%, rather 1%. The impact of the UHI is slightly more evident, with LWC and Heathrow exceeding Criterion 1 for a greater number of hours in 1976 and 2003 and Heathrow for 1989.

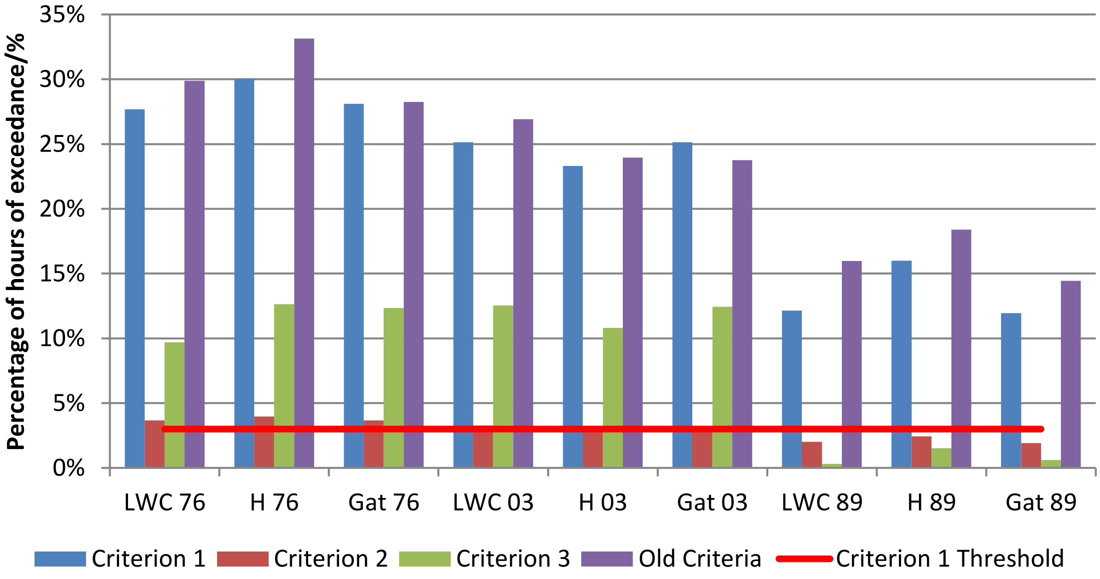

Figure 41 Percentage of occupied hours that the uninsulated base model exceeds the CIBSE overheating criteria per location and baseline year

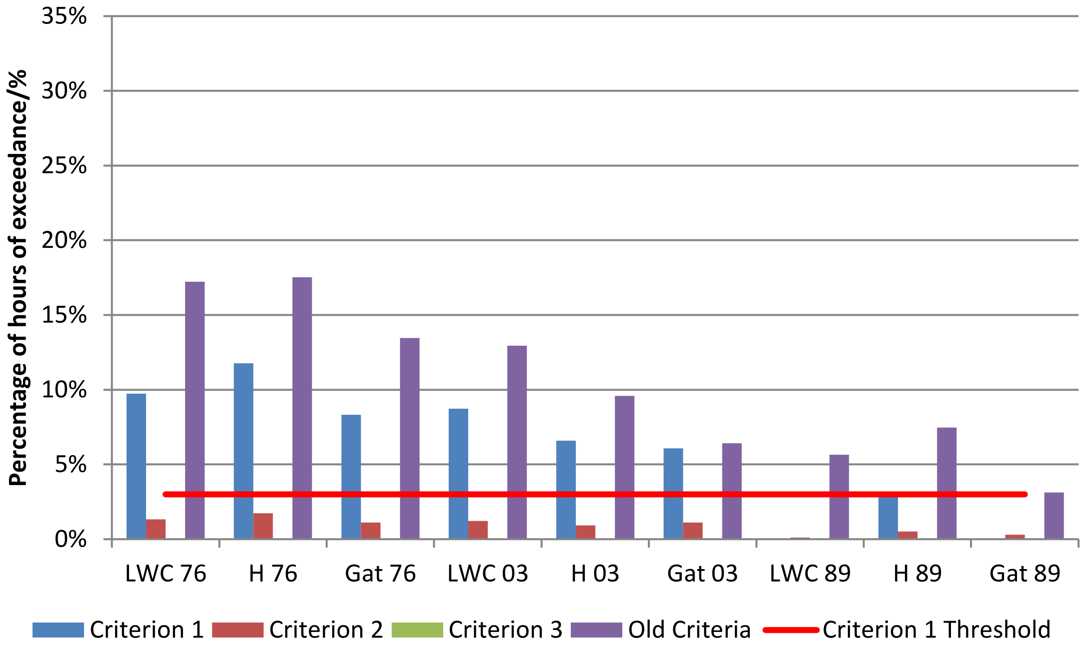

Figure 42 Percentage of occupied hours that the retrofitted insulated and night-cooled model exceeds the CIBSE overheating criteria per location and baseline year

This differences in results are explained by two factors, the fabric characteristics of the building and the ventilation strategy. The heat fluxes into the building during occupied hours are greater for the uninsulated building compared to the insulated. The heat from solar gains and additional internal heat gains are trapped within the fabric of the building during the night and the external temperature differences between the sites are not as big a factor. The operative temperatures all exceed 28°C in the uninsulated model for more than 50% more occupied hours compared to the insulated as a result of this, as shown by the old criteria for Figure 41 and Figure 42.

The other factor that impacts the results is the metric used to assess overheating. The adaptive comfort criteria outlined in TM52, is dependent on the difference between the outdoor running mean and the internal operative temperature. It assumes that occupants exposed to higher external temperatures will adapt their clothing and individual comfort according to their local environment (CIBSE, 2013b). At LWC, the mean maximum temperatures are at least 1°C higher than at Gatwick, apart from in 1989. According to the adaptive criteria there is not a large difference in levels of overheating between LWC and Gatwick for the uninsulated basecase. However, when comparing the old overheating criteria (CIBSE, 2006), the operative temperatures at LWC do exceed 28°C for more hours than Gatwick. As with the uninsulated basecase, when using the old criteria, the temperatures at LWC and Heathrow exceed 28°C for more hours than Gatwick when the building is insulated and night cooled. The impact of location is greater when using this metric, as it simply relies on a stationary temperature exceedance.

Heathrow shows a greater level of overheating in 1976 and 1989 than LWC for both building models. This could be partly explained by the lower wind speeds in the weather file as shown in Table 15. In 1989, the wind speeds at Heathrow are slightly higher than at LWC, however in the other years, the mean summer wind speeds are 20 – 30% lower. LWC has the highest wind speeds of any location due to it being located at a greater height than normal Met Office weather stations, which has been highlighted as a possible issue when using the site in modelling.

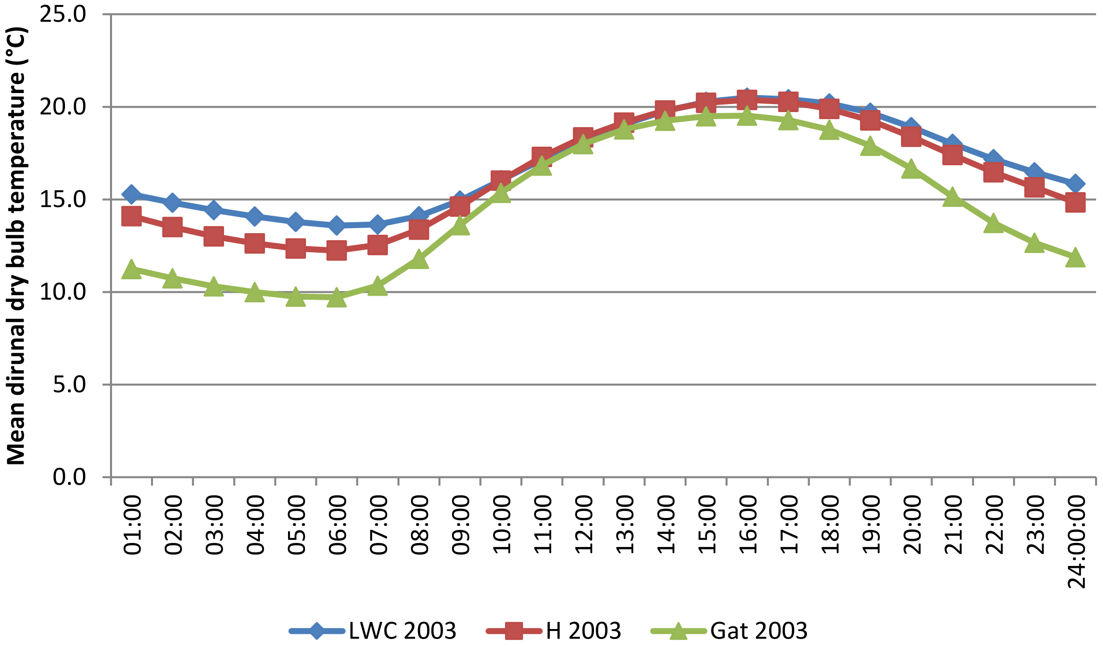

Figure 43 Mean diurnal dry bulb temperatures for each location for 2003 baseline

Gatwick has the lowest mean minimum temperature as shown in Table 14 shows the temperature characteristics of each of the baseline years for each location for the summer period May to September. When night cooling is used, the UHI effect, which is predominantly a night time phenomenon has a greater impact on the internal temperatures. When comparing the mean diurnal dry bulb temperature as shown in Figure 43, Gatwick has a larger diurnal temperature range compared to LWC and Heathrow. When night cooling is used, this diurnal temperature difference does have an impact on the results. The level of overheating at LWC and Heathrow is greater than at Gatwick, even though LWC has higher wind speeds for each baseline year it is more centrally located. The larger scale impact of the UHI produces greater levels of overheating at LWC and Heathrow. But the minor differences between LWC and Heathrow could be explained by the microclimatic impact of the local wind speeds.

5.8.2 Adaptation Strategies

The adaptation strategies were modelled using one baseline year, 2003 for all locations. Table 17 and Table 18 show the results of the adaptation strategies applied to the retrofitted, night-cooled building for the 2003 location for all 3 locations. One model has windows orientated north to south (signified by retro in the results) and the other orientated East to West (signified by EW in the results). Without any adaptations, the retrofit building fails the overheating assessment, but only for 1% of hours for all three locations. A cool roof and walls effectively reduce the level of overheating within the building for all locations. Adding shading to the South façade is slightly more effective at reducing the Tmax exceedance (represented by Criterion 3) at LWC and all three locations pass the assessment. A combination of cool walls, cool roofs and additional shading results in no overheating in occupied hours.

Table 17 Percentage of occupied hours that the adapted models exceed the CIBSE overheating criteria per location

Model	Location	Criterion 1 exceedance	Criterion 2 exceedance	Criterion 3 exceedance	Assessment Pass/Fail
Retro	LWC 03	9%	1%	0%	Fail
	H 03	7%	1%	0%	Fail
	Gat 03	6%	1%	0%	Fail
Retro Cool	LWC 03	2%	0%	0%	Pass
	H 03	0%	0%	0%	Pass
	Gat 03	0%	0%	0%	Pass
Retro Shading	LWC 03	1%	0%	0%	Pass
	H 03	0%	0%	0%	Pass
	Gat 03	0%	0%	0%	Pass
Retro Combined	LWC 03	0%	0%	0%	Pass
	H 03	0%	0%	0%	Pass
	Gat 03	0%	0%	0%	Pass

When the building is orientated East – West instead of North – South, overheating increases in all scenarios as shown in Table 18. This is due to the additional solar gains throughout the day. Without any adaptations, the building fails all three criteria for all three locations. LWC exceeds Criterion 3 for 5% of the time, more than twice the level of exceedance in Heathrow and Gatwick. Criteria 1 and 2 are exceeded for similar amounts of time for each location and Criterion 1 is exceeded frequently for near to 20% of time in all 3 locations.

Table 18 Percentage of occupied hours that the East - West orientation adapted models exceed the CIBSE overheating criteria per location

Model	Location	Criterion 1 exceedance	Criterion 2 exceedance	Criterion 3 exceedance	Assessment Pass/Fail
EW	LWC 03	19%	2%	5%	Fail
	H 03	18%	3%	2%	Fail
	Gat 03	19%	3%	2%	Fail
EW Cool	LWC 03	10%	1%	0%	Fail
	H 03	7%	1%	0%	Fail
	Gat 03	7%	1%	0%	Fail
EW Shading	LWC 03	12%	2%	1%	Fail
	H 03	11%	1%	0%	Fail
	Gat 03	11%	1%	0%	Fail
EW Combined	LWC 03	2%	0%	0%	Pass
	H 03	0%	0%	0%	Pass
	Gat 03	0%	0%	0%	Pass

When orientated EW and with the addition of cool roof and walls, the level of overheating is reduced, but all 3 locations still fail the assessment, with LWC overheating the most. Shading is less effective at this orientation than cool surfaces. All three locations fail the assessment again, with LWC again overheating the most. The shading types modelled are 1m overhangs and fins, deeper constructions could have been more effective at reducing solar gains into the building. When cool surfaces and shading are combined, all three locations pass the assessment.

For each orientation and adaptation strategy, the location of the building does have an impact on the level of overheating. When the model is orientated North to South, being located at LWC does result in a greater number of hours exceeding Tmax and failing Criterion 1. The UHI effect has a greater impact when the building is orientated East to West. When the building is located in a site with higher ambient air temperatures it overheats for a greater number of hours as night cooling is not as effective.

5.8.3 Future climate scenario

Table 20 and Table 21 show the overheating results for the 2050s medium emissions scenario, for each location and for each orientation and adaptation strategy. As shown in Table 19, dry bulb temperatures are projected to increase by an average of 3.7°C and both minimum and maximum temperatures increase. The difference in temperature characteristics between the current 2003 and future 2050s scenario is shown in Figure 44. As a result, the building overheats for all scenarios, except the South Facing combined adaptation strategy. The building more frequently exceeds the criterion, with the base retrofit model overheating for almost 50% more time compared to the 2003 baseline results presented previously. The adaptation strategies do decrease the level of overheating, but only the combined strategy passes. Shading is as effective as cool walls and roofs, rather than being more effective as when modelled with the baseline year as shown in Table 17.

Table 19 Temperature characteristics of all locations for the 2050s (2003 baseline) period for May to September

	Mean (°C)			Min (°C)	Max (°C)
Weather file	Tmean	Tmin	Tmax	Tmin	Tmax
LWC 03 2050s	21.7	11.1	35.9	9.1	41.8
H 03 2050s	21.1	9.3	35.4	6.9	41.6
Gat 03 2050s	21.7	11.1	35.9	9.1	41.8

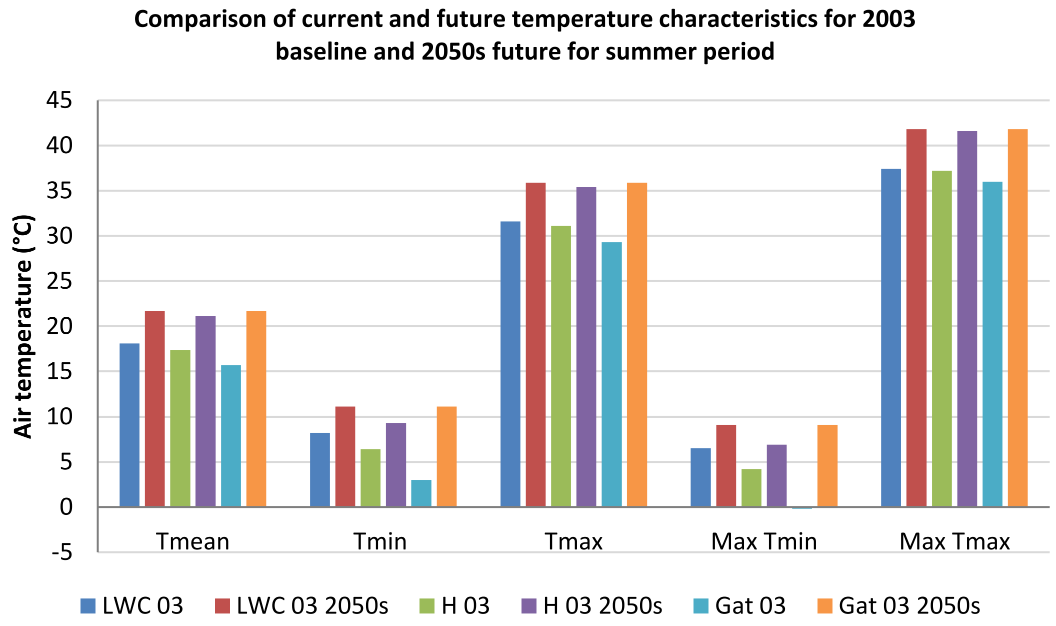

Figure 44 Comparison of current and future temperature characteristics for 2003 baseline and 2050s future for summer period

Table 20 Percentage of occupied hours that the adapted models exceed the CIBSE overheating criteria per location for 2050s medium emissions scenario

Model	Location	Criterion 1 exceedance	Criterion 2 exceedance	Criterion 3 exceedance	Assessment Pass/Fail
Retro	LWC 03	17%	2%	1%	Fail
	H 03	14%	2%	0%	Fail
	Gat 03	14%	2%	0%	Fail
Retro Cool	LWC 03	7%	1%	0%	Fail
	H 03	5%	1%	0%	Fail
	Gat 03	3%	1%	0%	Fail
Retro Shading	LWC 03	8%	1%	0%	Fail
	H 03	5%	1%	0%	Fail
	Gat 03	3%	1%	0%	Fail
Retro Combined	LWC 03	0%	0%	0%	Pass
	H 03	0%	0%	0%	Pass
	Gat 03	0%	0%	0%	Pass

Table 21 Percentage of occupied hours that the orientated adapted models exceed the CIBSE overheating criteria per location for 2050s medium emissions scenario

Model	Location	Criterion 1 exceedance	Criterion 2 exceedance	Criterion 3 exceedance	Assessment Pass/Fail
EW	LWC 03	26%	3%	7%	Fail
	H 03	25%	3%	7%	Fail
	Gat 03	26%	3%	7%	Fail
EW Cool	LWC 03	17%	2%	1%	Fail
	H 03	18%	2%	2%	Fail
	Gat 03	18%	2%	1%	Fail
EW Shading	LWC 03	19%	3%	2%	Fail
	H 03	15%	2%	1%	Fail
	Gat 03	15%	2%	1%	Fail
EW Combined	LWC 03	8%	1%	0%	Fail
	H 03	6%	1%	0%	Fail
	Gat 03	5%	1%	0%	Fail

When the building is orientated East-West it overheats for a greater number of hours, similarly to the baseline year. The base case model exceeds Tmax for almost 30% of hours and Tupp is exceeded for 7% of hours. Shading is slightly more effective than cool walls and roofs, except for LWC. Both strategies reduce the exceedance of all 3 criteria.

