A Fine Scale Assessment of Urban Greenspace Impacts on Microclimate and Building Energy in Manchester

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Abstract

Climate change projections estimate a rise of approximately 3 °C by the 2080’s for most of the UK (under a medium emissions scenario at 50% probability level, 1961-1990 baseline). Warming is of particular concern for urban areas due to the issues of urban densification and the Urban Heat Island (UHI) effect. To combat warming, one adaptation strategy that has been suggested for urban areas is increasing the proportion of greenspace, such as parks, gardens, street tree plantings, and green roofs. While a number of studies have investigated the cooling effect of greenspace in terms of park size, proximity to a park, or area covered by tree canopy, little is yet known about the specific types of greenspace that contribute to its cooling effectiveness and how this relates to building energy demand.

This thesis employs an interdisciplinary approach to model fine-scale changes to greenspace for a temperate northern UK city, linking the resulting microclimate changes to building energy consumption in commercial buildings. Using the urban microclimate model ENVI-met, two study areas (one urban one suburban) were modelled with seven different greenspace scenarios (a base case representing current field conditions, +5% new trees, +5% mature trees, +5% hedges, addition of a green roof on the largest building, changing all current greenspace to grass only, and changing all current greenspace to asphalt only) for a summer day in July 2010. The models were calibrated based on measured air temperature data and then analysed for microclimate changes due to each greenspace scenario. Both the modelled and measured microclimate data were then used to inform a series of building energy models using IES-VE 2012 for three commercial building types, estimating summer cooling and winter heating trade-offs due to greenspace effects.

For the most effective scenario of adding 5% mature trees to the urban case study, the microclimate modelling estimates a maximum hourly air temperature reduction of nearly 0.7 °C at 5 pm and surface temperature reductions up to 1.7 °C at 3 pm. In the suburban case study, a 5% increase in mature deciduous trees can reduce mean hourly surface temperatures by 1 °C between 10 am and 5 pm, while the worst case scenario of replacing all current vegetation (20% of the study area) with asphalt results in increased air temperature of 3.2 °C at mid-day.

The building energy modelling estimates a reduction of 2.7% in July chiller energy due to the combination of reduced UHI peak hours and eight additional trees (four on the north side and four on the south side) of a three-storey shallow plan building. These energy savings increase to 4.8% under a three-day period of peak UHI conditions. While winter boiler energy usage shows large reductions for a building in an urban
location with a low proportion of greenspace (as compared to a suburban location), this benefit is marginal when analysed in terms of carbon trade-offs between summer cooling and winter heating requirements.
Declaration

I hereby swear that no portion of the work referred to in this the thesis has been submitted in support of an application for another degree or qualification of this or any other university or institute of learning.

Cynthia Skelhorn
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List of Abbreviations and Symbols

α - absorptivity
β - Bowen ratio
ξ - emissivity
σ - Stefan-Boltzmann constant, W m$^{-2}$ K$^{-4}$
μm - micrometre
°C - degrees Celsius
°F - degrees Fahrenheit
ADI - Alternating Directly Implicit method
AGU - American Geophysical Union
ASHRAE - American Society of Heating, Refrigeration, and Air-Conditioning Engineers
BADC - British Atmospheric Data Centre
BRE - Building Research Establishment
CBD - Central Business District
CET - Central England Temperature
CFC - chloro-fluoro carbon
CFD - Computational Fluid Dynamics
CH$_4$ - Methane
CIBSE - Chartered Institution of Building Services Engineers
CLG - Communities and Local Government
CO$_2$ - Carbon Dioxide
DSM - Dynamic Simulation Model
ET - Evapotranspiration
EU - European Union
GHG - Greenhouse Gas
GIS - Geographic Information Science
GWP - Global Warming Potential
h$_c$ - coefficient of heat transfer, W m$^{-2}$ K$^{-1}$
H/W - Height to Width ratio
H$_2$O - Water
HVAC - Heating, Ventilation, and Air Conditioning
IPCC - Intergovernmental Panel on Climate Change
ISO - International Organization for Standardization
K - Kelvin
I - global solar irradiance, W m$^{-2}$
LAD – Leaf Area Density, m$^2$ plant surface per m$^3$ air volume
LAI – Leaf Area Index, m$^2$ leaf area per m$^2$ shaded ground area
LBC – Lateral Boundary Condition
$L_{\text{sky}}$ – Longwave radiation to sky, W m$^{-2}$

m - metre

N-DEEM – Non-Domestic Energy and Emissions Model

NGO – Non-Governmental Organisation

N$_2$O – Nitrous Oxide

O$_3$ – Ozone

PgC – Petagrams of Carbon

PBL – Planetary Boundary Layer

PPM – Parts Per Million

PSA – Partial Shaded Area

Q – net radiation flux, W m$^{-2}$

QH – sensible heat, W m$^{-2}$

QE - latent heat, W m$^{-2}$

QG - ground heat, W m$^{-2}$

$R^2$ – coefficient of determination

RAD – Root Area Density, m$^2$ root surface per m$^3$ soil volume

RH – Relative Humidity

SEE – standard error of the estimate

Std dev – standard deviation

SVF – Sky-View Factor

$t_0$ – outdoor ambient temperature

$T_{\text{sol-air}}$ – sol-air temperature

UBL – Urban Boundary Layer

UCL – Urban Canopy Layer

UCZ – Urban Climate Zones

UHI – Urban Heat Island

UHII – Urban Heat Island Intensity

UK – United Kingdom

UKCIP – UK Climate Impacts Programme

UKCP09 – UK Climate Projections 2009

UNFCCC – United Nations Framework Convention on Climate Change

USA – United States of America

UV – Ultraviolet

W/m$^2$ or W m$^{-2}$ – Watts per square metre

WBGU – German Advisory Council on Climate Change

$Z_0$ – roughness length, m

$Z_d$ – zero-plane displacement, m
Publications Arising from Thesis

Skelhorn, Cynthia; Lindley, Sarah; Levermore, Geoff (2014) The impact of vegetation types on air and surface temperatures in a temperate city: A fine scale assessment in Manchester, UK. Landscape and Urban Planning, 121, 129-140.
1 Introduction

1.1 Introduction

Mounting evidence over the past three to four decades supports the theory that global climate change is underway and that some of this change is inevitable due to past emissions. Even with ambitious mitigation strategies, the UK Climate Projections Briefing Report (Jenkins et al., 2009) reasons that the time lag in the climate system will mean that past emissions have already assured much of the climate change that will occur in the next 30-40 years. Warming is of particular concern for urban areas due to the issues of increasing urbanisation and the Urban Heat Island (UHI) effect, whereby urban areas have been shown to be up to 7 °C warmer than surrounding rural areas (Watkins et al., 2002).

While some degree of change is likely to be inevitable, it may be possible to limit the overall risk incurred by populations through the development of adaptation and mitigation strategies. The distinction between adaptation and mitigation is not always clear (Brooks, 2003) and some strategies are considered as both types of intervention, but they can be generally distinguished in their methods of application.

Mitigation strategies attempt to directly reduce greenhouse gas emissions (Hedger, 2003), particularly carbon dioxide (CO$_2$), which is estimated to have the greatest Global Warming Potential (GWP) of the greenhouse gases (Alexander and Fairbridge, 1999; Le Treut et al., 2007; Masters, 1991). Mitigation strategies include carbon capture and storage (through soils, water, or tree and vegetation plantings), energy demand reduction (leading to reduction in CO$_2$ emissions that result from burning of fossil fuels), and a shifting focus to low carbon technologies. In contrast, adaptation strategies tend to recognize that past emissions are leading to current and future warming and therefore attempt to deal with the direct and indirect impacts resulting from associated hazards, including sea-level rise, increased intensity and frequency of heat waves, increased flooding, and drought. Adaptation strategies may include ‘hard engineering’ solutions, such as building projects (e.g. flood defence systems), or ‘soft engineering’ solutions, such as microclimate alterations through changes to the built environment (Holmes and Hacker, 2007). Some strategies may serve both mitigation and adaptation purposes, as in the case of vegetation, which serves as an adaptation in terms of its cooling ability, but also as mitigation in its ability to sequester carbon dioxide during growth (Akbari et al., 1992; Uri et al., 2012; Peng et al., 2008).

The increased use of greenspace, such as parks, gardens, street tree plantings, and green roofs, has frequently been noted (Gill et al., 2007; Bowler et al., 2010) as a
strategy which provides several benefits for urban areas, including temperature reduction and surface water runoff reduction. Other studies have also noted the potential for reductions in building energy consumption through additional greenspace (Davies et al., 2008; Santamouris et al., 2001). This research employs an interdisciplinary approach to link microclimate changes and the resulting impacts on building energy consumption for urban areas. The research adds to knowledge of the specific types and amounts of greenspace that may be beneficial, particularly in the context of UK climate change scenarios.

1.2 Aims and Objectives

The two aims of this research are: 1) to quantify the influence of a range of greenspace scenarios on microclimate; and 2) develop estimates of changes to building energy consumption that may result from greenspace additions. Using two case studies in Manchester, the work has the following interrelated objectives:

- To develop scenarios of realistic fine-scale changes in the type and amount of urban greenspace and evaluate changes in key microclimate parameters, including air temperature, surface temperature, wind, relative humidity, and mean radiant temperature;

- To estimate summer and winter seasonal changes in building energy consumption due to effects of vegetation, including shading of building surfaces, changes in dry bulb temperature, and wind speed; and

- To make recommendations for the most effective use of greenspace in connection with its related impacts on commercial building energy and microclimate.

A number of studies have investigated the cooling effect of urban greenspace using analytical modelling approaches (e.g. (Gill et al., 2007) and empirical models, e.g. (Chang et al., 2007). Empirical models have considered the distance over which the urban greenspace ‘oasis effect’ occurs, for example in relation to park size (Upmanis et al., 1998), sky-view factor (SVF) (Spronken-Smith and Oke, 1999) or the area covered by tree canopy (Shashua-Bar and Hoffman, 2000). However, relatively little is yet known about the relationships between groups of factors, such as the size, composition, and locations of greenspace parcels, which together influence their effectiveness as soft engineering solutions for reducing energy demand during periods of high temperatures.

The availability of such information would provide a key input into the climate adaptation and mitigation strategies developed at city and neighbourhood scales,
Chapter 1

providing much needed additional knowledge to planners, local authority managers, and citizens regarding applications of urban greenspace (Coles and Grayson, 2004; Gill et al., 2008).

1.3 Research Approach

1.3.1 Context of the Research

In order to investigate changes in microclimate due to differing types of vegetation, the research employed both empirical and modelling approaches, with an emphasis on the latter. The empirical data were necessary for calibrating and assessing the microclimate model fitness and determining relationships between air temperature indices and amount of tree canopy cover, while modelling was an essential tool for assessing microclimate and building energy consumption changes. Figure 1-1 provides an outline of the data collection and modelling processes undertaken in the research as they relate to the research objectives.

Figure 1-1 – Research Objectives and Related Methods

In developing a methodology for this research, it was important to consider some of the broader contextual issues that frame the approach. Investigations were undertaken in the Greater Manchester conurbation, with a great many uncontrollable variables, including weather patterns, ongoing changes to the urban fabric, such as building works and movements of people in and out of buildings. Byrne (2002) discusses the reductionist approach, which views the world by its component parts, analyses the
connections between various parts, and then infers or deduces relationships, causes, and outcomes. While this research investigates the particular relationship between greenspace and building energy consumption, it might be viewed as reductionist in that only certain variables can be quantified, e.g. temperature and units of energy, while in reality, many other components (or variables) are not easily measured, such as the building usage or occupant behaviour. Although the methodology necessarily involves quantitative data (e.g. data on building energy consumption during different seasons, temperature, humidity, sky-view factor) these are also related to qualitative factors, such as tree species and building types. In the final stages, it will be essential to consider the qualitative aspects alongside the quantitative analysis to interpret the results.