5.9 Conclusions

5.9.1 Summary of the methodologies used and their results

The aim of this chapter was to test new climate data sources in the form of CIBSE DSY weather files. The analysis in this chapter aimed to test how the differences between the new DSY weather files impacts overheating in a naturally ventilated office. These differences were first analysed by quantifying the UHI intensity by using LWC and LHR as urban reference points and LGW as a rural reference point and quantifying key weather variables within the files. This analysis answered the second research questions as it showed how new and existing sources of climate data can be analysed to provide more in-depth analysis of the UHI effect in London. The analysis showed how the variety in the weather files potentially impacts building performance due to two main factors, the UHI effect and the severity of the hot period within each baseline year.

The results highlight how important it is that practitioners understand how both the weather variables and building, and ventilation design will impact the predicted levels of overheating. The use of the CIBSE weather files and application to a case study also answered the first research question as this is a direct use of climate data in building performance analysis. The key findings of the analysis in this chapter are discussed next in terms of how they can used to inform building design.

The main differences in the weather files show that 1989 is the coolest year; 2003 has higher peak temperatures and lower night time temperatures than 1976 and consequently higher UHI intensities are more frequent in 2003 compared to 1976. However, 1976 has the longest heatwave period as outlined in TM49. The modelling results confirm the impact that these differences have on the level of overheating. For each location, 1976, the year with the longest heatwave overheats the most.

The UHI effect has the greatest impact on overheating for insulated, night cooled buildings. The difference between the sites is most obvious in 1976 and 2003, when the UHI effect is greater. This is evidently due to the use of night ventilation, as the diurnal range of external temperatures between the more centrally located sites is lower and less heat is ventilated out of the building. The choice of metric has an impact on the level of overheating between sites. Buildings within the centre of London will pass the new adaptive criteria with higher internal temperatures, as the outdoor running mean will be higher.

There is evidence of how the differences in wind speeds between LWC and Heathrow influence the level of overheating, however the diurnal temperature range seems to have a greater impact on the results between the sites than wind speeds. Gatwick has lower wind speeds than LWC for all three baseline years, but still overheats for less time. The modelling work in the case study did not model wind shelter effects due to surrounding buildings and the wind exposure of a centrally located office may differ significantly compared to the model even if it were located near LWC.

5.9.2 How can these findings help building designers?

The results in this chapter have provided an in-depth analysis of the differences between the CIBSE weather files, this is both in terms of their weather characteristics and how these characteristics capture the UHI effect in London. The case study also provides evidence of the effects of retrofitted climate adaptation strategies as outlined next.

In the current climate, the additional adaptation strategies, shading and cool surfaces, reduce the level of overheating enough for the retrofitted building to pass the overheating criteria. Shading is found to be marginally better than cool surfaces. The UHI effect is still evident when applying the adaptation strategies. When the building window facades are orientated to East – West, the additional solar gains increase the level of overheating by almost 50%. At this orientation the additional adaptation strategies do reduce the level of overheating, but the building still fails the criteria. It is only when both cool surfaces and solar shading strategies are combined that the building passes the criteria. The testing of adaptation strategies answered the third research question as the effect of the strategies on overheating was quantified and analysed.

In the 2050s period, the level of overheating is increased for both the retrofitted and East – West orientated building. The retrofitted building only passes the overheating criteria with a combination of adaptation strategies. The impact of the UHI effect is similar to the current climate. In the 2050s, when the building is East – West orientated, the impact of the UHI is less evident and there is only a small difference between the sites. Even with a combination of adaptation strategies, all the models fail the overheating criteria. From these findings, the level of overheating in the 2050s would make the building highly uncomfortable building to work in without any additional adaptations. In this scenario, additional measures would have to be taken. This could be achieved through strategies such as microclimatic UHI mitigation interventions, for example wide spread greening or additional mixed-mode ventilation.

The work in this chapter has shown how new CIBSE DSY weather files can be used to model the impact of the city-scale UHI effect on overheating. In major cities across the UK, weather files are limited by the data availability as highlighted in Chapter 4. Point source data from urban stations will be impacted by the local microclimate and location of the station. Microclimate models exist which can be used to model neighbourhood-scale areas of cities and output data at a variety of spatial and temporal scales. These sources of climate data can then be used within the building design by factoring them into building performance simulation to test design adaptation strategies. This chapter used CIBSE DSY as the climate data source, whilst tthe next chapter uses the results from a neighbourhood-scale microclimate model to analyse how green and cool roofs impact the performance of a building.

6 Effectiveness of green and cool roofs and insulation at reducing overheating and energy use in an existing office in London

6.1 Introduction

The aim of this chapter is to test the effectiveness of retrofitted building adaptations in the form of green and cool roofs and insulation for an existing office in London. Insulation is traditionally retrofitted to buildings as a requirement of building regulations (DCLG, 2013). Green and cool roofs as outlined in Chapter 2 have been used to reduce overheating risk and energy use in multiple building types. The adaptation strategies have both an impact on the direct heat transfer into building and can cool the local microclimate, referred to in this chapter as the “indirect” effects. The chapter aimed to factor in existing modelled microclimatic climate data in the building design process to be able to test both the direct and indirect effects of the roofs.

The work in the previous chapters has used data which was limited in terms of its spatial and temporal scale. Observed weather station data is limited to point sources, usually located in rural areas of cities, as shown in Chapter 3. Urban weather stations also have limitations, due to the microclimate surrounding them and the quality and quantity of data availability. Cities such as Birmingham and Manchester have a nocturnal UHI effect, but as the work in Chapter 4 demonstrated, finding suitable urban weather stations is challenging. To capture the UHI effect in London when modelling buildings, CIBSE developed DSY weather files for locations other than Heathrow. However, from the literature review in Chapter 2, at the neighbourhood-scale the local microclimate can impact building performance significantly.

6.2 Review of the effects of green and cool roofs on building performance

Green, or vegetated, roofs consist of a growing medium planted above a waterproof membrane. The depth of the substrate varies typically between 60mm to 400mm (CIBSE, 2013a). Green roofs reduce heat transmission into the building fabric compared to conventional roofs due to their lower surface temperatures (Liu and Baskaran, 2003). In addition, green roofs reduce air temperatures through evapotranspiration which increases the latent heat flux away from the surface, when sufficiently irrigated.

Highly reflective or ‘cool’ roofs reduce the absorption of solar radiation and hence reduce the surface temperatures of the roof. A literature review by the US EPA (US EPA, 2011) found measured surface temperatures of conventional roofs to be 31-47°C hotter than overlying air whilst cool roofs stay within only 6-11°C warmer in a variety of Canadian and American cities. A cooler roof will result in reduced heat transfer into the building as with green roofs and hence reduce cooling loads (Akbari et al., 2001). Cooler surfaces also affect the sensible heat flux and therefore cool roofs impact the ambient air temperatures.

6.2.1 Impact on overheating

6.2.1.1 *Green roofs*

Green roofs’ passive cooling performance is affected by the foliage density, represented by the leaf area index (LAI), soil layer thickness, foliage height, type of plant, amount of building insulation and climatic conditions such as ambient temperature, relative humidity and wind speed (Theodosiou, 2003). Niachou et al. measured how green roofs impact internal air temperatures for a non-residential building near Athens (Niachou et al., 2001). With the addition of a green roof, the internal daily mean air temperatures were reduced by 2°C. The roof reduced the number of hours the internal air temperatures exceeded 30°C by 13%. When naturally ventilated, the percentage of hours exceeding 30°C were reduced from 68% to 15%. The study also found that green roofs impact surface temperatures to a greater extent on non-insulated roofs compared to well insulated roofs. Jaffal et al. modelled a green roof in TRNSYS and varied the Leaf Area Index and the amount of insulation for a family dwelling (Jaffal et al., 2012). The application of a green roof reduced mean indoor temperatures for a typical hot summer period by 2°C. By increasing the level of insulation, the impact of the green roof on reducing internal temperatures decreased, whilst changes to the LAI had less of an impact. Parizotto and Lamberts compared the thermal performance of green roofs to ceramic and metallic roofs for a temperate climate in Brazil (Parizotto and Lamberts, 2011). The green roof reduced internal temperatures by 0.5 – 1°C during a warm week. The extra thermal mass provided by the green roof was the most important characteristic that helped improve the thermal performance. Sfakianaki et al. found that green roofs reduce summer surface temperatures by 0.4°C to 0.6°C when simulating Greek residential buildings (Sfakianaki et al., 2009). They found that green roofs were most effective at increasing indoor thermal comfort when installed onto naturally ventilated buildings. Zinzi and Agnoli. Compared the impact of green and cool roofs on residential buildings in three Mediterranean climates and varied amount of insulation (Zinzi and Agnoli, 2012). The non-insulated buildings had greater number of hours where the operative temperature exceeded 28°C and only in the most extreme climate was there a significant number of hours where the operative temperatures exceeded 30°C. Cool roofs were the most effective at reducing operative temperatures, whilst green roofs performed slightly less well. Green roof performance was affected by the amount of irrigation provided.

6.2.1.2 *Cool roofs*

Cool roofs increase the albedo of roof surfaces, varying the optical and thermal properties. Kolokotroni et al. monitored the effect of cool roofs on an office building in London, and then used these measurements to calibrate a TRNSYS model of the building (Kolokotroni et al., 2013). The painted cool roof resulted in the surface temperature of the roof always being at a lower temperature than the internal ceiling. Comfort was significantly increased by increasing the albedo of the roof, the number of hours above 28°C is almost halved when varying the albedo from 0.1 to 0.7. Synnefa et al. simulated the impact of cool roofs on residential buildings for a wide variety of climates (Synnefa et al., 2007). When increasing the albedo to 0.65, there were resulting reductions in the number of discomfort hours across all climates. Cool roofs also resulted in decreases in indoor temperatures by up to a maximum of 3.7°C. Romeo and Zinzi. Measured the impact of cool roof on a school in Sicily (Romeo and Zinzi, 2011). Internal summer temperatures were reduced by 2.3°C on average. Using a calibrated TRNSYS model, in rooms with lower solar gains, there was a significant reduction in the number of hours the operative temperature was higher than 27°C and 29°C, with some rooms seeing a reduction of 25%. Higher insulation levels were found to decrease the impact of cool roofs at reducing the hours of discomfort.

6.2.2 Impact on energy balance

6.2.2.1 *Green roofs*

Green roofs can increase energy savings by increasing the level of insulation on poorly insulated roofs – savings are reduced however, for already well insulated buildings which meet current regulatory standards (Castleton et al., 2010). Thicker soil on roofs decreases heat gains into the building but dry roofs save less energy than moist roofs due to lower levels of evapotranspiration. Sailor et al. modelled the direct impacts of green roofs on the energy use of offices and dwellings in four different climate zones (Sailor et al., 2012). The highest savings in all offices were due to the reduced gas consumption in colder climates of between 10,000 and 20,000 kJ/m^2. Increasing the Leaf Area Index (LAI) (a dimensionless number representing the projected leaf area per unit area) of soil surface, decreased the gas savings more than altering the soil depth, but increased the cooling energy savings and resulted in an overall energy saving and cost reduction due to the additional shading and evapotranspiration effects. Niachou et al. simulated the effect of green roofs for a typical office block in Athens (Niachou et al., 2001). The addition of a green roof resulted in annual heating and cooling savings of up to 44% on uninsulated roofs. This was reduced to less than 10% annual savings for moderately and well insulated roofs. The addition of night ventilation increased energy savings in the summer. Jaffal et al. (2012) modelled a green roof in TRNSYS based on the same heat balance equations developed by Frankenstein et al. (Frankenstein et al., 2004) and implemented by Sailor in EnergyPlus (Sailor, 2008). For a house based in an oceanic temperate climate, increasing the LAI decreases cooling demand and increases heating demand as with previous studies. Insulation is shown to have a much greater impact on annual energy demand, potentially decreasing heating demand by up to 48% compared to an uninsulated green roof. Ascione et al. found that green roofs reduced the space heating energy use in winter compared to a traditional roof in London, whilst there was a reduction in the amount of energy needed for space cooling in summer (Ascione et al., 2013).

6.2.2.2 *Cool roofs*

Kolokotroni et al. modelled the impact of cool roofs in an office in London. There was a winter energy penalty and summer energy savings, resulting in annual energy saving of 5% (Kolokotroni et al., 2013). Increasing insulation levels were found to decrease the energy savings and lower ventilation rates resulted in higher energy savings. The optimum parameters for energy savings were an albedo of 0.6 – 0.7 and air change rate of 2 ACH. Levinson & Akbari simulated the impact of cool roofs on heating and cooling energy demand for four office types for 236 US cities (Levinson and Akbari, 2010). Cooling demand reduction was greater in old offices compared to new ones, for old offices savings ranged from 0.8 – 15 kWh/m^2. The energy penalty in terms of increasing heating demand was always less than the reduction in cooling loads, with older offices having higher heating energy penalties. Synnefa et al. carried out a parametric analysis simulated cool roof coatings on residential buildings for a variety of climates (Synnefa et al., 2007). The results showed that the climate of the location and the U-Value of the roof were the two main factors that affected energy savings. Jo et al. investigated the impact of cool roof on an office block in Phoenix containing a data processing centre, which have higher than usual cooling loads (Jo et al., 2010). Replacing the conventional roof achieved monthly electricity reduction of up to 3%. The impact of the cool roof was also greater for a less insulated roof.

6.2.3 Summary

The evidence within the literature shows that installing both green and cool roofs can mitigate overheating and result in annual energy savings:

- Green and cool roofs have been shown to increase thermal comfort when installed on a variety of buildings and in a variety of climates.
- The balance between summer and winter energy savings that determines the overall annual energy use is a key factor.
- It is clear is that the potential energy savings from retrofitting both roofs is greater than on a well-insulated new building.

The balance between thermal comfort and energy savings for these technologies is complex and needs to be further understood for London. The comparison between green and cool roofs and insulation and the impact on the annual energy balance has not yet been examined in detail for London. If green and cool roofs are to be used as viable design options in London, both their effect on summer thermal comfort and annual energy use needs to be understood. A designer can then decide as to how effective a roof will be on an existing building and will be able to compare them to traditional energy saving technologies such as insulation.

6.3 Objectives

As this chapter investigated the effectiveness of building adaptation strategies, the work in this chapter aimed to answer the third research question as green and cool roofs can also be considered as climate adaptation design strategies. To be able investigate both the direct and indirect effects of the roofs, the work in this chapter used the outputs of a neighbourhood scale microclimate model. The Atmospheric Dispersion Modelling System 4 Temperature and Humidity (ADMS T&H) was used to simulate the effect of green and cool roofs on near surface air temperatures and humidity for a location in Central London. The existing results were from a previous microclimate modelling (Jansz, 2011, 2012), see Appendix B for further details. Considering these aims, the work in this chapter had the following objectives:

- Provide integrated methodologies to assess how neighbourhood scale climate data be factored into building simulation.
- Assess what the impact of neighbourhood scale urban climate mitigation measures in the form of green and cool roofs have on the annual heating and cooling energy balance and thermal comfort of an office. These effects can be assessed both in terms the direct heat transfer into the building and the effect on the local microclimate.
- Compare the effect of green and cool roofs to traditional retrofitted design adaptations such as insulation.
- Assess if integrating the neighbourhood scale results into building simulation is an effective methodology.

The work in this chapter was published in two journal papers:

Virk G et al. (2014) The effectiveness of retrofitted green and cool roofs at reducing overheating in a naturally ventilated office in London: Direct and indirect effects in current and future climates. Indoor Built Environment.

Virk G et al. (2015) Microclimatic effects of green and cool roofs in London and their impacts on energy use for a typical office building. Energy and Buildings.

6.4 Methodology

The case study in this chapter uses the outputs from a microclimate model and building simulation software to analyse the direct and indirect impacts of installing green and cool roofs in an area of central London, around Victoria Station. The microclimatic model was originally developed to analyse the impact of green and cool roofs on local temperature perturbations (Jansz, 2011) – see section 2.2.2.1 for details of ADMS modelling and how climate data perturbations are produced. This case study uses the microclimatic modelling outputs from the previous work to analyse the direct and indirect effects of the roofs on:

- Summertime overheating
- Annual energy balance

6.4.1 Microclimate modelling

6.4.1.1 *The case study site*

The Victoria Business Improvement District (BID) is a partnership between the local authority and local businesses whose aim is to develop projects and services that benefit the trading environment (Land Use Consultants & Green Roofs Consultancy, 2010). Its boundaries are shown in Figure 45. The selection of buildings that were assumed to be able to support a green or cool roof was based on results from an audit of green infrastructure commissioned by the Victoria BID, which assessed their suitability for supporting a green roof (Land Use Consultants & Green Roofs Consultancy, 2010). The audit concluded that 25 ha out of the total 29 ha of roof space could potentially support a green roof, as shown in Figure 45.

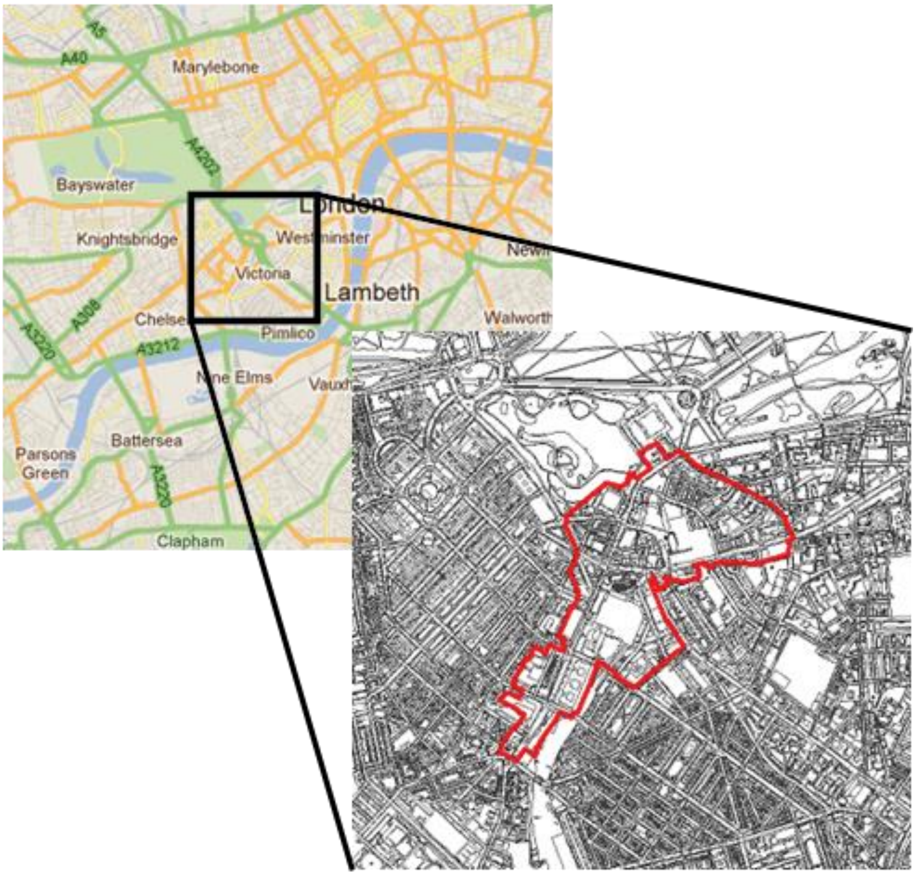

Figure 45 Case study site in Central London. The highlighted area is the Victoria BID.