One reflective point of the research was not to assume that additional greenspace is automatically positive and beneficial, an assumption that underpins many recent research projects on this topic, such as the Benefits of Urban Greenspace (BUGS) project carried out in the EU (De Ridder et al., 2004). The BUGS project aimed to assess the impact of greenspace on environmental quality and social well-being in urban areas, but first assumed benefits of additional green space and then developed methodological tools to measure those benefits. As described by Smith (2002), this approach may be viewed as verificationist, which primarily looks for confirming evidence, rather than critically appraising the range of evidence. Recent discussion of ecosystem disservices (Douglas, 2012; Lyytimaki and Sipila, 2009) confirms the need for a balanced approach in evaluating changes to urban areas.

Because the majority of related research has been performed in climates which are hot and arid (Akbari, 2002; Potchter et al., 2006) or hot and tropical (Santamouris et al., 2001), it seems evident that additional greenspace is a central tool in climate change adaptation and mitigation scenarios for those areas. However, for more temperate climates such as that of the UK, it is important to look at seasonal trade-offs in energy consumption that may result from additional greenspace. Using greenspace to keep temperatures lower in summer may result in decreased use of air-conditioning, but it may also make temperatures lower in winter, thereby increasing energy use for heating. When considering deciduous trees, however, the loss of canopy cover in winter should still permit solar gains, and thereby have a neutral effect on winter energy consumption. While this research does not account for the full range of greenspace functions, such as pollutant removal, or aesthetic and psychological benefits, it analyses the seasonal trade-offs in terms of air and surface temperatures, and building energy consumption.
1.3.2 Research Questions and Hypotheses

The literature review (Chapters 2 and 3) will demonstrate the need for additional research into the interrelationship of greenspace characteristics, microclimate, and building energy consumption, particularly in relation to adaptation and mitigation strategies for climate change and UHI reduction in the UK. Considering these relationships, this research addresses the following questions and hypotheses:

- What are the changes in microclimate (air temperature, surface temperature, wind and relative humidity) due to different types and sizes of urban greenspace?
  
  o Hypothesis: Greenspace influence on microclimate depends on the specific type of greenspace as well as the urban morphology of the neighbourhood in which it is added;

- Is the area of greenspace as a proportion of total area correlated to air temperature indices (average, maximum, or minimum air temperature or Urban Heat Island Intensity)?
  
  o Hypothesis: Area of greenspace as a proportion of the area under investigation will have a negative linear relationship with at least one indicator of air temperature;

- Which greenspace effects, such as shading, evapotranspiration, and changes to wind speed, have the most influence on building energy consumption?
  
  o Hypothesis: Considering shading, evapotranspiration, and wind, shading will have the largest impact on building energy consumption;

- What is the trade-off between summer cooling and winter heating energy consumption when considering the microclimatic influences of greenspace?
  
  o Hypothesis: The benefit of reduced summer cooling energy will outweigh any detriment to winter heating energy caused by additional greenspace.

Figure 1-2 shows the relationship between the different components of building energy consumption, with the connection between building energy consumption and the external environment, especially the influence of vegetation, forming the central questions in this research.
1.4 Relevance of the Research

The research has been undertaken within the context of climate change, urban densification and the Urban Heat Island (UHI) effect as the broad backdrop. Of the three issues, the most immediate is the evidence regarding the Urban Heat Island and the effect on the health and comfort of urban populations. Numerous pieces of research have demonstrated the phenomenon of the UHI effect (Oke, 1982; Oke and Maxwell, 1975; Santamouris et al., 2001; Watkins et al., 2002) and related public health concerns regarding the relatively warmer temperatures that occur in urban areas (Hacker and Holmes, 2007; Harlan et al., 2006) compared to their rural counterparts.

Additionally, Leitmann (1991) has highlighted energy supply and demand issues that are specific to urban environments. He describes a number of reasons to focus on urban energy, such as:

- Urban consumers tend to use energy more intensively than rural;
• Urban energy use often requires environmental sacrifice and often degradation of surrounding, more rural areas;

• Urban population and economic growth are higher than in rural areas, leading to increased urban demand; and

• Urban energy is more susceptible to market policies.

This research considers energy from the demand side by estimating potential reductions in energy demand that may be achieved through the effective use of greenspace to moderate temperatures, wind speeds, and other microclimatic variables. Alteration in microclimate is frequently cited (Dimoudi and Nikolopoulou, 2003; Jesionek and Bruse, 2003) as one climate change adaptation strategy for urban areas. Vegetation has the direct effect of acting as a carbon sink and the indirect effect of potentially lowering temperatures and thereby changing the energy consumption patterns and related emissions of buildings (Akbari et al., 2001). This links back to the previously discussed ideas of adaptation and mitigation, with urban greenspace having the potential to act in both capacities. It may adapt urban areas to warmer temperatures by providing a cooling effect, but also play a role in mitigation strategies by reducing building energy emissions and acting as a carbon sink for urban areas.

1.5 Structure of the Thesis

The thesis outline that follows this introduction is as follows:

• Chapters 2 and 3 provide the literature review, background, and context for the research;

• Chapter 4 details the methodology employed throughout all aspects of the research;

• Chapter 5 describes the use of iButton temperature sensors and an analysis of the relationship between several temperature indices and proportion of tree canopy cover;

• Chapters 6 describes the sensitivity testing and calibration of the microclimate model ENVI-met;

• Chapter 7 provides the detailed results for the microclimate modelling using ENVI-met;

• Chapter 8 presents results of the building energy modelling through two different methods; and finally

• Chapter 9 is a summary discussion and conclusions arising from the research performed in this thesis, along with recommendations for future work.
2 Climate Change and Relationship to Urban Areas and Buildings

This research has been undertaken within the context of climate change, urbanisation and the UHI effect. Whilst a detailed review of each area is beyond the scope of this research, it is nevertheless important to provide a summary of relevant research in each area in order to develop an appropriate foundation for the work.