6.4.2 Microclimate modelling: ADMS 4 Temperature and Humidity

The studies in this chapter use the outputs of the Atmospheric Dispersion Modelling System 4 Temperature and Humidity (ADMS T&H). The model requires the user to enter the upwind meteorological data, including hour by hour air temperature, cloud cover, wind speed and relative humidity, which is used with minimum Monin-Obukhov length, the height at which the meteorological data has been collected and the ratio of ground heat flux to net radiation (G/Q*) to derive the upwind heat flux terms. In addition, it requires the spatial variation of land use characteristics across the domain of interest (albedo, surface resistance to evaporation and thermal admittance) along with parameters which describe the urban morphology, in order to derive the local variation in heat flux terms. Further details of the required inputs and for details of how to run the software are outlined in the ADMS T&H User Guide (CERC, 2010b).

6.4.2.1 *ADMS modelling methodology*

A 2 km by 1.8 km domain that encompassed the Victoria BID was modelled in ADMS T&H as shown in Figure 45. It was assumed that 90% of the area of all the roofs identified could be retrofitted with green roofs in the Victoria BID Green Infrastructure Audit could be vegetated or covered with high-albedo paint (i.e. into a green or 'cool' roof). The remaining 10% of the roof area was assumed to be occupied by plant, flues or access walkways and not available for adaptation. The following four land use scenarios were modelled:

1) The existing land use,
2) A green roof scenario, where 90% of the area of all potential roofs are 'greened' and irrigated,
3) A green roof (dry in summer) scenario, where 90% of the area of all potential roofs 'greened' but assumed dry in the summer (Jun –Aug),
4) A cool roof scenario, where 90% of the area of all potential roofs have an albedo 0.7.

Year-round modelling was undertaken for each of the land use scenarios using a CIBSE Test Reference Year (TRY) weather file and a morphed 2050s TRY weather file[23]. The microclimate modelling results are not an output of this thesis but are included for reference in Appendix B.

The weather data selected to represent typical current conditions was the CIBSE TRY (Levermore and Parkinson, 2006) for London Heathrow (Levermore and Parkinson, 2006). In addition, cloud data for each of the months of the CIBSE TRY was retrieved from MIDAS database (Met Office, 2012), for each of the months of interest for the Heathrow weather station. Further to this, the wind speed of the weather file was adjusted to reflect the fact that the case study site is in the city centre rather than the outskirts of London, where the weather station is situated. The process uses the methodologies included in the CERC Meteorological Input Module technical specification (CERC, 2010d) and CERC Boundary-Layer Structure technical specification (CERC, 2010c).

The future meteorological data used in this study was generated using UK Climate Projections (UKCP09)(DEFRA, 2009), under the medium emissions scenario and for 50th probability percentile. This study has used monthly climate projections for the 25km grid square in central London, for the 2050s period, accessed from the UKCP09 User Interface (DEFRA, 2012). This study uses a current Heathrow TRY, which was morphed using the UKCP09 weather projections using the methodology outlined in Technical Memorandum 48 (CIBSE, 2009), which is based on the previous UK Climate Projections (UKCIP02). For the purposes of this project, the morphing methodology was selected

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[23] The use of the TRY weather file is also discussed later in the chapter.

due to its transparency and so that direct comparisons could be made between the results gained from the current and future weather file.

6.4.2.2 *Outputs and data processing methodology*

Hourly outputs of air temperature and relative humidity at a height of 1.5 m (chosen to represent near surface temperatures of the roofs) were generated for each modelling run at 50m intervals of an output area sized 250 m x 250 m. The height of 1.5 m was selected as being standard for near-surface air temperature measurements in urban as well as rural areas (Oke, 2006a). These receptor locations were chosen as the buildings in this area are the height of the building modelled in the case study. These outputs were averaged for the whole area and used to edit a weather file to be input into a building model, details of which are outlined next.

6.4.3 Building Simulation Model

To model the direct and indirect effects of the roofing strategies on an office, this case study used Design Builder 3.0.0.105 (DesignBuilder Software Ltd, 2014), which is a building modelling interface for the dynamic thermal simulation engine EnergyPlus 7.0.0.036 (U.S. Department of Energy (US-DOE), 2016). As this Chapter aimed to test the effectiveness of the adaptation strategies and retrofitting an office to meet UK building regulations, an approved building performance model was used instead of EnergyPlus.

Green roofs will cool the building directly through a combination of increased thermal mass, increased insulation, evaporative cooling and to some extent increased solar reflectance. The cooling capacity will also be influenced by the amount of irrigation and vegetated cover. The effectiveness of cooling of any green roof is therefore difficult to model accurately as there are so many different parameters to consider. Design Builder was chosen as the modelling tool as it has one of the most holistic, validated green roof models readily available. The EnergyPlus green roof module was developed and successfully validated by Sailor (2008). The module is based on the FASST model developed by Frankenstein et al. (2004) which considers the heat and moisture balances at both the soil and foliage surface. Cool roofs can also be modelled by varying the physical properties of the outer construction of the roof in the building model.

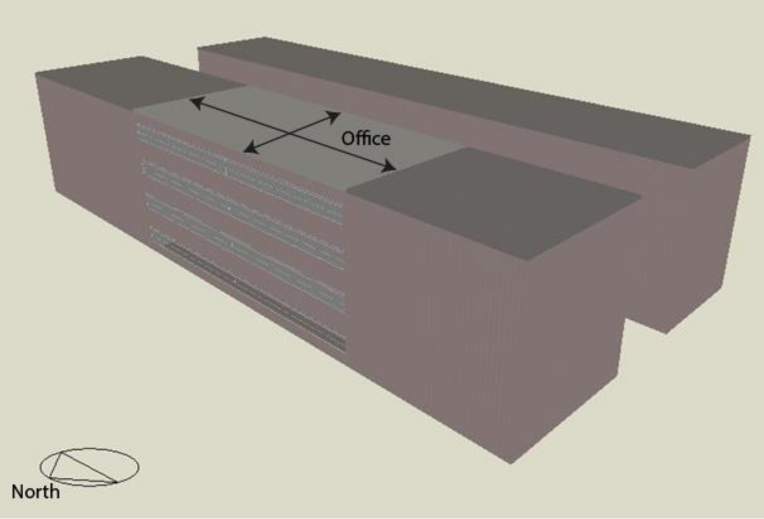

Figure 46 3D representation of Design Builder building model

6.4.4 Details of basecase model and the variants

The office is a four story rectangular block with a total floor area of 2000m^2 based on a model developed by Demanuele et al. (2011). The building is orientated north/south, each floor is a single zone with dimensions 33x4x15m, the 3D representation is shown in Figure 46. As the Victoria BID has a high building density, the office is surrounded by three separate component blocks to simulate the effect of shading from adjacent offices. There is a 50% glazing ratio on all facades, which can be opened by 20%, the glazing has a g-value of 0.7. The internal shading consists of internal blinds with high reflectivity slats, which close if the glare index is greater than 22. The construction details are shown in Table 22.

Table 22 Construction details of the base building model with U-Values

Construction	U Value (W/m^{2}K)
Basecase Roof	2.76
External Wall	0.32
Internal Floor	0.22
Glazing	1.98

The physical parameters chosen to represent a standard green or cool roof were chosen using evidence from the literature. Kolokotroni et al. (2011) and Synnefa et al (2007) both found an optimum albedo for cool roofs is between 0.6 – 0.7, this case study used 0.7. The green roof parameters were chosen to be similar to the baseline used in Sailor (2008). The green roof and dry green roof are exactly the same but have different irrigation schedules. The green roof is irrigated throughout the year, using Design Builder's "Smart" schedule. The dry green roof is not irrigated for months June to August as was assumed for the modelling in ADMS.

Table 23 Physical properties of Green Roof model in Design Builder

Green roof properties		Units
Soil thickness	0.15	m
Height of plants	0.1	m
Leaf area index	2	LAI
Leaf reflectivity	0.22	
Leaf emissivity	0.95	
Mean stomatal resistance	100	s/m
Max volumetric moisture content at saturation	0.5	
Min residual volumetric moisture content	0.01	
Initial volumetric moisture content	0.15	

The underlying structure of the roof was kept constant for all of the scenarios, as this case study concentrates on the relative change between the roof types. The roof type variations are outlined below:

- Basecase – asphalt roof with albedo 0.1.
- Green Roof – specified as a layer replacing asphalt, details are in Table 23. The green roof has a U-value of 1.36 W/m^{2}K.
- Dry Green Roof – irrigation schedule was altered, roofs are not irrigated in the summer
- Cool Roof – asphalt roof with painted with highly reflective paint, with albedo 0.7.

6.4.4.1 *Weather file production*

Weather files were produced which included the effects of the urban microclimate, by incorporating the average hour by hour ADMS temperature and humidity perturbations from the output area into the CIBSE TRY and the morphed 2050 TRY[24]. The 'TRY' weather file takes into account the UHI by including the modelled microclimatic perturbations caused by the surrounding urban environment as outlined in Section 6.4.2.2, but does not model the microclimatic effect of the green and cool roofs. The 'TRY' weather file represents climate data outputs of the basecase neighbourhood without any design adaptations, which would capture the UHI effect as the upwind weather file is based at London Heathrow, which is a semi-urban site.

The 'Perturbed' weather files include the additional perturbations for each of the modified roofing scenarios – green, dry green and cool. The weather data was converted into the format required by EnergyPlus (EPW file) using the EnergyPlus Weather and Statistics Conversions utility. To model the direct and indirect (combined) effects of green and cool roofs, the case study building was run with the four weather files described above. To model the direct effects of the roofs the TRY weather file was used for all roofing scenarios. The indirect effects are calculated as being the difference between the two sets of results.

The basecase roof was then varied by increasing insulation levels to meet current regulatory standards as outlined in UK Part L Building Regulations (DCLG, 2013). The insulated roof was varied in the same way as the uninsulated roof as outlined above. Details of the insulated roof scenarios are outlined below:

- Insulated basecase roof – added layer of 0.2m thick mineral wool insulation, with U-value 0.18 W/m^{2}K.
- Insulated green and cool roofs – varies the outer layer of the roofs as per the uninsulated scenarios.

For overheating analysis, a DSY weather file is usually used, but the work in this chapter uses a TRY as the base file for all simulations as microclimatic modelling used a TRY weather file as the upwind weather file.

6.4.4.2 *Ventilation, Activity and HVAC details*

The internal gains, heating and cooling set points, ventilation rates and HVAC assumptions are outlined in Table 24. The internal gains and temperature set points for the model were specified using the Open Plan Office Template from the UK National Calculation Methodology (BRE, 2009).

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[24] See Section 5.3 for details of morphing methodology.

For the overheating analysis, the building is naturally ventilated, the level of ventilation was modelled to vary with occupation schedule and the maximum outside air change rate was set at 3 ACH.

The value for the auxiliary energy for the fans, pumps and controls are based on a typical air-conditioned office as outlined in ECON 19 (Department of Environment, 1998). The coefficients of performance (CoP) used are quite low[25]. As with the base insulation level chosen, they represent a low performance system that would exist in a building that required a retrofit in order to reach current regulatory standards.

Table 24 Details of internal gains and infiltration (CIBSE, 2006)

Internal Gains		**Units**
Occupation schedule	07:00 – 19:00	Weekdays only
Metabolic Rate	120	W/person
Occupancy Density	0.11	person/m^2
Lighting Density	15	W/m^2
Equipment Density	15	W/m^2

Infiltration		**Units**
Infiltration	0.7	ACH

Figure 47 Activity, ventilation and HVAC system

Temperature Set Points		**Units**
Cooling set point	24	°C
Heating set point	22	°C
Ventilation		
Ventilation fresh air rate	10	l/s/person
HVAC		
Auxiliary Energy	60	kWh/m^2
Heating system CoP	0.65	
Cooling System CoP	1.2	

All the models have the same internal gains, activity schedules and HVAC system efficiencies, the roof constructions are only varied.

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[25] The impact of this is discussed later on in the Chapter in Section 6.4.2.

6.4.4.3 *Analysis presented*

Design Builder can output a wide range of environmental parameters. For the overheating analysis, the internal operative temperature and the outdoor dry bulb temperature are needed to assess the level of comfort in the building. Overheating was assessed against CIBSE TM52 criteria, the methodology is outlined in Section 2.2. The guidance recommends that new and renovated buildings should be designed to fall within Category 2 limits for naturally ventilated buildings. In summary, Criterion 1 assesses the frequency of overheating within the building, calculating how often the operative temperature exceeds the ±3 K above T_{comf}, which is the limit defined as $T_{max.}$ Criterion 2 assesses the severity of repeated overheating. Finally, Criterion 3 assesses whether the maximum comfort temperature has been exceeded for any period where there is excessive overheating. If a building fails two of the criteria for occupied hours, it is classed as overheating. Results for the "Old Criteria" recommended in CIBSE Guide A are also presented. As outlined in Section 2.2 and Section 5.2, compliance with the criterion is achieved when operative temperatures do not exceed 28°C for 1% of occupied hours (CIBSE, 2006). This will be referred to as the Old Criteria in this chapter.

For the energy analysis, this case study used the heating and cooling energy consumption output by Design Builder. The cooling period is defined as May to September, the heating period is defined as the rest of the year.

6.5 Results

6.5.1 Overheating Criteria

6.5.1.1 *Direct effects.*

To assess the direct effects of each roofing scenario, only the results using the *TRY* weather file (rather than the *Perturbed* weather file) were analysed in terms of their performance for each overheating criteria. Table 25 shows the percentage of occupied hours for which each roofing scenario exceeded the three criteria. The results are split into current and future climate scenarios and include the perturbed results, which will be discussed after this section. All results refer to percentage of occupied hours that the three criteria are exceeded.

Table 25 Percentage of occupied hours that the models exceed the CIBSE overheating criteria[26]

		Percentage of occupied hours exceeding criteria		
Scenario	**Roof Type**	**Criterion 1**	**Criterion 2**	**Criterion 3**
TRY	Basecase	8%	11%	0%
	Green	3%	5%	0%
	GreenDry	3%	5%	0%
	Cool	1%	2%	0%
Perturbed	Basecase	9%	11%	0%
	Green	3%	5%	0%
	GreenDry	3%	5%	0%
	Cool	1%	2%	0%
TRY 2050	Basecase	28%	24%	2%
	Green	14%	14%	0%
	GreenDry	14%	14%	0%
	Cool	8%	11%	0%
Perturbed 2050	Basecase	29%	26%	2%
	Green	13%	12%	0%
	GreenDry	15%	17%	0%
	Cool	7%	11%	0%

In the current climate, the building overheats under all roofing scenarios according to the new criteria. They all fail due to not meeting two of the three criteria. The basecase overheats for 8% of occupied hours. Green roofs reduce the likelihood of exceeding Criterion 1 by 5%. They also reduce

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[26] See Section 5.2 for definition of Criteria.

the severity of overheating by reducing the percentage of hours Criterion 2 is exceeded by 6%. In current climates dry green roofs are as effective as irrigated green roofs. Cool roofs are the most effective at reducing overheating within the building. The building only overheats 1% for Criterion 1 and 2% of the time for Criterion 2. All roofing scenarios do not exceed Criterion 3 in the current climate.

For future climate scenarios the building overheats to a much greater extent for all roofing scenarios. The basecase fails all three criteria and overheats frequently and severely, failing Criterion 1 for 28% and Criterion 2 for 24% of occupied hours. Criterion 3 is not met for 2% of occupied hours. The addition of a green roof reduces the number of hours Criterion 1 is exceeded by half, while reducing the hours of exceedance for Criterion 2 by 10%. Irrigated green roofs perform the same as dry green roofs. However, even though there is a comparative reduction in the number of hours of overheating, both scenarios exceed Criteria 1 and 2 for 14% of occupied hours. Cool roofs are again the most effective at reducing the number of hours and severity of overheating. Both Criteria 1 and 2 are exceeded for 11% or less of occupied hours. Only the basecase exceeds Criterion 3.

The direct impacts of the roofs can be visualised by analysing the temperature profiles for a typical hot week during the summer period for the TRY results. Figure 48 and Figure 49 show the effect of the roofing strategies for a week in July. The variable T_{out} represents the outdoor dry bulb temperature, T_{max} is the maximum comfort temperature and T_{upp} is the upper limit temperature as defined earlier for a category 2 building.

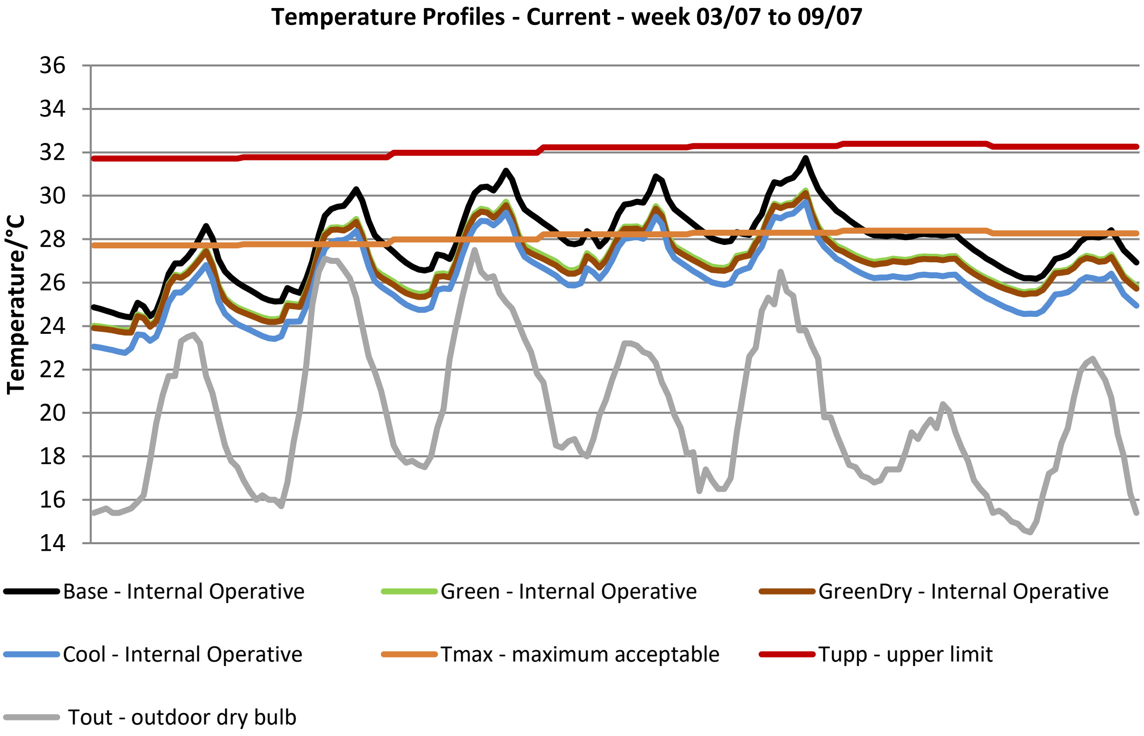

Figure 48 Operative temperature profiles for a typical week for each roofing scenario in the current climate

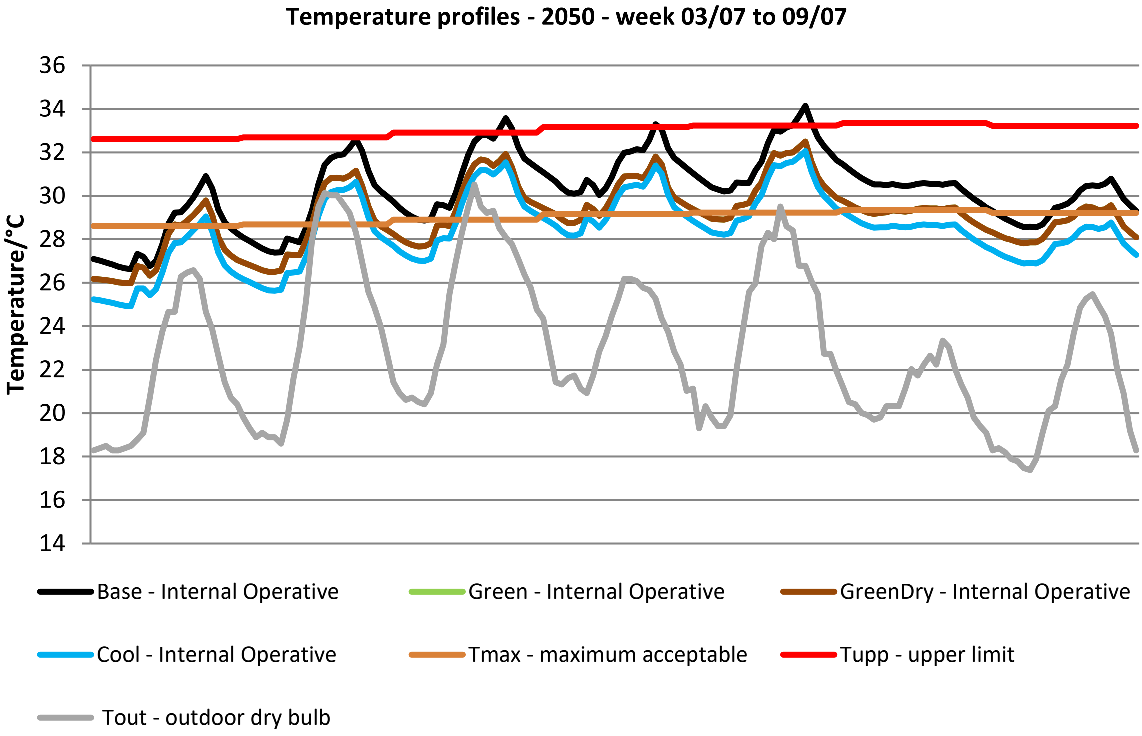

Figure 49 Operative temperature profiles for a typical week for each roofing scenario in the future climate

In the current climate, the operative temperature exceeds the T_{max} as the week progresses but does not exceed the T_{upp} for any scenario. The basecase exceeds this temperature for almost all of the occupied hours for days 3 – 5. The addition of a green or cool roof reduces the number of hours of overheating. In the future climate, by day 4 and 5, all the roofing scenarios are overheating for the majority of the day by exceeding T_{max}. However, only the basecase exceeds T_{upp} during hours of peak solar gain.

6.5.1.2 *Indirect effects.*

The indirect effects of the roofing scenarios can be assessed by analysing how the perturbed weather files impact the indoor temperatures compared to the TRY weather file. The perturbed results represent the combined effect of the direct and indirect impacts of the roofs. As the perturbations represent area averaged air temperatures 1.5m above the roof surface for the output area, the indirect effects of the roofs are the impacts these air temperature perturbations have on the indoor environment.

The indirect effects were calculated by taking the difference between the perturbed and the TRY results for the percentage of occupied hours each comfort criterion is exceeded in Table 25. The impact of the microclimatic modelling, which subsequently altered the temperature and relative humidity in the weather file have little impact on the level of overheating within the building. This is evident in Table 25 where in the current climate scenario, the perturbed results all differ from the TRY results by less than 1%. In the future climate scenario, the impact of the microclimate is slightly greater. The differences in Table 25 show the perturbed basecase model overheats by 1% more than the TRY basecase model for Criterion 1 and 2% for Criterion 2. The difference between the irrigated green roof and dry green roof is more evident when the microclimatic perturbations are included in the weather file. For Criterion 2, the change from the basecase for irrigated green roofs is a reduction of 4% for Criterion 2 and 1% increase for dry green roofs. The microclimatic effect of the cool roof impacts the results less than the green roof.

6.5.1.3 *Impact of insulation.*

The results for insulated roofing scenarios are shown in Table 26. This analysis is only concerned with how the added insulation would impact internal comfort and also the effectiveness of the roofing strategies. Therefore, only the TRY weather file was used, and the dry green roof was not modelled with added insulation.

Table 26 Percentage of occupied hours that the insulated models exceed the CIBSE overheating criteria[27]

		Percentage of occupied hours exceeding criteria		
Scenario	**Roof Type**	**Criterion 1**	**Criterion 2**	**Criterion 3**
Insulated TRY	Base	7%	9%	0%
	Green	5%	8%	0%
	Cool	5%	8%	0%
Insulated TRY 2050	Base	26%	23%	1%
	Green	25%	21%	1%
	Cool	24%	21%	1%

Comparing the results from Table 25 and Table 26, the added insulation reduces the number of hours of overheating for the basecase. In the current climate, the insulation decreases the percentage of hours of exceedance for Criterion 1 by 1% and Criterion 2 by 2%. In the future climate, exceedance of Criteria 1 and 2 are reduced by 2% and Criterion 3 by 1%. The added insulation also reduces the effectiveness of both green and cool roofs in both climate scenarios. In the current climate scenario, both green and cool roofs now overheat for the same amount of time. Green roofs now exceed Criteria 1 and 2 by an added 2% and 3% respectively. Cool roofs have exceeded Criteria 1 and 2 by an increase of 4% and 6% respectively.

In the future climate scenario, the impact of the added insulation is even greater. For the basecase the added insulation has a positive impact and reduces the exceedance of Criteria 1, 2 and 3 by 3%, 5% and 1% respectively. Green roofs now exceed the Criteria 1, 2 and 3 by 12%, 9% and 1%. Cool roofs are affected the most by the added insulation and now see an increase in exceedance of 17%, 10% and 1% for Criteria 1, 2 and 3. In the future climate scenario, cool roofs are still slightly more effective than green roofs.

6.5.1.4 *Comparison of old and new CIBSE overheating criteria*

The new CIBSE overheating criteria has only recently been published and is more complex than the previous one outlined in the 2006 edition of CIBSE Guide A (CIBSE, 2006). The old criteria deemed overheating as the percentage of occupied hours that a building's operative temperature exceeded 28°C. The major difference between the two sets of overheating criteria is that the old criteria is stationary and does not take into consideration occupant's ability to gradually adapt to rises in

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[27] See Section 5.2 for definition of Criteria.

external temperatures. By applying the two criteria to the results from this study, they can be compared to highlight some of the advantages of using an adaptive comfort criterion.

Figure 50 shows the percentage of hours of exceedance for the new and old CIBSE overheating criteria for all the roofing scenarios modelled with the TRY. The results in the figure show the percentage of hours that two of the new overheating criteria are exceeded.

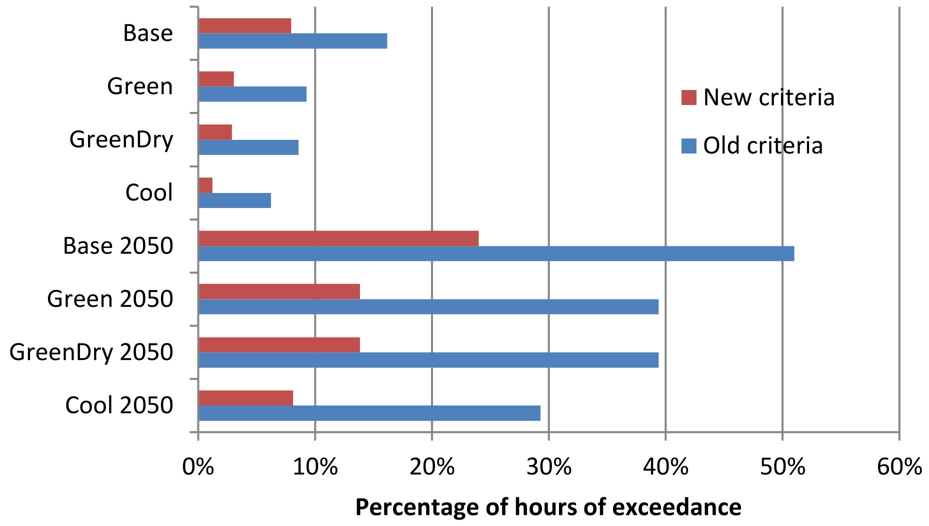


Figure 50 Comparison of old and new CIBSE overheating criteria for the TRY results

As the results from the roof modelling in Figure 51 show, the building exceeds the new criteria to much less of an extent than using the old criteria. This is especially true in the future climate scenario, where the basecase overheats for 50% of the occupied hours. The advantage of using the old criteria is that it is simple, quick to calculate and more easily interpretable. However, as these results show, they probably overestimate the extent of overheating. For future planning, this could potentially lead to overdesign and unnecessary costs in naturally ventilated buildings.

6.5.2 Energy balance of green and cool roofs

The results using weather files which contain the microclimatic effects of the different roofing strategies from ADMS are labeled *Perturbed*. Those which use the same weather file across all building models use the *TRY* weather file. Table 26 shows the values for the total heating, cooling and annual energy usage for the uninsulated and insulated results.

6.5.2.1 *Uninsulated Results*

The combined (direct plus indirect) impacts of the green and cool roofs were calculated by subtracting the energy demand figures for the Perturbed weather file results from each of the roofing strategy modelling runs from the basecase run. Figure 51 and Figure 52 represent the absolute change from the basecase of heating, cooling and annual energy demand for each of the roofing strategies in the current climate and in the 2050s.

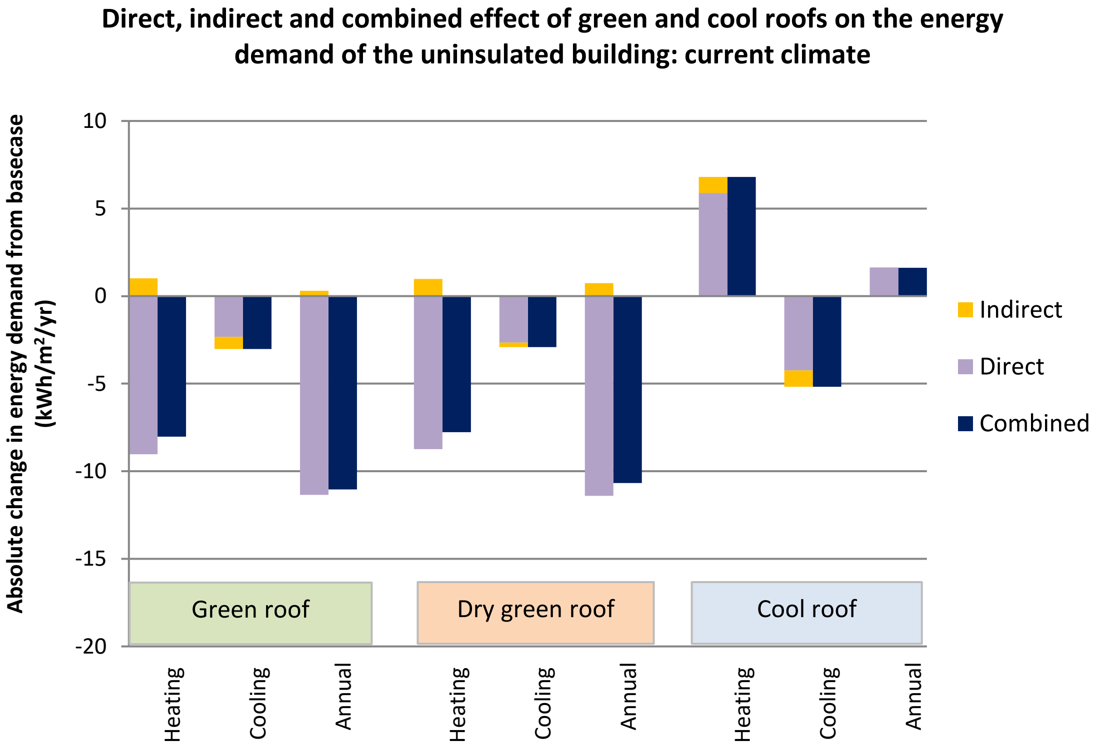


Figure 51 Change in energy demand for heating and cooling due to direct, indirect and combined effects of green and cool roofs, in the current climate scenario

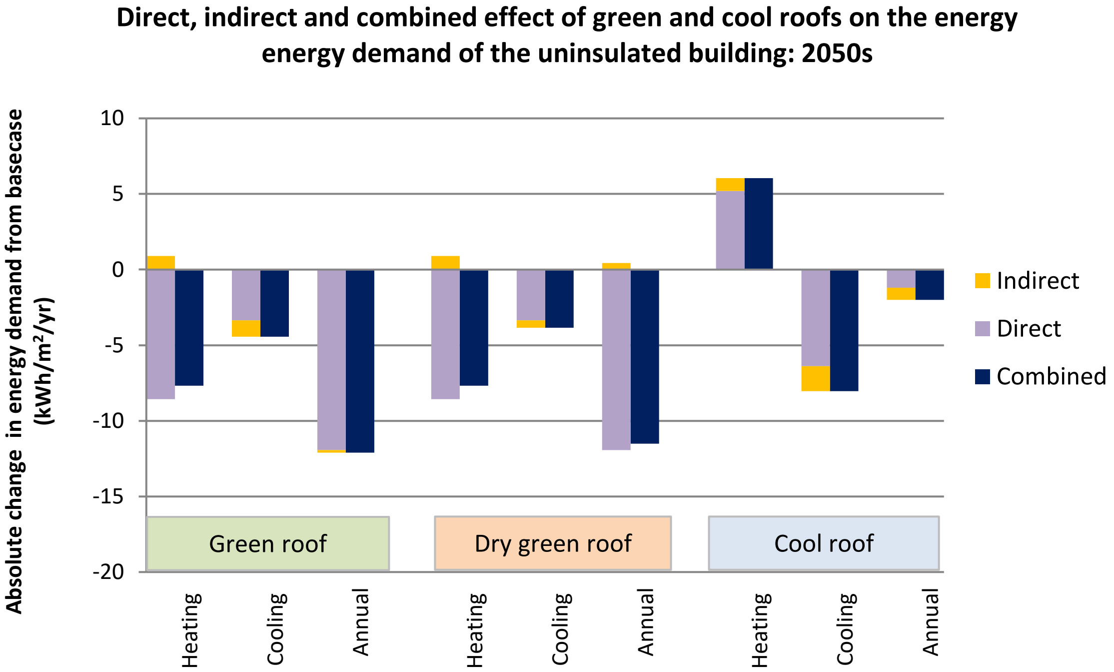


Figure 52 Change in energy demand for heating and cooling due to direct, indirect and combined effects of green and cool roofs, in the future climate scenario

Direct effects

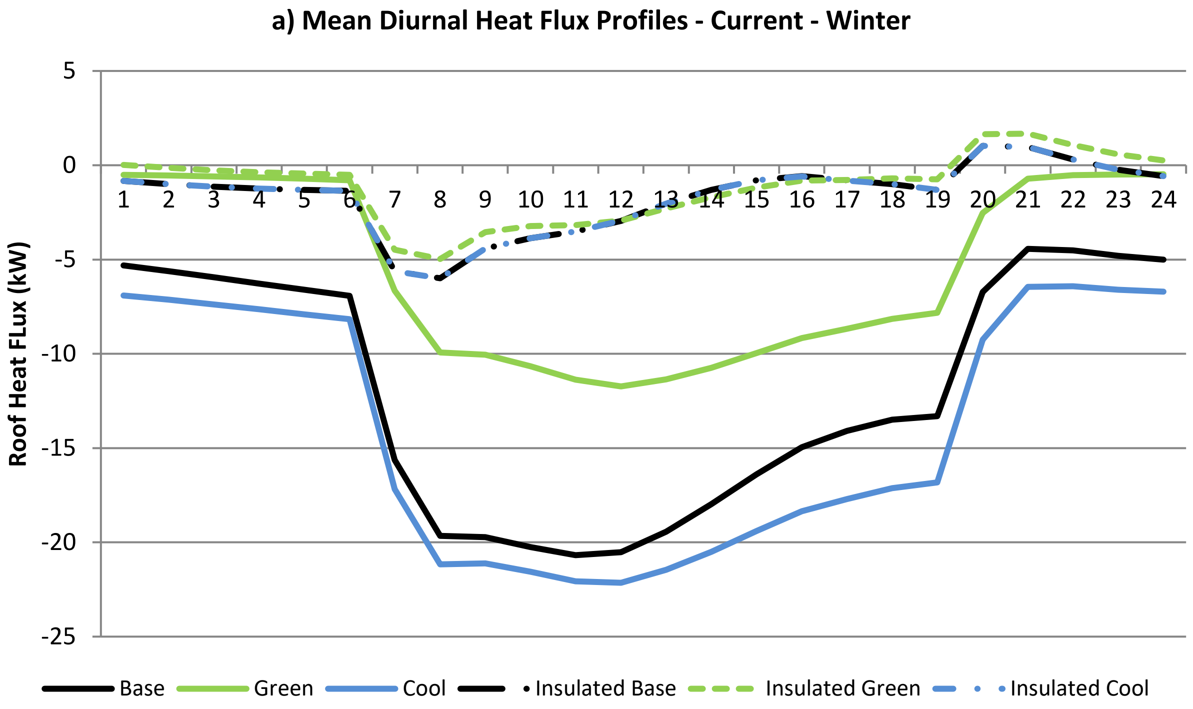
London currently has a heating-dominated climate, with more than 80% of the annual heating and cooling energy demand being used for heating (using the results of the uninsulated case study building). The energy balances in the current climate for all roofing scenarios are largely influenced by how the roofs affect the heating demands. For the basecase roof, heating makes on average of up to 83% of the annual energy use in the current climate as shown in Table 26. Due to warmer winters in the 2050s, this reduced to 65% in future climate scenario. As a result of warmer temperatures throughout the year in the 2050s, the heating energy use decreases by 27% and cooling energy use doubles, with an overall annual reduction in energy use in the 2050s, with heating still dominating the annual energy balance. These results assume no population acclimatization to a warmer climate. Analysis of the effects of the roofs on the uninsulated building follows and is split into heating, cooling and annual impacts.