This chapter will first provide a brief introduction and overview of the most current knowledge on climate change as this is an issue of global concern, affecting populations differentially, depending on scale and particular location being studied. Following on from the discussion of climate change is the topic of the UHI effect. This topic is especially relevant because the percentage of world population in urban areas is expected to increase from approximately 47% in 2000 to nearly 70% by 2050 (United Nations, 2008), implying that changes in climate, for human populations, will have a greater impact on urban areas. In the UK, the percentage of the population living in urban areas is already estimated at 90%, and while this is unlikely to increase, planning policies favouring brownfield and infill development since 2000 have led to urban densification (Dallimer et al., 2011). The final section discusses building energy consumption, in terms of climate change and the UHI effect.

2.1 Climate Change

Generally, climate is defined as the ‘average weather’ (IPCC, 2007, p.96) of a place and can be analysed globally or locally. Climate depends on a number of interacting factors, such as latitude, topography, land cover, atmospheric composition and proximity to water bodies, but on a global scale is primarily governed by the balance of incoming versus outgoing forms of radiation. This balance can be changed in three main ways: 1) changes to incoming solar radiation, such as changes in the sun’s energy output; 2) changes in shortwave radiation reflected back to space, such as reflectance off clouds or the surface; and 3) changes in outgoing longwave radiation resulting from changes in the atmospheric or cloud composition (Le Treut et al., 2007).

Figure 2-1 provides a illustration of the concept of the Earth’s radiation balance. The figure shows that, of the 342 Watts per square metre (W/m\(^2\)) of incoming solar radiation, only 168 W/m\(^2\) (49%) reaches the surface, while 107 W/m\(^2\) (31%) is reflected by clouds, aerosol, and atmospheric gases or the surface, and the remaining 20% is absorbed by the atmosphere (Kiehl and Trenberth, 1997). On the outgoing longwave side, a total of 492 W/m\(^2\) is leaving the surface; 24 W/m\(^2\) in the form of thermals, 78 W/m\(^2\) as latent heat, and 390 W/m\(^2\) as surface radiation. A large portion, 324 W/m\(^2\) (66%) of this surface radiation returns to the surface due to greenhouse gases.
Carbon dioxide, methane, and other greenhouse gases are important for maintaining a hospitably warm temperature, referred to as the ‘natural greenhouse effect,’ but current theory, data, and modelling regarding global changes in climate provide strong evidence that anthropogenic emissions of these gases are leading to enhanced warming globally, as further explained in Chapter 2.1.2 (Forster et al., 2007; Hedger, 2003; Joint Science Academies, 2005; Warren, 2007).

2.1.1 Components of Global Climate

A number of factors contribute to global climate, including greenhouse gases, aerosols, surface albedo, the cloud albedo effect, solar irradiance, and changes in sunspot cycles (IPCC, 2007; Warren, 2007). The effect of each component is referred to as radiative forcing, generally defined as the difference between incoming solar and outgoing infrared radiation as measured in Watts per square meter (Hoffert and Caldeira, 2004). A more technical definition of radiative forcing used by the IPCC is from Ramaswamy et al. (2001, p.353), which defines it as, “the change in net (down minus up) irradiance (solar plus longwave; in W/m²) at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values.” The unperturbed values referred to are based on a reference year of 1750, taken to be the start of the industrial era (Forster et al., 2007).

Positive forcings lead to warming of the climate system, while negative forcings lead to cooling. Some components act in both positive and negative directions. Clouds, for
example, act as both emitters of energy, which is released as latent heat when water vapour condenses in their formation, and as reflectors of solar radiation to keep the surface cool (IPCC, 2007; Trenberth, 2004). Figure 2-2 illustrates the positive and negative forcing attributed to each climate component and the net anthropogenic component.

![Figure 2-2 - Radiative Forcing by Component](Source: IPCC, 2007)

The IPCC (2007) concludes that current warming is attributable to anthropogenic greenhouse gas emissions occurring in the last century with the effect on global average temperature being an overall increase of 0.74 °C from 1906 to 2005, including a rapid rise of 0.55 °C from the 1970’s to 2006.

### 2.1.2 Greenhouse Gases

Important in maintaining global climate are the greenhouse gases, including carbon dioxide (CO₂), water vapour, methane (CH₄), nitrous oxide (N₂O), and chloro-fluoro carbons (CFCs). Without these gases to absorb approximately two-thirds of the outgoing longwave radiation and radiate it back to the surface, the land and oceans would have an average temperature of about -18°C. The effect of greenhouse gases is that the earth maintains a hospitable temperature of closer to 15°C (Hoffert and Caldeira, 2004; Lindzen, 1990).

The properties that affect the individual contribution of each gas to overall global warming include its concentration, ability to absorb longwave radiation, rate of
increase, and atmospheric lifetime (Rodhe, 1990). The collective effect of these properties is referred to as the Global Warming Potential (GWP) of the gas. Table 2-1 provides a summary of these properties for the principal greenhouse gases, showing that the combination of these properties leads to an estimate of 60% of total warming over the next one hundred years being attributed to carbon dioxide.

Table 2-1 – Relative Contributions of Greenhouse Gases

<table>
<thead>
<tr>
<th>Greenhouse gas</th>
<th>Principal sources</th>
<th>Atmospheric concentration (ppm)</th>
<th>Annual rate of increase (%)</th>
<th>Relative greenhouse efficiency</th>
<th>Atmospheric lifetime (years)</th>
<th>Contribution over 100 years (as % of total contribution)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide (CO₂)</td>
<td>Fossil fuels, Deforestation</td>
<td>353</td>
<td>0.5</td>
<td>1</td>
<td>50-200</td>
<td>60</td>
</tr>
<tr>
<td>Methane (CH₄)</td>
<td>Wetlands, rice, livestock, fossil fuels</td>
<td>1.7</td>
<td>1</td>
<td>25</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Nitrous Oxide (NO)</td>
<td>Fuels, fertiliser, deforestation</td>
<td>.310</td>
<td>0.2</td>
<td>200</td>
<td>130</td>
<td>5</td>
</tr>
<tr>
<td>Ozone (O₃, in troposphere)</td>
<td>As a pollutant is due to interaction of sunlight with hydrocarbons and nitrogen oxides from vehicles, power stations, and industry</td>
<td>.010-.050</td>
<td>0.5</td>
<td>2000</td>
<td>0.1</td>
<td>8</td>
</tr>
<tr>
<td>Chloro-fluoro carbons (CFC’s)</td>
<td>Foams, aerosols, refrigerants, solvents</td>
<td>.00028-.00048</td>
<td>4</td>
<td>12000-15000</td>
<td>65-120</td>
<td>12</td>
</tr>
</tbody>
</table>

Source: compiled based on data reported in Flavin (1989), as shown in Masters (1991), Rodhe (1990), and Alexander and Fairbridge (1999)

A graph of the absorption spectra for the main components of the atmosphere, as shown in Figure 2-3, indicates that 70-75% of solar radiation is transmitted through the atmosphere and downward toward the Earth’s surface, while only 15-30% of the outgoing infrared is transmitted through a narrow atmospheric window that occurs around 10 µm. Also shown in Figure 2-3 is that water vapour absorbs across a fairly wide range of wavelengths, but CO₂ and other gases absorb in a few narrow bands. Some overlap does occur between the absorption spectrums for water vapour and other gases with carbon dioxide and ozone, in particular, absorbing in certain wavelengths not covered by other gases.
Table 2-2 summarises the change in overall absorption of longwave radiation as each atmospheric component is removed and the associated change in radiative forcing.

**Figure 2-3 – Radiation Transmitted by the Atmosphere at Various Wavelengths**

(Source: Image created by Robert A. Rohde / Global Warming Art based on Spectral Calculator of GATS, Inc. using the methods of (Gordley et al., 1994) and spectroscopic database of (Rothman et al., 2005))
Climate change science tends to focus heavily on the roles of carbon dioxide and methane as the two most influential greenhouse gases because they are more abundant and rapidly increasing as compared to some gases (especially fluorinated gases) with significantly higher GWP’s. However, a controversial point concerns the role of water vapour. Although water vapour is the most abundant greenhouse gas (Forster et al., 2007; Mockler, 1995) it is generally understood to be controlled by feedback (i.e., it increases as warming increases) rather than as a driver of climate change (Forster et al., 2007). Additionally, while humans have little effect on water vapour, the amount of CO₂ is heavily influenced by anthropogenic sources and has increased approximately 35% during the industrial era (IPCC, 2007).

### 2.1.3 Natural and Enhanced Greenhouse Effect

Additional warming above and beyond natural causes is often referred to as the enhanced greenhouse effect (EGE) and most warming is attributed to carbon dioxide, as detailed in the previous section. Human impact on CO₂ concentration is through two primary routes: 1) increases in CO₂ from burning fossil fuels, and 2) reductions in CO₂ uptake and storage by plants through deforestation and other land use changes (Houghton, 2007; Masters, 1991). Figure 2-4 provides a detailed illustration of the carbon cycle while Figure 2-5 highlights the increase in emissions from fossil fuels and land use changes during the past 50 years.
Figure 2-4: The Global Carbon Cycle in the 1990s.
Units are PgC or PgC year\(^{-1}\). (Source: Houghton, 2007)

Figure 2-5 – Carbon Emissions from Fossil Fuel Combustion and Land Use Change Compared to Increase in Atmospheric CO\(_2\)
Two predominant sources of natural climate change, solar and volcanic, have been studied extensively (Krivova and Solanki, 2004; Lockwood, 2008; Tett et al., 1999; Wirsing, 2004), but the current consensus is that human impact since 1750 outweighs these (Hegerl et al., 2007; IPCC, 2007; Lockwood, 2008). This is primarily due to the fact that modelling studies are not able to explain the warming trends unless human inputs are considered.

Analysis and reconstruction of past climate variation indicate that such changes were caused by natural changes in radiation balance (Hegerl et al., 2007), such as the amount of incoming solar radiation. For instance, Milankovitch cycles are changes in Earth’s orbit which affect the amount of solar radiation at each latitude, but not the global annual mean. Furthermore, no large reduction in northern summer insolation is expected for another 30,000 years. Another solar variation is the energy output of the sun, which varies slightly (0.1%) in 11-year cycles. However, according to specialists in solar system research at the Max Planck Institute, reconstructions of solar radiative output show that the irradiance has been relatively constant since the 1970’s while temperature has been rapidly increasing since this time (Krivova & Solanki, 2004; Wirsing, 2004).

Analysis of ice cores demonstrates that atmospheric CO$_2$ can be correlated with Ice Ages, being low in cold glacial times (190 ppm) and high in interglacials (280 ppm). Although climate shifts also occurred during the last Ice Age, they were probably not accompanied by a large change in global temperature. More likely the shifts were within the overall balance of the global system. The current alarm is that the concentration of CO$_2$ in the atmosphere has increased very rapidly and is at a record high (379 ppm) compared to the past half-million years (IPCC, 2007). Higher values have only occurred millions of years ago and the recent rise has been very rapid, a process that would likely have taken over 5000 years in the past.

### 2.1.4 Policy Response to Climate Change Evidence

Leading analysis and statements on climate change take place primarily through the Intergovernmental Panel on Climate Change (IPCC), set up in 1988 under the United Nations Environment Programme and World Meteorological Organisation. A series of negotiations culminated in the United Nations Framework Convention on Climate Change (UNFCCC) signed by 155 countries at the 1992 Earth Summit in Rio de Janeiro, Brazil (Hedger, 2003). The Kyoto Protocol to the UNFCCC, adopted in 1997 and effective in February 2005, requires developed countries that have ratified the Protocol to reduce greenhouse gas emissions. Joint statements from the academies of science for 11 nations and a previous statement, signed by 16 nations in 2001 (8 are in
the 2005 statement, but 8 are different) give a total of 19 nations that have endorsed the IPCC reports and urge action in line with UNFCCC principles.