Heating

As shown in Figure 51 and Figure 52, when applying green roofs to the uninsulated building, there is a reduction in heating demand of 12% in both climate scenarios. The construction of the roof includes a growing medium for the vegetation, which is 0.15 mm thick. This acts as insulation onto the outer surface of the roof, reducing heat being released from the building. The contrast to the cool roof, which results in an energy penalty of around 10% in both climate scenarios, is shown by the winter mean diurnal roof heat fluxes in Figure 53. The cool roof has greater heat fluxes away from the building compared to the basecase, due to its reflective properties less heat is absorbed at the surface. The green roof reduces the amount of heat lost through the roof and results in a saving compared to the basecase. In the future climate scenario as shown in Figure 52, the same results are observed. The only difference is that the change from the basecase is greater in the 2050s, green roofs are relatively more effective in the future climate. Green and dry green roofs reduce the amount of heating energy compared to the basecase, by 15% each. Cool roofs result in a heating energy penalty of 12%.

Cooling

Cool roofs are more effective at reducing cooling demand in both climate scenarios as shown in Figure 51 and Figure 52. The surface temperature of the roof is always lower than the internal ceiling, resulting in outward heat fluxes throughout the whole day, see Figure 53. Green roofs do reduce cooling demand, by 22% compared to 37% respectively. The cooling mechanism of the green roofs is related to their ability to cool through evapotranspiration away from the surface. The results show that changes in albedo are more effective at cooling than this process. This is evident when comparing the green and dry green roof in the current climate. The dry green roof is slightly more effective in the current climate, reducing cooling demand by 19% compared to 17%. As it is drier, its albedo increases and there is a greater heat flux out the building. The irrigated green roof has a total mean summer heat flux of 40 kW out of the building, whilst the dry green roof has a total of 50 kW. In the future climate scenario, there is no difference between irrigated and dry green roofs. In the 2050s the cooling demand for all roofs increases and all the roofs are relatively less effective at reducing cooling demand in the 2050s than in the current climate. Cool roofs are still the most effective at reducing cooling demand in the 2050s.



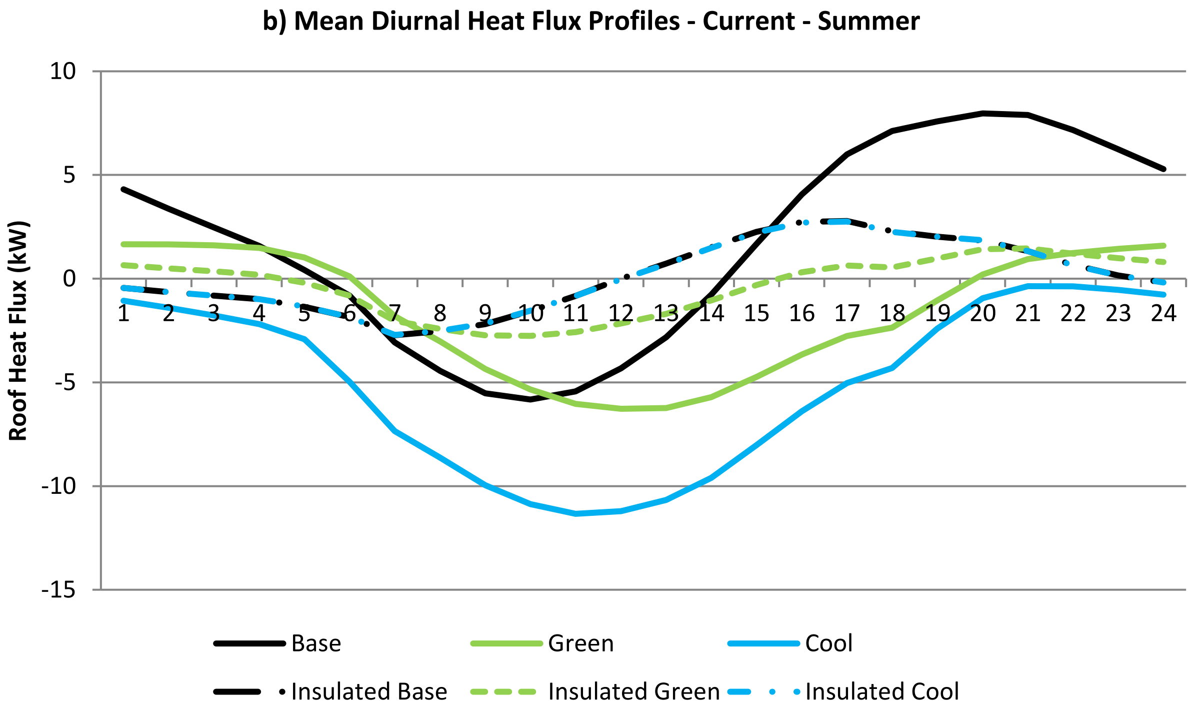


Figure 53 Mean diurnal roof heat fluxes for the roofs and insulated roofs in the current climate for a) Winter and b) Summer periods – negative heat fluxes indicate heat flow out of the building

Annual

Green and dry green roofs result in annual energy savings compared to the basecase in both climate scenarios. This is due to the savings produced in both cooling and heating seasons, resulting in annual savings of 13% in current climates and 15% in the 2050s. Due to the heating energy use being so much higher than cooling in the current climate, cool roofs result in an annual energy penalty for an uninsulated building, with an annual increase in demand of 2%. In the 2050s, cooling demand makes up a greater proportion of the annual demand at 35% compared to 17% in the current climate. As cool roofs are more effective in the summer than in the winter in the 2050s, they result in an overall reduction in annual energy demand of 2%. All roof types result in an annual energy savings in the 2050s. This case study does not consider the potential extra energy used for irrigation. This added energy use would impact the annual energy usage of green roofs due to summer energy penalties, especially in projected warmer and dryer future climates, resulting in additional benefits of cool roofs.

Indirect effects

This case study assumed the indirect cooling above the surface of the building will impact boundary conditions for conduction and convection through varying the input weather files. Perturbations to temperature and humidity were adjusted in the input weather files based on microclimatic modelling of the different roofing scenarios.

In terms of heating, these indirect perturbations have a small impact on the results in both climate scenarios. There is a small increase in heating demand of around 1 to 2% due to the indirect cooling at the surface of the roof. For cool roofs, this formed around 14% of the total (direct and indirect) increase in heating demand. For green roofs, the increase in heating demand is more than offset by the savings achieved due to the direct effects of changes to the thermal properties of the roof.

In the summer season, the indirect effects of all the roofs have a greater impact on demand than in the winter. This is as expected due to the increased effectiveness of the roofs in the summer, compared to the winter, due to their cooling mechanisms. Irrigated green roofs are more effective than dry green roofs due to their greater capacity to cool through evapotranspiration when regularly irrigated. These indirect effects were found to be around 23% of the total cooling demand (direct and indirect) reductions found for the irrigated green roof, falling to around 8% of the total for the dry green roof. Cool roofs are found to be the most effective at indirect cooling, reducing cooling demand by 7% in the current climate, contributing to 18% of the total reduction in cooling demand.

In the future climate scenario, the absolute impacts on heating demand reduces and the impact on cooling demand increases for all the roofs, with cool roofs still being the most effective. Annually, in the current climate, only the indirect effects of dry green roofs increase energy demand (by 1%). In the 2050s, the indirect effects of cool roofs reduce cooling demand by 1%.

6.5.2.2 *Results comparing insulated and uninsulated roofs*

The results for the modelling runs for the insulated building are shown in Figure 54 and Figure 55. The impact of insulation is analysed in two ways; the combined impact of insulation and the roofs on an already insulated roof and the relative effectiveness of green and cool roofs on the insulated roof. By comparing the results for the insulated green and cool roofs to the insulated basecase roof, the direct and indirect effects of adding green and cool roofs to a well-insulated roof are assessed. Comparing the results of the roofs to the uninsulated basecase roof shows the impacts of adding insulation and at the same time, adding a green or cool roof. The difference between the combined results and the sum of the direct and indirect effects, is the impact attributed to the insulation. The labels of the results therefore represent the following:

- Combined – show difference between an insulated roofing scenario using the Perturbed weather file and the uninsulated basecase model using the TRY weather file
- Insulation – the proportion of the combined results attributed to insulation
- Direct and indirect – proportion of combined results attributed to direct and indirect effects of green and cool roofs

Table 27 shows the values for the total heating, cooling and annual energy usage for both the uninsulated and the insulated results. It is clear from comparing the results for the uninsulated and insulated results, for both climate scenarios and all roofing models, insulation significantly reduces heating and cooling demand.

Table 27 Energy demand modelling results for the uninsulated and the insulated case study building

		Modelled: Energy Demand (kWh/m^2/yr) for the uninsulated building							
		Current climate				**2050s climate**			
		Basecase	**Green roof**	**Dry green roof**	**Cool roof**	**Basecase**	**Green roof**	**Dry green roof**	**Cool roof**
Perturbed weather file	Heating	69.3	61.2	61.5	76.1	50.5	42.8	42.8	56.6
	Cooling	13.9	10.9	11	8.8	27.6	23.2	23.8	19.6
TRY weather files	Heating	As above	60.2	60.5	75.1	As above	41.9	41.9	55.7
	Cooling	As above	11.6	11.3	9.7	As above	24.2	24.2	21.2
		Modelled: Energy Demand (kWh/m^2/yr) for the insulated building							
		Current climate				**2050s climate**			
		Basecase	**Green roof**	**Dry green roof**	**Cool roof**	**Basecase**	**Green roof**	**Dry green roof**	**Cool roof**
Perturbed weather file	Heating	53.4	53.8	53.9	54.3	36.4	36.7	36.7	37.5
	Cooling	13.2	12.1	12.4	12.1	26.8	25.1	25.7	24
TRY weather files	Heating	As above	52.9	53	54	As above	35.8	35.8	36.8
	Cooling	As above	12.7	12.7	12.4	As above	26.2	26.2	25.8

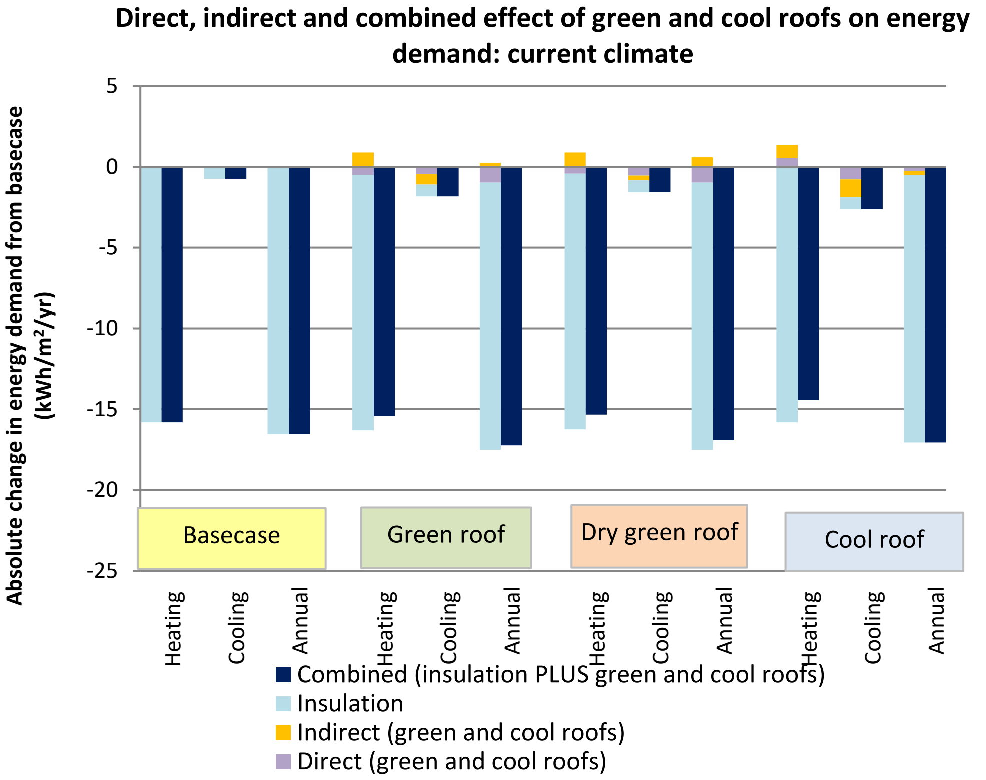


Figure 54 Effect of adding insulation and a green and cool roof on the annual energy demand in the current climate

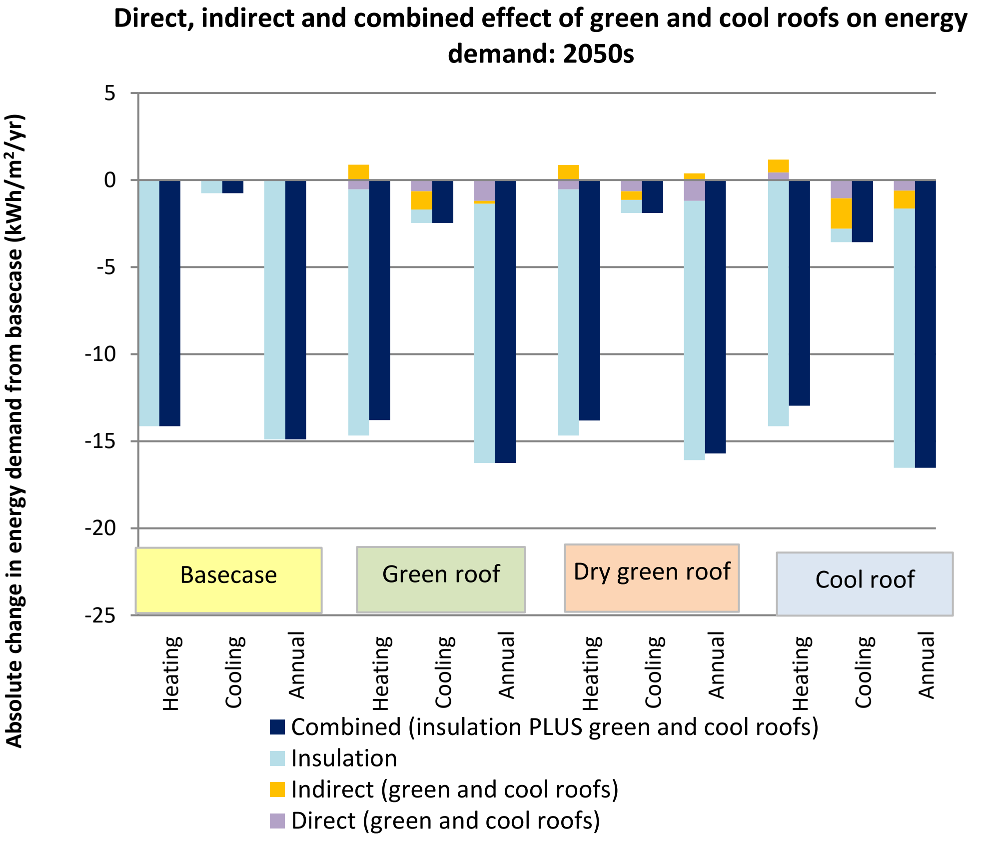


Figure 55 Effect of adding insulation and a green and cool roof on the annual energy demand in 2050

When adding insulation to the roof, insulation does what it is designed to do, i.e. reduces heat transfer in and out of the building. This is evident in the heat flux plots in Figure 53. All the roofs' mean diurnal winter heats fluxes are the same apart from the green roof. The green roof is slightly more effective at conserving heat due to its added insulation. Insulating the roofs is the most effective method of saving energy in any scenario, as the winter heating is the main energy usage.

As shown in Figure 54, the difference in heating demand compared to the uninsulated basecase does not differ by more than 1% across all the insulated green and cool roofs in both climate scenarios. In the summer, the impact of the insulation is to reduce the relative effectiveness of the roofing strategies. Comparing the changes from the uninsulated basecase, adding insulation and a green or cool roof is half as effective as just installing roof insulation. This is due to insulation reducing the heat fluxes out of the building as shown in Figure 53. The insulation also slightly increases the amount of cooling demand as more heat is kept in the building by the insulation. Cool roofs are still the most effective option at reducing cooling demand. Annually, insulation decreases the amount of energy used across all roofing scepnarios compared to the uninsulated building. In the current climate, green roofs reduce annual demand by around 1% due to the savings in cooling demand compared to insulating the basecase. In the 2050s, green and cool roofs reduce annual demand by around an additional 2% compared to just adding insulation.