A number of other organisations also participate in debate and provide public statements on the state of climate change science. These include the American National Academy of Sciences, the European Academy of Sciences and Arts, the American Geophysical Union (AGU – the world’s largest organisation of Earth scientists), country-specific societies and programmes, e.g., Royal Meteorological Society (UK), UK Climate Impacts Programme, and the scientific Advisory Council on Global Change (WBGU) set up by the German government (Brazdil et al., 2005).

Interestingly, since the July 2007 release of a non-committal statement by the American Association of Petroleum Geologists, there are no scientific organisations of national or international standing that are dissenting on the IPCC consensus view. Recent research by Oreskes (2004) found no academic disagreement with the consensus opinion. Oreskes research analysed abstracts of 928 papers from refereed scientific journals 1993-2003, looking for opinions on climate change from the science community. Searches were performed using the keyword "global climate change" and then divided into five categories. Seventy-five percent were in one of three categories: explicit endorsement of the consensus position, evaluation of impacts, mitigation proposals (explicit or implicit acceptance); 25% dealt with methods or paleoclimate and were therefore classed as taking no position.

2.1.5 Anticipated Effects of Climate Change in the UK

With projected temperature increases of 1.4 – 5.8°C above the 1990 baseline by 2100, the IPCC (AR4-WG1) (2007) further states that it is very likely (>=90% probability) that most of the rise in the last century is attributable to human-made emissions. With a view to curbing these emissions, the UK Climate Impacts Programme (UKCIP) has documented many of the changes taking place in the UK (Jenkins et al., 2009), including:

- A rise of 1 °C in Central England Temperatures (CET) since 1970;
- Sea-surface temperatures around the coast are about 0.7 °C warmer than 30 years ago;
- Annual precipitation, which has changed little since 1766, appears to have increased in winter and decreased in summer; in the past 45 years, heavy rainfall events are contributing a greater proportion to winter rainfall;
- Severe windstorms are more frequent in recent decades but not moreso than the 1920’s; and
The rate of sea level rise around the UK has been higher since the 1990's than the previous rate of 1mm/yr for most of the 20th century.

Based on the latest scientific understanding and climate modelling projections, the UK Climate Projections (UKCP09) provides climate change projections based on a range of carbon emissions scenarios (Jenkins et al., 2009). The new projections are changed from the former UKCIP02 (UK Climate Impacts Programme 2002) projections in that they now contain probabilistic scenarios, which reflect the uncertainty due to the limits of modelling and incomplete understanding of the climate system in its entirety (ibid.). Each climate outcome is now shown with a statistical range which reflects the degree of certainty which can be supported by current evidence. Projections are provided for a number of atmospheric (ie., mean temperature, relative humidity, precipitation rate) and marine variables (ie., total cloud, sea level pressure) for several temporal periods (generally, a month, season, or year) at 25 km resolution under three emissions scenarios (high, medium, and low) and three probability levels (10%, 50%, and 90%). A weather generator can also provide daily and hourly projections and outputs at a resolution of 5 km.

A few examples of projections for the 2080's included in UKCP09 under the medium emissions scenario (central estimate relative to a 1961-1990 baseline) include:

- An increase in mean winter temperature of 2-3 °C, with slightly larger changes in the southeast. A stronger increase of 4 °C in mean summer temperature, but with a stronger north-south gradient so that parts of Scotland may warm by only 2.5 °C, while southern England warms slightly more than 4 °C;
- The summer daily maximum temperature increases by 2.8-5.4 °C, again with a north-south gradient (low to high); and
- Central estimates of mean annual precipitation change are close to zero everywhere, but vary significantly in winter and summer, especially from place to place, with generally wetter winters based on projections of 10%-30% wetter over most of the UK.

These scenarios and projections provide a probabilistic framework of potential climate outcomes for research that wishes to include an adaptation element based on the most current understanding of climate change.
2.2 Urbanisation and the Urban Heat Island

Although climate change is an important context for the work, understanding the current status of knowledge of the urban heat island is equally important. Greater proportions of the global population are either moving to or being caught up in the process of urbanisation. In Europe, the percentage of total population in urban areas is expected to increase from 71% in 2000 to nearly 84% in 2050 (United Nations, 2008). In the UK, only 8% of the surface area is urban (Barker, 2006) but approximately 90% of the population are living in urban areas (United Nations, 2008). While these percentages may remain stable for the UK, a policy of urban densification and brownfield regeneration since 2000 has led to decline of greenspace in nine of the thirteen largest cities in England since 2001 (Dallimer et al., 2011). The trend toward urbanisation and urban densification is important to local climate because it changes the structure and fabric of the landscape, thereby changing energy balance in urban areas to greater heat storage. This alteration leads to a measurable difference in temperature between an urban area and surrounding rural areas, a phenomenon referred to as the urban heat island (UHI) effect (Landsberg, 1981; Oke, 1969).

As shown in Figure 2-6, the typical UHI profile is characterised by a heat centre, the area of greatest temperature difference between the urban and rural area. This centre is surrounded by a plateau of elevated temperature and then a cliff-like boundary that generally follows the city’s perimeter (Oke, 1982).

![Sketch of an Urban Heat-Island Profile](http://eetd.lbl.gov/HeatIsland/HighTemps)

Figure 2-6 - Typical Urban Heat Island Profile
2.2.1 Surface Energy Balance and the Urban Heat Island

The concept of energy balance is central to the understanding of the UHI phenomena. Energy balance has different terms and meanings for different academic disciplines. For instance, in physics, energy balance is understood as energy flows and transformations in a system, governed by the first law of thermodynamics, which states that energy cannot be created or destroyed, only changed from one form to another. In the context of this research, energy balance is better understood from the viewpoint of climatology and hydrology. In these disciplines, energy balance refers to the total of all energy inputs and outputs at a particular location, including solar, atmospheric transfer, and ground conduction (Trenberth, 2004).