The relative impact of the direct and indirect effects of the roofs varies when installed onto an insulated building. Indirect effects have a greater impact on the change in heat and cooling demand as shown in Figure 54 and Figure 55. These effects are assessed by comparing the insulated green and cool roofs to the insulated basecase. A green or cool roof has relatively little impact on heating demand compared to insulation. However, in the summer, a green or cool roof will reduce cooling demand compared to an insulated roof. Annually, this results in an overall reduction in energy demand across all roofs, around 1% for green and cool roofs in the current climate and around 2% in the future climate. The proportion of this saving due to indirect effects is greater; approximately half of the cooling demand savings are due to the indirect effects.

What the insulation analysis results show is that insulating the building is the most effective option to reduce annual energy use, in both climate scenarios. However, although a green roof might be more effective at reducing energy use on an uninsulated building, this is not the case when insulation is also added. As the insulation prevents heat loss in the winter, the main savings that can be made are during the summer cooling season. As cool roofs are more effective in the summer, the level of cooling demand savings are slightly greater on an insulated building.

6.6 Conclusions

6.6.1 Summary of the methodologies used and their results

This chapter aimed to test the effectiveness of green and cool roofs and insulation on building performance. As green and cool roofs have both direct and indirect effects, the work in this chapter factored in neighbourhood scale microclimatic modelling results into building simulation. Weather files now capture the city-scale UHI effect in London, but at lower neighbourhood to local spatial scales there is a limited amount of data available. The chapter provides a novel methodology of factoring in modelled climate data into CIBSE weather files in London. Microclimate modelling allows the indirect effects of design strategies such green and cool roofs to be modelled. Designers can then assess how both the direct and indirect effects of these strategies impacts building performance. Further discussion of this approach is found in Chapter 7.

This case study was able to test both the direct and indirect effects of green and cool roofs. This was achieved by using the 'Perturbed' weather files to model indirect effects and the in-built features of Design Builder to model the direct physical differences of green and cool roof constructions. The results of this chapter answer the first research question as microclimate data from a neighbourhood scale model were used to produce the 'Perturbed' weather files. The third research question was also answered as the case study tested the effectiveness of the climate adaptation strategies and a traditional adaptation strategy in the form of insulation.

6.6.2 How can these findings help building designers?

6.6.2.1 *Overheating analysis*

This overheating study used the new CIBSE overheating criteria to assess the effectiveness of green and cool roofs at reducing overheating in a naturally ventilated office building. The roofs were modelled as being retrofitted onto an existing building, which currently has a poorly insulated roof. The analysis of the impact of the roofs is split into direct and indirect effects. This is followed by the analysis of the insulated roofs.

6.6.2.1.1 Direct Effects

Even with the addition of green and cool roofs, all modelling scenarios show a period of occupied hours where the building is overheating according to the new criteria. However, in the current climate the basecase is the only scenario that overheats for more than 3% of the time. The addition of green or cool roof does reduce the percentage of hours that the building overheats. Cool roofs are the most effective option at reducing overheating within the building. Green roofs also reduce the level of overheating within the building, but to a lesser extent than cool roofs.

Drying green roofs only affect the results in the future climate scenario. Green roofs reduce air temperatures primarily by increasing the latent heat flux away from the roof, by increasing evaporation. As evaporation is proportional to temperature, this mechanism will be most efficient in the summer when the air temperatures are highest. If the green roofs are assumed to dry out, their cooling effect will be reduced. A small cooling effect does remain however, resulting from the assumed marginally higher albedo of dry earth compared to a typical roof and also the lower thermal admittance. Hence, the difference between the irrigated and dry green roofs is more apparent in 2050.

In the future climate scenario, the basecase overheats for almost a quarter of occupied hours, making the building frequently an uncomfortable environment to work in. The input weather files used for 2050 were medium emissions (50th percentile). There could potentially be even larger increases in air temperatures, which would only exacerbate the level of overheating within office buildings.

This case study concentrates on overheating within the building and thus only the summer period was evaluated. The results show that the reflective surface properties of cool roofs are more effective than green roofs at directly reducing heat transfer into the building and improving thermal comfort. As shown in Figure 56, the heat flux away from the building is greatest for cool roofs. This increased albedo is a more effective cooling mechanism than the latent cooling due to evapotranspiration of a green roof. However, when choosing what type of roof will be the most appropriate, the annual energy balance should also be taken into consideration.

Two studies that investigated the impact of cool roofs on the building energy use within London found that the application of the roofs resulted in an energy penalty in winter (Ascione et al., 2013; Kolokotroni et al., 2013). Studies have also shown that the added insulation provided by green roofs can reduce winter energy use for climates similar to London (Sailor et al., 2012). The choice of roof should therefore consider all these interrelated issues before a final decision is made.

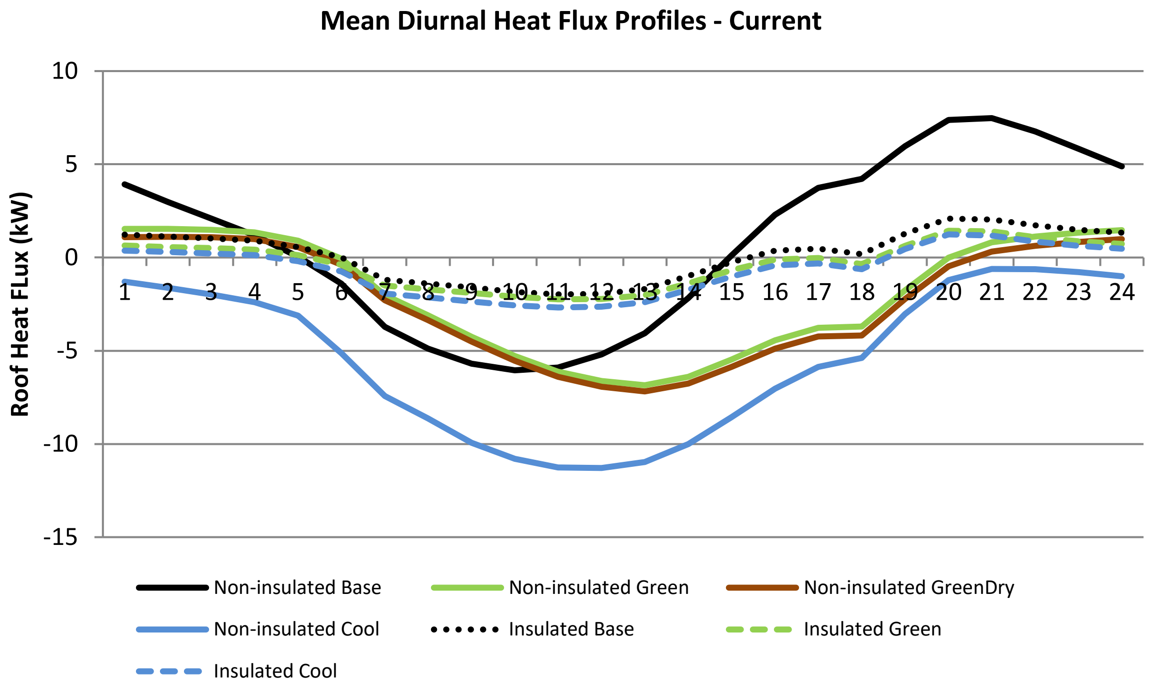


Figure 56. Mean diurnal heat flux of the both the non-insulated and insulated roofing scenarios for current climate, negative fluxes are out of the building

Another interesting aspect of the heat flux profile in Figure 56 is how such a profile would contribute to the urban heat island effect. Green and cool roofs are used to mitigate the UHI effect, as they decrease the amount of heat absorbed into the fabric of the building and cool the surrounding microclimate. The basecase does the opposite, as solar radiation is absorbed throughout the morning and afternoon, the heat flux into the building increases and heat is stored in the thermal mass. At around 21:00 to 22:00, the direction of the heat flux reverses from a peak and heat begins to be emitted out of the building and contributes to UHI effect. This trend is typical of standard UHI profiles (Oke, 1982).

6.6.2.1.2 Indirect effects

In terms of indirect cooling, green roofs are more effective than cool roofs. This is evidenced from the microclimatic modelling of the roofs, which showed that green roofs are slightly more effective at reducing daily rooftop air temperatures than cool roofs, for a variety of meteorological conditions. The results show that cool roofs are most effective when solar radiation is greatest, which usually precedes the daily temperature peaks as shown in Appendix C. Hence, green roofs temperature perturbations are greatest in the evening and cool roofs in the morning.

Compared to direct effects, the indirect cooling of the roofing scenarios has little impact on reducing overheating. In current climates, the temperature and humidity perturbations have no significant impact on the internal operative temperatures whatever the roofing scenario.

In 2050, the indirect effects have a slightly greater impact on reducing overheating. UKCP09 projections for 2050 that are used in this study have days which are clearer and have higher temperatures of up to 3 to 5°C. The microclimatic modelling results in Appendix C show that green and cool roofs are more effective in clearer conditions. This is reflected in the overheating results, where the microclimatic cooling from the perturbations is more effective in the warmer, clearer conditions in 2050. As with the direct effects, the difference between irrigated and dry green roofs is also only noticeable in these drier conditions in the future climate scenarios.

In terms of reducing overheating within this office model, the differences in fabric and surface properties have greater impact on heat transfer through roof than differences in reductions in rooftop air temperature. This study is limited to one single building model and consequently some assumptions have been made as to how indirect cooling of the roofs impacts the building. The study has assumed that the indirect cooling effect of the roofs at a height of 1.5m above the roof surface will directly impact the internal environment by perturbing air temperatures and relative humidity. In reality, as has already been previously outlined in the literature review in Chapter 2, the cooling effect at rooftop level will not have the same impact on the rest of the building. The impact of the roofs on the whole building will depend on the local topography, such as how high the roofs are situated and what the aspect ratio (Height/Width) of the street canyon is. The vertical cooling effect of the roofs was not modelled in ADMS. The perturbations used in the study were area averages at a rooftop level.

6.6.2.1.3 Effect of insulation

The level of insulation on the basecase roof was increased to meet current regulatory standards. The U-value (in W/m^{2}K) for the non-insulated basecase roof was 2.76, non-insulated green roof was 1.36 and insulated basecase was 0.18. This had two main impacts on the levels of overheating. The first was that the added insulation slightly reduces overheating for the basecase. The second is that insulation significantly reduces the effectiveness of both green and cool roofs in both climate scenarios. Although the level of overheating is still reduced for all scenarios, the insulation significantly affects the heat flux in and out of the building compared to a non-insulated roof as shown in Figure 56. The insulation reduces the magnitude of the heat fluxes compared to non-insulated roofs and results in the green and cool roofs heat flux profiles being similar to the basecase roof. A cool roof has a constant negative heat flux as shown in Figure 56. This is in agreement with measurements carried out by Kolokotroni et al. (2011), where the surface of the cool roof was always at a lower temperature than the ceiling.

6.6.2.2 *Energy balance analysis*

The energy balance study investigated the effectiveness of green and cool roofs at reducing energy demand when retrofitted to a conditioned office in central London. The impacts of the roofs were compared to using traditional energy saving technologies such as insulation. The analysis also used the temperature and humidity outputs from microclimatic modelling to assess the impact of how the indirect cooling of the roof's impacts energy use.

Green roofs are most effective at cooling during the evening, whilst cool roofs are most effective between morning and midday when solar gains are high, as outlined in the literature review and also evident in the microclimatic modelling results in Appendix B. This difference in peak cooling capacity will impact UHI mitigation. There is evidence of this in the building modelling, where the cool roofs heat flux is always negative in the summer and out of the building, whilst green roofs do absorb some incoming solar radiation.

Due to the characteristics of the London climate, the impact roofs have on heating demand largely determines the annual energy balance. Green roofs with their added layer of insulation are more effective than cool roofs at reducing annual energy demand in the current climate, mainly due to the winter energy penalty of cool roofs. In the 2050s, heating demand is modelled to decrease and cooling demand to increase, resulting in cool roofs reducing annual energy demand compared to the current climate. The impact of adding insulation reduces the relative effectiveness of green and cool roofs. Insulation is the most effective technology at reducing annual energy use. The addition of a green or cool roof onto an insulated roof reduces cooling demand, the proportion of this which is attributable to indirect effects is greater for the insulated roofs than for uninsulated roofs. The annual energy balance could be affected by the low performance HVAC system modelled, a more efficient system could reduce the energy penalty experienced by cool roofs in winter and enhance their benefits.

This case study assumed that the cooling effect at the near surface of the roofs would impact internal air temperatures. As the result show, for both uninsulated and insulated scenarios, the indirect effect is small but can reduce annual energy demand by up to 2%. However, this case study is limited to one building and presumes that the indirect rooftop cooling will impact the whole building. Further work needs to be carried out to understand how multiple roofs will impact local air temperatures and the extent that rooftop cooling impacts street level air temperatures.

6.6.2.3 *Other benefits of roofs*

When weighing up the costs and benefits associated with green and cool roofs, numerous issues arise. For example, in addition to thermal effects, green roofs are known to decrease storm water runoff and hence reduce urban flooding, increase biodiversity, filter various air and water pollutants and sequester carbon dioxide (Getter et al., 2009; Getter and Rowe, 2006; Rowe, 2011). A cost benefit analysis of a green roof undertaken by Clark et al. (2008), which valued the uptake of NOx and avoided storm water infrastructure costs, suggests that a green roof has a 25-40% lower net present value than a normal roof over a 40 year period. However, it has also been shown that as green roofs dry out, their cooling effect reduces drastically. As summers are predicted to become drier (UKCP09, 2010), to maintain the same degree of ambient cooling, they would require irrigation. This may be an issue for the water supplies of the South of England. Green roofs also raise humidity and have higher upfront capital costs than the cool roof alternative. Cool roofs have another benefit of potentially being able to contribute to climate change mitigation through global changes in radiative forcing if deployed worldwide (Akbari et al., 2008).

If cool roofs reduce the amount of cooling energy being used by a building, they can consequently reduce anthropogenic emissions. These advantages could outweigh the negatives of any potential additional global warming, such as those found by Jacobson and Ten Hoeve (2011), that varying the albedo of surfaces could have. Evidence in the literature suggests that the potential additions to global warming caused by high-albedo surfaces are small in comparison to their potential savings.

7 Summary, discussion and future work

The aim of this research was to investigate methods of integrating climate data from varying spatial and temporal scales and sources into the building design process using building simulation. The work in this thesis uses urban climate data at two different scales, the city scale and the neighbourhood scale. The urban climate data is from both observed and modelled sources. In a warming climate and with increasing urbanisation, being able to use these data sources to analyse the effects of the urban climate will be beneficial to designers and planners within building and urban design.

The work in Chapter 3, 4 and 5 analyses new and existing forms of climate data to provide a more in-depth analysis of features of the urban climate such as the UHI effect. The work in Chapter 5 and 6 analysed the impact of these effects on building performance and also tested adaptation strategies. As green and cool roofs can both impact the direct and indirect heat transfer into a building, they were a suitable adaptation strategy to test in the context of building design and the urban climate. These were retrofitted to an existing building to quantify their effect and also compare them to traditional insulation.

In order to assess how the urban climate can be factored into building design and to answer the research questions, research objectives were set in Chapter 1. As this thesis is the output of an EngD, sponsored by CIBSE, these research objectives were met through a number of case studies with outputs that can be used to expand industry knowledge. The individual studies provide a number of useful research outcomes and novel contributions, but collectively the research demonstrates how complex integrating the urban climate into building design is. The research highlights how potential future work and guidance can be developed to further increase knowledge and integration of the urban climate into building design. The detailed research outcomes for each Chapter is summarised next.

7.1 Summary of research outcomes

7.1.1 Chapter 3

At the city scale, measurements from weather stations have traditionally been used to analyse the climate. Their limitation is that they represent point measurements in generally semi-urban or rural locations. Models provide an alternative source of data and can simulate climate variables at the city-scale at a variety of spatial and temporal scales.

Chapter 2 analysed how modelled city-scale climate data for London can be used to quantify the Urban Heat Island effect. Previous evidence has shown that the location of a building within London's UHI has an impact on cooling loads. The UHI intensity can be used at the early stages of design to indicate how buildings located within the centre of London will perform differently to those located in rural areas. At the city-scale, the UHI intensity has traditionally been derived from observed datasets. These point sources are limited to certain locations within London. The most temporally extensive datasets are from Met Office weather stations.

The LSSAT database used in the study represents the most spatially extensive observed dataset used an array of sensors across London for relatively cool years, 1999 – 2000. The MORUSES modelled data represents a gridded dataset for a single warm summer in 2006, it has greater spatial variation compared to the observed data. The revision of CIBSE Guide A resulted in a comparison of UHI intensities of the observed and modelled datasets.

The frequency of occurrence of night time UHI intensities does not vary significantly between the two datasets. At high intensities of 4.5K and above, the observed and the modelled data produce similar intensities. Gridded modelled datasets allow analysis of the spatial variation of London's UHI. Usually, this limited by choice of urban or rural reference point. Using defined annular distances from the centre of the city, the mean UHI intensity can be calculated.

Using Heathrow as a rural reference point reduced the intensity of the UHI profile. Heathrow is also shown to have its own UHI compared to the surrounding area. By using a more rural reference point in Wisley, the maximum UHI intensity of the diurnal profile was shown to increase from 2.5 K to 5 K.

During the day, the UHI intensity of more central regions is negative in comparison to rural areas. The urban surface absorbs a greater amount of energy during the day compared to the rural surface due to a greater surface area and their properties.

The modelled data was shown to provide spatial and temporal analysis of the UHI varies in cities such as London. The analysis showed that the radial distance from the centre of the city can be used as an accurate measure of the overall difference between urban and rural air temperatures. The choice of reference point has a significant impact on the estimated intensity, highlighting the limitations of point references. The next section discusses the UHI analysis of point references from weather stations in Birmingham and Manchester and their suitability for creating new urban weather files.

7.1.2 Chapter 4

Extensive series of point measurements from weather stations have been used to create CIBSE weather files used in building simulation. London has the advantage of having long time series of temperature measurements from an urban station, which was used to create a new urban DSY (CIBSE, 2014).

Following the publication of Technical Memorandum 49, London has DSYs for three different locations. These represent urban, semi-urban and rural locations. Birmingham and Manchester also have weather stations in more urban locations relative to where their current DSY are based. As with other CIBSE weather file locations, these are situated in rural locations. This could affect overheating analysis of developments within the centre of the cities.