Near-surface temperature is determined by the energy exchange between the surface and the air above a particular area. Taha (1997) notes that urban surfaces significantly alter the fluxes of heat and moisture, as compared to ‘undisturbed’ climates and that urban-rural differences are further amplified by anthropogenic heating, moisture, and pollutants (discussed in more detail in Section 2.2.2).

While most studies have demonstrated the UHI through temperature measurements, a few have investigated the UHI in relation to changes in the surface energy balance. Bäckström (2006) uses a simplified surface balance equation for daytime, a concept that is also illustrated in Figure 2-7.

![Figure 2-7 – Illustration of Radiation Balance in an Urban Area](http://www.ruf.rice.edu/~sass/UHI.html, 12/12/08)
\[ Q = K_\downarrow - K_\uparrow + L_\downarrow - L_\uparrow \]

Where:
- \( K_\downarrow \) = incoming direct and diffuse short-wave radiation
- \( K_\uparrow \) = reflected short wave radiation
- \( L_\downarrow \) = incoming long-wave radiation from the atmosphere
- \( L_\uparrow \) = outgoing long wave radiation from the surface

The net radiation flux, \( Q \), can be further divided into sensible, latent, and ground heat:

\[ Q = Q_H + Q_E + Q_G \]

where:
- \( Q_H \) = sensible heat, which is the heat transferred between the surface and the atmosphere;
- \( Q_E \) = latent heat, the energy absorbed or released when a liquid or vapour is changing state;
- \( Q_G \) = ground heat, the heat transferred from or to the soil below the surface.

Imbalances in surface radiation are accounted for by convection to or from the atmosphere as sensible or latent heat, and conduction between the surface and the soil below as ground heat. It should be noted that the surface energy balance described here relates only to near-surface climatic processes, with no direct translation to a region's general climate.

Oke (1987) uses the concept of the Earth-Atmosphere (E-A) system operating at different scales (macro-, meso-, local, and micro-) when considering energy balance. To further enhance understanding of UHI, Oke (1976) developed the concept of the Urban Canopy Layer (UCL) and the Urban Boundary Layer (UBL). At the microscale, the UCL consists of the air up to roof level and is governed by processes operating in street canyons, while the local to meso-scale UBL lies above the UCL and is primarily affected by the generalised urban surface (Oke, 1987). It is important to be aware of differences in observations at each level: surface, UCL, and UBL.

The energy releasing capabilities of urban surfaces, and related urban heat island effects, are best observed on clear, calm nights (Figueroa and Mazzeo, 1998; Upmanis et al., 1998) because of the increase in longwave emitted to the atmosphere and the lack of heat loss through convection. Additionally, the microclimatic exchanges in the UCL should be considered in relation to the mesoscale UBL. Oke (1982), in describing the energetic basis of the UHI, notes a vertical thermal structure, with increasing depth of the UBL away from the leading edge of the urban-rural divide and up to the height of the planetary boundary layer (PBL). An illustration of the PBL, UBL, and UCL concept is shown in Figure 2-8.
2.2.2 Factors Affecting the UHI

As with any physical system, it is useful to gain an understanding of the various parameters and processes that contribute to the observed effects. A number of factors contribute to the UHI, including:

- Decreased evaporative cooling due to the change in land cover, resulting in less vegetation and more concrete, paving, and buildings (Oke, 1982);

- Increasing Bowen ratio (Beta), which is the ratio of sensible to latent heat, whereby lower vegetation cover in urban areas leads to a larger proportion of sensible heat so that Beta is larger for urban areas (4 or 5) as opposed to rural vegetation canopies (0.8-1.5) (Taha, 2004);

- Thermal properties, including albedo and emissivity, of building and construction materials, such as tar, asphalt, and brick (Oke, 1987);
• Reflection of short-wave radiation, reduced heat loss through long-wave radiation, and reduced wind speed due to the canyon structure created by tall buildings, which are often measured in terms of sky-view factor (SVF) (Oke, 1982); and

• Anthropogenic heating due to waste heat from buildings and vehicles (Oke, 1982; Smith et al., 2009; Taha, 2004).

Reduction in UHI intensity is primarily due to weather patterns, such as strong winds and increased advection, leading to mixing of urban and rural air (Oke, 1982).

2.2.3 Evidence for the UHI Effect

A number of studies have documented the UHI effect for various places, including Athens (Katsoulis and Theoharatos, 1985), Buenos Aires (Figuerola and Mazzeo, 1998), Szeged, Hungary (Unger, 2001), and London (Watkins et al., 2002) with findings ranging from 1°C to 7 or 8 °C (Taha, 2004). Of course, the magnitude of the UHI intensity will differ depending on the geographical location, spatial extent of the city, and the specific seasonal and climatic conditions under which it is measured (Oke, 1982; Taha 1997; Taha, 2004). Urban heat islands have been generalised by Oke (1982) as thermal anomalies with significant spatial and temporal variability. Spatial factors include canyon geometry, building materials, and vegetative cover. Temporally, UHI intensity is generally at a maximum within 3-5 hours after sunset (Oke, 1987) because the increase in heat absorbing surfaces and decrease in evapotranspiring surfaces result in greater absorption of solar radiation in the day and slower loss of radiation at night (Davies et al., 2008). Figure 2-9 illustrates the general air and surface temperature differences that might be observed over different land uses during the day and night.
Figure 2-9 – Daytime/Nighttime Surface and Air Temperature Differences for Different Land Uses
(Surface temperatures are notably higher and more variable than air temperatures during the day, but are similar at night. (Source: (US EPA, 2012) as modified from Voogt (2000))

Oke (1973) demonstrated that the UHI intensity is approximately proportional to the fourth-root of the population for most North American and European cities, while Torok et al. (2001) demonstrated a relationship between UHI intensity and log of population for Australian towns and cities. The authors further note that the effect is likely to be less for Australia than for Europe or North America, perhaps due to differences in population density and building practices.