Data is available for one urban station in Manchester located at Hulme and two urban stations in Birmingham, Winterbourne and Edgbaston. As with the London Weather Centre, all of these weather stations are non-standard Met Office weather stations. The availability of data, location and quality of weather station observations is common issue in cities across the UK. Subsequently, all of the analysis was impacted by these limitations.

The analysis for Birmingham showed that Winterbourne is not an appropriate urban weather station, due to its park-based location – the UHI intensity does not increase above 1 K. Edgbaston has a more typical diurnal UHI profile, with a larger number of higher intensities occurring at night. Images of both sites highlight the potential issues with non-standard Met Office weather stations. Their location and surrounding microclimate impact their observations.

Analysing the UHI intensities during heatwave periods (August 2003 and July 2006) for both cities resulted in an increase in nocturnal intensities. The analysis for Manchester differed to Birmingham, as 2 rural weather stations were compared to 1 urban station. The difference between the 2 rural sites was evidenced by the difference in diurnal UHI intensity profiles and the frequency distributions. The Ringway weather station is located near a larger airport and more centrally than Woodford and this impacts how high the UHI intensity is. This difference was further emphasised during the heatwave period analysis, the UHI intensities for Hulme compared to Woodford are higher than Hulme compared to Ringway.

Both sets of analyses highlight that using data from more urban weather stations can result in UHI intensities of greater than 5 K. The underlying issues of the location and microclimate surrounding the stations needs to be considered carefully if these sites are to be used as new weather file locations. These factors include being located on rooftops and surrounded by green space. The height at which the stations are placed will be impacted by alterations to wind profiles. The other issues are the longevity of the datasets and the number of variables available for each site. To synthesise a weather file requires other crucial variables such as wet bulb temperature, cloud cover and solar radiation. These could be sourced from other surrounding stations.

The data is also limited to 14-16 years, whilst the London weather stations have such as LWC and LGW have 30 years' worth of continuous data. This could potentially affect which years are chosen as DSYs using the methodology from TM49. The next section outlines the first testing of the London DSYs produced using the methodology in TM49.

7.1.3 Chapter 5

The TM49 weather files were released during the course of this EngD. The work in Chapter 5 analysed how the CIBSE weather files be used to quantify the impacts of the Urban Heat Island effect on overheating within an office.

The release of new CIBSE DSYs for London allows practitioners the choice as to which is the most appropriate weather file dependent on location. The weather files capture the urban heat island effect. The addition of two baseline years also allows the sensitivity of the design to different heatwave events to be tested.

Initial testing demonstrated how the new DSYs impact the level of overheating when modelling an existing naturally ventilated office within London using dynamic thermal simulation software. An analysis of the UHI effect of the three locations for the three different baselines showed that baseline years with longer and more intense summer heatwave events 1976 and 2003, have more frequent extreme UHI intensities. The location of the files highlighted differences between the sites is at night, where the mean and maximum Tmin are for Heathrow and Gatwick are all lower than LWC.

Modelling of a naturally ventilated office confirmed how the differences between baseline year and location impacts overheating assessment:

- For all locations, the year with the longest heatwave overheats the most.
- The difference in location has the greatest impact on overheating for buildings that are night cooled due to the UHI effect.

The choice of overheating assessment criteria has an impact on the level of overheating between sites. Buildings within the centre of London will pass the new adaptive criteria with higher internal temperatures, as the outdoor running mean will higher.

Adaptation strategies such as shading and cool surfaces reduce the level of indoor overheating when retrofitted to buildings and they were shown to be more effective when combined. Mitigating overheating in future climate scenarios for buildings with naturally ventilated buildings with poor insulation, window orientations to the South and West and lacking opportunities for purge ventilation strategies will prove challenging. The results highlight the potential need for additional measures such as microclimatic UHI mitigation interventions.

A limitation of this study was that it uses one main archetype. A single floor of a building could be influenced by heat transfer and airflow from other floors. The study was also limited to representing one natural ventilation strategy – deep plan cross ventilation. Different building types would have varying sensitivity to the external environment. For example, many new building archetypes have lower infiltration rates and smaller window openings. They would potentially be less sensitive to external temperatures. Expanding on this study by testing more archetypes and ventilation strategies could test this and other issues.

The relationship between the weather variables and subsequent level of overheating is complex. The differences between the heatwave periods, peak day time and minimum night time temperature profiles and wind speeds for all three years will vary the level of overheating and needs to be further investigated. The results further emphasise the recommendation in TM49 of the need for all years to be modelled during overheating assessment, in order to highlight these differences and test the sensitivity of the building design to these parameters. The next section discusses how neighbourhood-scale climate data can be incorporated into weather files to assess the impact of building and microclimate mitigation measures on building performance.

7.1.4 Chapter 6

The CIBSE weather files can be used to model the city-scale UHI effect. But when designers need to analyse the impact of more localised mitigation measures and design decision, other data and modelling tools are needed. The work in Chapter 6, provided an integrated methodology to assess how neighbourhood-scale climate data from a microclimate model can be factored into building simulation. The outputs from the microclimate model were used to assess what the impact do neighbourhood-scale urban climate mitigation measures in the form of green and cool roofs have on the annual energy balance and thermal comfort of an office in Central London. The evidence from both the studies show that:

- Retrofitted green roofs can reduce summer and winter energy use in a conditioned building and can also reduce the level of overheating in a naturally ventilated building. However, their effectiveness in the summer is dependent on the level of irrigation.
- Cool roofs are more effective at reducing summertime overheating than green roofs. However, in the current climate they result in an annual energy penalty, due to their winter performance. In projected 2050 climates, they result in an annual energy saving. Compared to a green roof the future energy savings for a cool roof are lower in the winter and higher in the summer.
- Thermal insulation is the most effective energy reduction technology. Insulation generally reduces the effectiveness of green and cool roofs at reducing overheating.

These results highlight issues that designers could potentially face when retrofitting buildings. If a roof has to be altered to meet current regulations, then the traditional approach would be to add insulation. But this traditional approach could be less effective at reducing overheating and energy use compared to using green or cool roofs. The non-insulated cool roof in study considerably outperforms the basecase insulated roof. The results also show how increased insulation levels negate a lot of the beneficial direct effects of the roofs. A potential solution to this could be more flexible regulations which are evidence based. Rather than having a fixed U-value that refurbished roofs must meet, the annual impact of the roofs on the energy use and comfort of the building could be assessed. This approach could lead to additional challenges in terms of the industry following complex compliance procedures, as there could be a potential knowledge gap in both the modelling and assessment of buildings.

Future work could investigate how the net effect of multiple green or cool roofs impact rooftop and street canyon temperatures and the consequent impact on the local buildings. This could then inform future planning and policy by providing evidence of the mitigation potential of wide-scale installation of green and cool roofs. What is clear is that the roofs should be considered on a case-by-case basis. Planners should assess the impact to the local environment and compare that to potential advantages such as overheating reduction and energy savings. They are only one of the options available to mitigate UHI effects in a warming climate and further work needs to be carried to confirm how the net effects of multiple green and cool roofs contribute to UHI mitigation on a larger spatial scale.

Microclimatic results from a neighbourhood-scale climate model were integrated into a CIBSE weather file. The edited weather files allowed an analysis of the indirect effect of green and cool roofs. This novel methodology had not been applied to previous case studies in London and this approach can be replicated in the future. As outlined in Chapter 2, climate models are not readily available to the average user and due to their complexity often require high computing power. What this research shows is that when results are available, they can be used to provide more in-depth analysis to building performance studies.

The outputs from the studies in this research have been used in current CIBSE guidance and can be used to inform future CIBSE guidance and case studies. The outputs demonstrate how decision support tools in the form of dynamic thermal simulation building models and climate models can be used to inform the design process at a variety of spatial and temporal scales. Especially at the early stages of design, methodologies and outputs from this research can be used to identify and prioritise any climate mitigation and building adaptation strategies.

7.2 Limitations of research

In each chapter there has been some discussion into the limitations of the research in this thesis, but it is worth understanding the main limitations of the work as it highlights areas of future work. The urban climate data used in this thesis at both the city and neighbourhood scales focused on air and operative temperatures. The review in Chapter 1 explained how policy makers are focusing on urban warming resilience due to future climate change and the potential public health issues associated with overheating. But as outlined in the literature review in Chapter 2, there are many other climate variables that have an impact on building performance and human comfort. Variables such as solar radiation and albedo, wind speed and direction and humidity often require specific models and observations, which although obviously connected to the outputs in this thesis require further investigation. The use of CIBSE weather files for London did allow for differences in these variables to be factored into the research as three different locations were analysed.

The London Plan includes policies towards improving air quality in cities such as London (GLA, 2018a, 2018b). There are also acoustic variables to consider when designing in urban areas (ANC, 2018). When considering overheating mitigation measures, both of these variables will influence the design of ventilation strategies, especially in more dense urban environments.

The case studies in Chapter 5 and 6 included overheating assessments and a limit of this research is the focus on existing office archetypes. The UHI effect is predominantly a nocturnal phenomenon and as outlined in Chapter 2, heat related stress often occurs at night in homes. CIBSE has recently released an overheating assessment methodology for homes, Technical Memorandum 59 (CIBSE, 2017). With the release of this methodology, similar case studies can be developed for homes. The office case studies in this thesis are also limited by modelling retrofitted design adaptations on existing buildings.

The studies used climate data from a variety of sources including the MORUSES model, Met Office weather stations and ADMS Temperature & Humidity model. The modelling outputs from MORUSES have been validated and the modelling assumptions are outlined in (Bohnenstengel et al., 2011). The limitations of the Met Office weather station data has been discussed in Chapter 4, as the “urban” weather stations were non-standard WMO stations (WMO, 2008). The microclimatic modelling results from ADMS have a few limitations that have also been discussed in more detail previously. The ADMS Temperature & Humidity model has limited validation (Maggiotto et al., 2014) and it is understood that if the model were to be used commercially it would need to go under more rigorous testing and validation. The methodology of integrating the microclimate results also makes assumptions on the indirect cooling effect of the green and cool roofs. It is assumed that the near surface temperatures output from the model would affect natural ventilation entering the building. To validate this assumption required more complex CFD modelling.

7.3 Implications for industry and recommendations for future work

In the London Environment Strategy, the GLA proposes that there needs to be more accessible location specific data and modelling to provide evidence of the impacts of the UHI (GLA, 2018a). The Environment Audit committee report on Heatwaves concludes that local councils need alert systems during heatwave events and overheating mitigation measures based on evidence from real case studies (House of Commons, 2018). Both highlight the ongoing need for integrated policy tools and design guidance.

There have been a number of studies which have integrated new forms of climate data in policy tools. Taylor et al. (2015) used the MORUSES data to map the effects of urban heat island, housing, and age on excess heat-related mortality in London. The maps produced as part of this study are available through the GLA website (GLA, 2016b) and combines UHI information during a heatwave summer (2006), modelled indoor temperatures for individual dwellings in London for this time period and population age, as a proxy for heat vulnerability, and distribution. The same authors also produces UHI time series maps using the same modelled MORUSES data (GLA, 2016a) for 2006. More studies and accessible outputs like this are needed but as discussed in Chapter 2, the MORUSES model and data are not accessible to the average user and require the Met Office computing network to produce results. These issues of accessibility are not only limited to regional climate models, but also to observed data within cities such as London.

The London Climate Change Partnership published a report reviewing the availability, quality and quantity of observed weather data in London and a survey of its user and their needs (Grimmond, 2013) (LCCP, 2019). The report proposed that all of the observed datasets in London should be collated through a central portal – London Climate Data Portal (LCDP). This would improve quality, evaluate gaps and ensure continuity of available data. A recent LCCP meeting concluded that there is still a lack of a LCDP and there needs to be improved spatial and temporal availability of data, which are easily accessible (Grimmond, 2019). A centralised, managed portal which ensure continuity and quality of data could then be used to validate NWP models, improve health forecasting through evidence-based policies on overheating mitigation and improve testing and evaluation of building performance modelling by understanding how the internal climate is affected by urban climates. This would ultimately lead to integrated policy tools, for example, tools which could quantify the impacts of proposed developments on future temperatures and recommend design mitigation measures.

Recent projects in London are aiming to apply microclimate case studies to building design and output location specific case studies. The Urban Albedo project has already carried out measurements and microclimate modelling of neighbourhood and street case studies in London, with an aim to accurately calculation and predict the albedo of the urban environments (Nikolopoulou, 2018) (Salvati, 2019) (University of Kent, 2018). The project aims to "use the microclimate outputs as local conditions for building energy performance simulations to investigate how urban albedo changes can improve building thermal performance" (Salvati, 2019) (University of Kent, 2018). This is a direct continuation of the work carried out in this thesis, using microclimate modelling as inputs into building simulation though an adapted CIBSE weather file.

There are a number of future studies which lead directly from the work in this thesis. At the building level, the impact of the urban climate on residential buildings and those with vulnerable occupants such as care homes could be carried out. The EAC emphasises a risk based approach future legislation and work should be take (House of Commons, 2018). Overheating risk will be greatest for vulnerable members of society and is a particular risk at night. Research projects such as ClimaCare aiming to better understand the negative health impacts in care homes (UCL, 2018). The release of TM59 provides a methodology for assessing overheating risk in homes and this can be applied to other residential buildings (CIBSE, 2017).

With the move to zero carbon buildings, the balance between savings in annual energy use and the impacts of zero carbon design on thermal comfort needs to be considered (Shrubsole et al., 2014). There is currently industry wide discussions into what constitutes a zero carbon building with stakeholders such as the UK Green Building Council and Passivhaus trust (Passivhaus Trust, 2019; UKGBC, 2019). As the industry moves towards zero carbon design, the role the urban climate has on larger residential or multi use developments will be critical to ensuring that buildings do not overheat in future climate scenarios. Any future work will need to consider the climate change and urban warming as part of the analysis, current and future legislation will potentially include analysis on the future resilience of building design (House of Commons, 2018).

At the neighbourhood level, the impact of green infrastructure is being advocated by urban planners in cities such as London and Birmingham (GLA, 2018a) (Birmingham City Council, 2017). Modelling tools and design guidance accompanying any outputs will be important to aid design at neighbourhood level. The impact of green infrastructure design mitigation strategies that cooling surrounding area will need to be understood at a location specific level.

CIBSE's role in this is to provide design guidance and knowledge services on the urban climate. CIBSE is already involved in the Urban Albedo project (Nikolopoulou, M, 2018) through its special interest groups. The work in this thesis provides further evidence of the knowledge gap in terms of design guidance, which is at neighbourhood and microclimate level. It is the most difficult scale at which to factor into building design as there are so many variables that affect a local microclimate. The selection and applicability of modelling and tools and data is crucial, this requires guidance for the average user. Future work should focus on further good practice guidance based on evidence from case studies.

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[28] Futurebuild is an industry event, not an academic conference. The work presented in this reference was not peer reviewed and was meant to provide an overview of the Urban Albedo research project and its aims. Further information on the project can be found in Nikolopoulou, M (2018) and University of Kent (2018).

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9 Appendix A – Validation of the dynamic thermal simulation software EnergyPlus

The work in this thesis uses the dynamic thermal simulation software EnergyPlus (U.S. Department of Energy (US-DOE), 2016) to model internal temperatures and energy consumption. EnergyPlus is subject to continual empirical and comparative testing and validation (U.S. Department of Energy (US-DOE), 2019). The brief review in this section outlines evidence from studies that show that EnergyPlus models can accurately simulate variables such as air temperature for a variety of buildings. However, model accuracy can, of course, be affected by issues such as quality and complexity of modelling inputs.

The IEA Annex 58 carried out empirical validation of multiple building models, including EnergyPlus (IEA, 2015; Strachan et al., 2016). The study used two identical houses and measured three components; steady-state internal temperatures, a sequence of pseudo-random heat injections and a free-float period. Modelling teams from across Europe then simulated the houses as part of blind validation and then provided all measurements to adjust and remodel. Most models showed show good agreement in both the absolute predictions of temperatures and heat inputs, and the dynamic response.

One of the issues faced by building simulation models is the quality of input data. Glasgo et al. (2017) found that EnergyPlus did not accurately or consistently model energy consumption in homes due to the discrepancies between appliance and lighting specifications. Accuracy was always impacted by the complexities of modelling occupant characteristics. The study recommends a standard set of assumptions and conditions for occupancy and more detailed information about device-level energy consumption. Calibrating models with empirical data also has its complexities. An extensive review by Coakley et al. (2014) found that calibrating models faced issues with a lack of standard guidelines for model development, quality and simplification of modelling inputs and a lack of accounting for uncertainty. Improving the quality of weather data has been shown to improve the accuracy of indoor temperature simulations for a validation study of a house in Austria (Pereira et al., 2014). Empirical validation of EnergyPlus has been shown to have good results when modelling HVAC systems in a commercial building in Tennessee (Im et al., 2020). A calibrated model was shown to have less than 2% deviation in total energy consumption and maximum air temperature deviation of 1.14°C. The authors did find issues with interzone air mixing and the infiltration rate modelling differing depending on whether HVAC system was on or not.

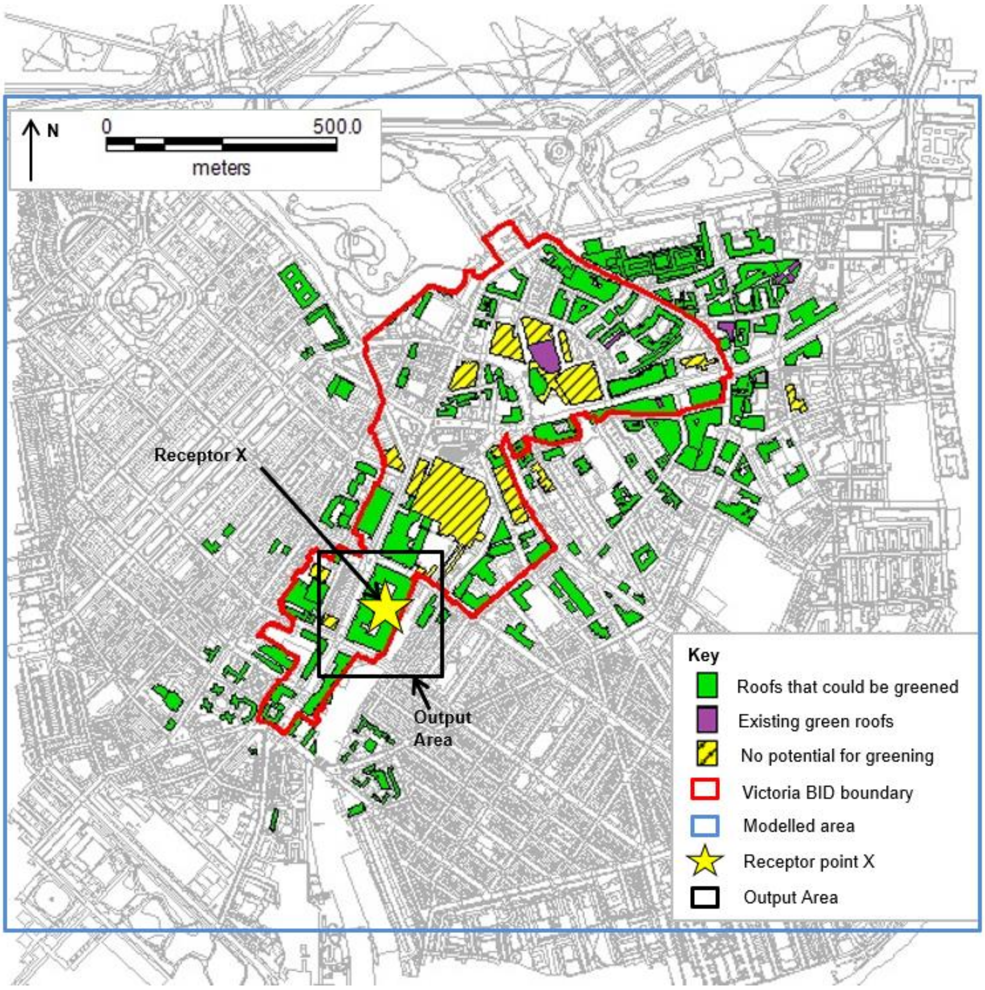
EnergyPlus has been used to model naturally ventilated buildings and validated against observational data in a number of studies. Olsen and Chen, (2003) validated EnergyPlus models using data from the Building Research Establishment's International Energy Agency's Empirical Validation Study (Lomas and Eppel, 1992) - they found the modelled air temperatures were in good agreement with measured data. Coakley et al. (2013) found that EnergyPlus usefully predicts the Predicted Mean Vote, which is highly correlated to activity levels and operative temperature in large mixed mode building in Ireland. Gu (2007) validated the EnergyPlus airflow network against laboratory measurements from the Oak Ridge National Laboratory test facility and found maximum differences in airflow and pressure was less than 5%. Zhai et al. (2011) evaluated EnergyPlus for three real UK buildings that used natural and hybrid ventilation against measured data. Of the three buildings modelled, the model accurately predicted air temperatures for one. The study highlighted current deficiencies with EnergyPlus include how accurately large opening and multi-story buildings are modelled. The authors recommend that more data such as on-site temperature, measured thermal mass, information on opening and wind pressures are needed to accurately validate thermal simulation models. Anđelković et al. (2016) validated EnergyPlus for multi-story naturally ventilated building with a double skin façade in Belgrade. The simulations used EnergyPlus Airflow Network algorithm. The results showed that modelled results were in good agreement with measurements for the cavity air temperatures. The cavity air velocity had a higher level of disagreement between the measurements and simulations, but this was due to differences in reporting intervals. Other studies validating free running test cells in Lisbon have found good agreement between simulation and measurements (Mateus et al., 2014). The study found average simulation error in air and radiant temperature is 1.4 °C and the average daily maximum error is 2.5 °C.

Recent studies from the UK have investigated validating EnergyPlus models used for overheating assessment in terraced houses (Roberts et al., 2019) and using the English Housing Survey, Energy Follow-Up Survey (EFUS) monitored dataset (DECC, 2013; Symonds et al., 2017). In both studies, the modelled results over predicted the maximum internal temperatures. Roberts et al. (2019) suggests that the differences resulting in overprediction of peak temperatures and diurnal swings in temperature could be attributed to sensitivity of the internal heat transfer algorithms. This sensitivity has been highlighted in a study by Petrou et al. (2019). Stock level comparison of overheating by Symonds et al. (2017) found that the lack of input data of building characteristics such as occupancy and local climatic conditions could explain the differences in model predictions.

The studies in this review highlight the issues with whole building simulations. The accuracy of outputs is dependent on a wide range of variables, including variations between modeller methodologies and quality of inputs. Considering these issues, the studies show that EnergyPlus can usefully model indoor temperatures and energy use and the author has ensured that best practice methodologies and inputs have been used within the research.

10 Appendix B – Microclimatic modelling results for green and cool roofs

The microclimate results in this appendix are from the work by Jansz (Jansz, 2011, 2012) and are used in Chapter 6. The published papers Virk. G et al. (2014) and Virk. G et al. (2015) outline the full details of the microclimate model and the climate data outputs used to edit CIBSE weather files. These weather files were subsequently used in the analysis that forms Chapter 6.



Land use type	Percentage of each land use type within study “Output Area”
Water	0%
Green space	0%
Domestic gardens	3%
MODIFIED ROOF	34%
Path	0%
Pavement/hard standing	18%
Road	16%
Rail	6%
Buildings (normal roof)	23%

Figure 57: Study site - showing the output area and the Victoria BID boundary. Sources of data: Victoria BID Green Infrastructure Audit GIS files (Land Use Consultants & Green Roofs Consultancy, 2010) and Cities Revealed Land Use database (Geoinformation Group, 2011). Source: Jansz (2011)

Table 28 shows the mean climatic conditions throughout the year and Table 29 shows how the temperature perturbations vary with seasonal conditions.

Table 28 Daily mean climatic values for each season

	Daily mean values				
Day type	**Cloud cover (Oktas)**	**Solar radiation (W/m²)**	**Temperature (°C)**	**Wind speed (m/s)**	**Relative humidity (%)**
Winter, cloudy	7.5	23	7.5	1.7	89
Winter, partly cloudy	5.6	36	5.6	2.3	82
Winter, clear-sky	2.6	58	4.4	1.9	78
Mid-season, cloudy	7.4	59	10.7	1.9	85
Mid-season, partly cloudy	5.7	121	11.5	1.7	79
Mid-season, clear-sky	2.6	137	9.6	1.6	76
Summer, cloudy	7.4	127	16.7	1.9	74
Summer, partly cloudy	5.5	200	17.4	1.7	71
Summer, clear-sky	2.6	285	17.9	1.6	71
Annual average	**5.5**	**118**	**11.4**	**1.8**	**79**

Table 29 Analysis of diurnal temperature perturbations

	Analysis of the diurnal temperature perturbations for each day type								
	Largest temperature perturbation during day (°C)			**Time of largest temperature perturbation**			**Mean daily temperature perturbation (°C)**		
Day type	**Green roof**	**Dry green roof**	**Cool roof**	**Green roof**	**Dry green roof**	**Cool roof**	**Green roof**	**Dry green roof**	**Cool roof**
Winter, cloudy	-0.55	As wet green roofs	-0.35	22:00	As wet green roofs	11:15	-0.23	As wet green roofs	-0.06
Winter, partly cloudy	-0.53		-0.3	23:15		11:15	-0.19		-0.06
Winter, clear-sky	-0.84		-0.46	01:00		10:15	-0.31		-0.09
Mid-season, cloudy	-0.55		-0.39	22:00		11:15	-0.26		-0.1
Mid-season, partly cloudy	-0.75		-0.79	22:00		11:00	-0.33		-0.21
Mid-season, clear-sky	-0.79		-0.83	23:15		10:00	-0.37		-0.23
Summer, cloudy	-0.96	-0.34	-0.58	20:30	23:00	11:30	-0.45	-0.14	-0.2
Summer, partly cloudy	-1.01	-0.38	-1	20:15	23:15	11:00	-0.49	-0.15	-0.33
Summer, clear-sky	-1.05	-0.38	-1.27	21:15	01:00	09:45	-0.48	-0.16	-0.44
Annual average	**-0.76**	**-0.6**	**-0.7**	**22.00**	**22.45**	**11:00**	**-0.34**	**-0.26**	**-0.2**

Figure 58 to Figure 60 show the mean diurnal microclimatic temperature perturbations for a range of meteorological conditions. The figures are split by type of season, defined in Table 28.

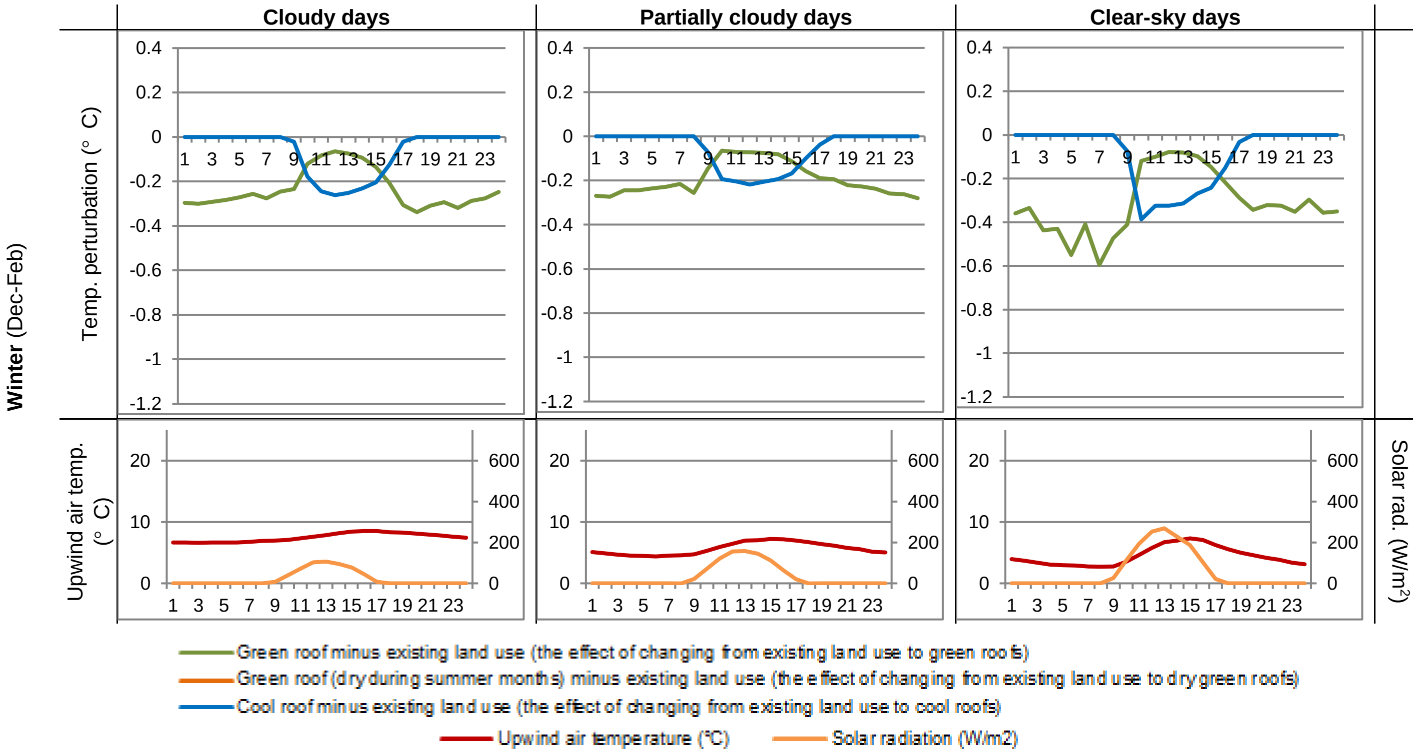


Figure 58 Average diurnal temperature perturbations for a range of meteorological conditions for the winter period

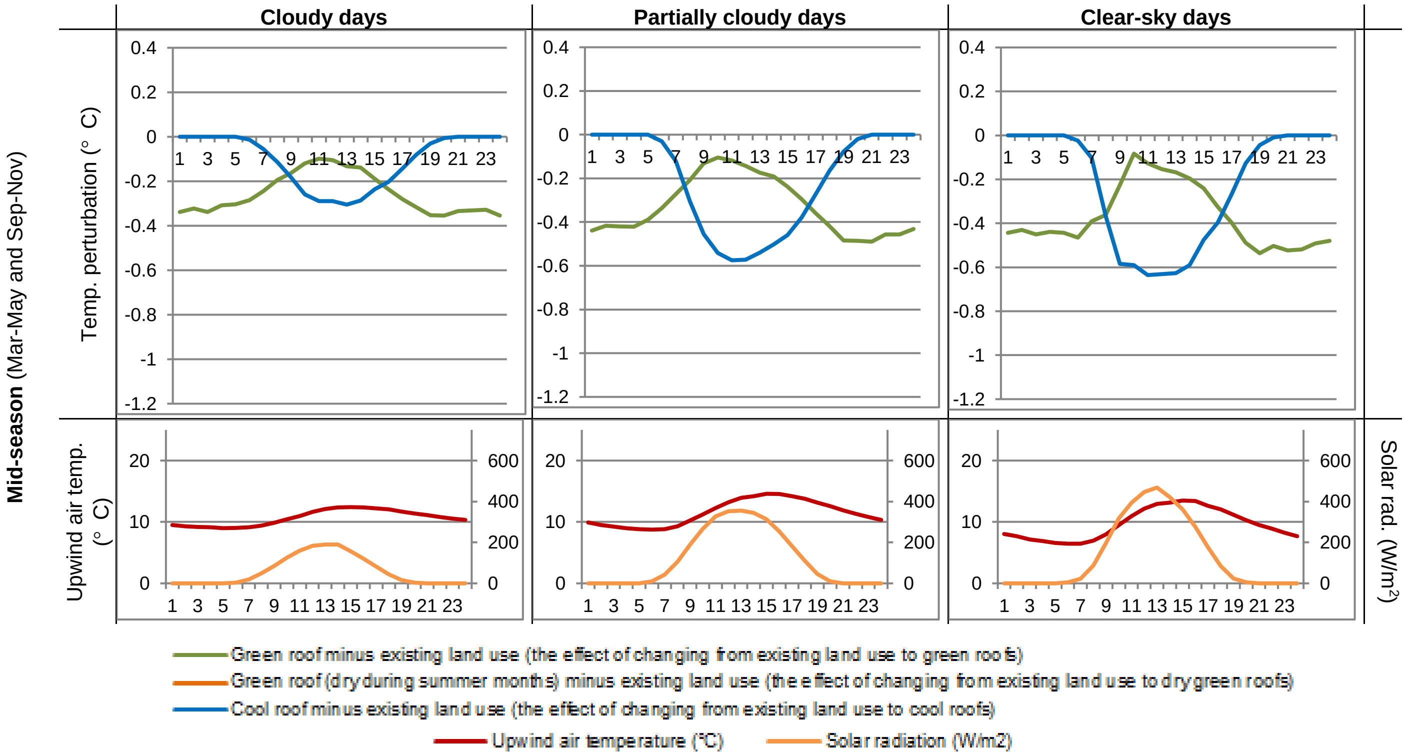


Figure 59 Average diurnal temperature perturbations for a range of meteorological conditions for the mid-season period

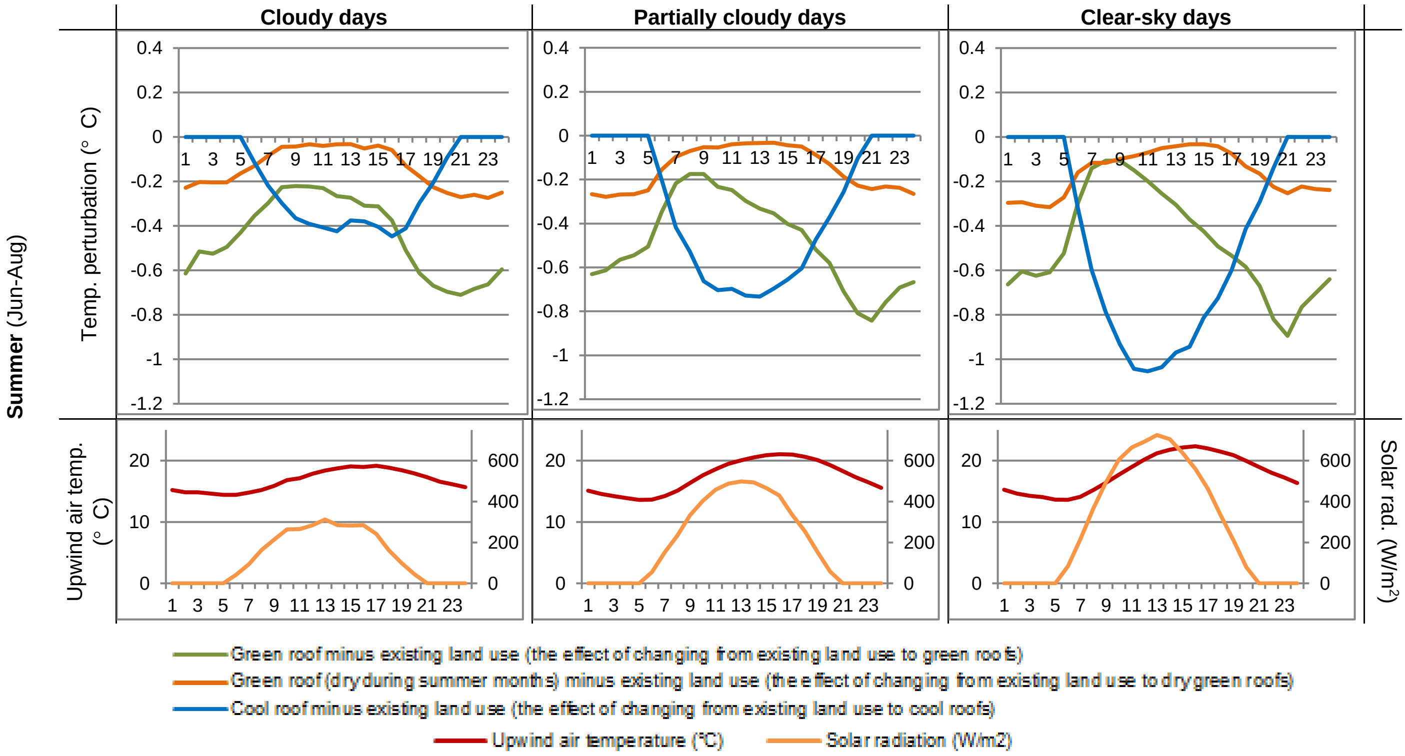


Figure 60 Average diurnal temperature perturbations for a range of meteorological conditions for the summer period

The graphs in Figure 58 to Figure 60 show that the largest temperature perturbations in external temperatures resulting from the installation of green and cool roofs occur on clear summer days, which have the highest average levels of solar radiation, the highest average temperatures and some of the lowest relative humidity, see Table 28.