For the UK, research by Watkins et al. (2007) on the London UHI demonstrated a relationship of 1/r² between UHI and distance from the thermal centre (r), with an average UHI (in 1999) of 2.8 °C. Recent work in Manchester found an average summer UHI of 1.44 °C and average winter UHI of 1.97 °C. The research also found strong correlations between low SVF (<0.65) and UHI, and a negative linear relationship between UHI and distance from the city centre (R²=0.64 for summer for both variables) (Cheung, 2011).

Modelling experiments performed by Montavez et al. (2008) concluded that urban morphology, particularly canyon geometry characterized by the Height to Width (H/W) ratio is the most significant factor in UHI intensity. Additionally, the study found that anthropogenic heat is a significant contribution when the difference between indoor and outdoor temperatures is large, as in very hot or very cold climates.
Research indicates that the UHI intensity is increasing for some cities, most likely due to increases in population, as demonstrated by Oke (1973) and Torok (2001). For instance, a first study of London by Luke Howard in the early 1800’s (1833) showed a UHI of -0.2 °C for the day and 2.0 °C at night. From the 1960’s to the 1980’s, studies by Chandler (1965) and Landsberg (1981) documented a UHI of 4.0 – 6.0 °C at night. In 2002, Watkins, et al. (2002) estimated a London UHI of up to 7 °C. Similarly, changes due to urbanisation for Athens, Greece have been documented for the period of 1925-1996, with a change in maximum temperature of about 2 °C in spring and summer, with less change in fall and none in winter (Philandras, 1999).

With the anticipated increased temperatures due to climate change and trend towards densification in the UK, it is possible that the UHI will increase in intensity. Identifying the specific factors (building geometry, building fabrics, etc.) that lead to increased intensity for a particular location will aid in developing the most suitable adaptation measures for that location.

2.2.4 Health Impacts of Elevated Temperatures

Section 2.2.2 concluded that increased temperatures, particularly in urban areas, can be attributed to the combined effects of vegetation loss, increase in heat absorbing surfaces, heat generated by vehicular traffic, waste heat from buildings, and other anthropogenic sources. Both positive and negative effects of the UHI phenomena have been discussed by various researchers. Most research has focused on adaptation and mitigation of negative effects, such as:

- Amplification and increased frequency of extreme heat events (McMichael et al., 2001) and the risk of heatstroke from elevated temperatures (McGeehin and Mirabelli, 2001);
- Higher rates of heat-related illness and deaths (Harlan et al., 2006; McGeehin and Mirabelli, 2001), particularly due to elevated nighttime temperatures which may limit a person’s ability to recover from extreme heat (Clarke, 1972);
- Higher temperatures causing accelerated chemical reactions for ground-level ozone (Wilby, 2007), commonly known as smog;
- Increases in air pollution due to the dust dome effect (Chang et al., 2007); and
- Changes in water quality, and changes in ecology related to infectious and vector-borne diseases (Kovats, 2001; Patz et al., 1996).

An example of these consequences is illustrated by the 2003 European heatwave, which led to temperatures of 3°C above normal, on average (Schäer, 2004), and contributed to an estimated 22,000 to 45,000 deaths (Kosatsky, 2005). In France, the
majority of victims were women (70%), elderly, and concentrated in urban areas (García-Herrera et al., 2010). The impacts of heat waves tend to be greater in urban areas, probably due to the UHI effect and higher levels of air pollution (McMichael et al., 2001).

However, some researchers acknowledge that climates similar to that of the UK also experience benefits, such as decreased winter heating loads and reductions in number of deaths due to cold (Davies et al., 2008; Hulme et al., 2002). The UK Climate Impacts Programme found that heating degree days (HDD) (a measure of the incidence in air temperature falling below a baseline of 15.5 °C) have decreased by 18.1% for London between 1961 and 2006. Cooling degree days (CDD) (a measure of the incidence of air temperatures above 22°C) increased by a total of 32.3 days for the same period (Jenkins et al., 2007).

Davies (2008) notes that the number of cold-related deaths in the UK is far higher than heat-related deaths and suggests that this should be taken into account before modifying the environment in such climates. A counterpoint to this suggestion is that heat is more of a risk than cold because there are fewer measures the body can take to adapt to extreme heat, and in the UK, people are adapted to generally cooler conditions. While people can add additional layers of clothing in the case of cold, fewer measures are available for combating heat stress.

While people may be able to adapt to gradual changes in average temperatures through acclimatization, an increase in the frequency and intensity of heat waves (Jenkins et al., 2009), “can exceed the physiologic adaptive capacity of vulnerable groups, such as infants, the elderly and those with pre-existing health conditions” (Warren, 2007, p.157).

Some research indicates that increased temperature will differentially affect populations, with an increased risk of mortality in cities at mid-latitudes and high latitudes that experience extreme heat infrequently. Cities such as Chicago, Philadelphia, and New York are likely to have higher death and illness rates when unusually high temperatures do occur. Other locations that are mild to hot year-round have a lower health risk, especially southern cities, like Miami, where residents are better acclimated to high temperatures (Kalkstein and Smoyer, 1993; McGeehin and Mirabelli, 2001). This suggests that climates such as that of the UK will face a greater risk of heat-related death and illness when faced with extreme heat simply because populations are not already acclimated.
2.3 Impacts of Climate Change and the Urban Heat Island on Building Energy Consumption

According to Communities and Local Government (2012a), the government department in the UK responsible for setting policies on local government and housing and planning-related issues, 40% of the UK’s energy consumption and carbon emissions come from heating, lighting, and equipment usage in buildings. In commercial buildings, approximately 50% of energy is used for heating and cooling. Under projected climate change scenarios, large rises in air-conditioning and portable fan use are expected, particularly in urban areas due to the UHI effect (Hitchin and Pout, 2000).

Under the Chartered Institution of Building Services Engineers (CIBSE) guidelines for thermal comfort in the UK, office buildings should maintain an internal temperature that does not exceed 28 °C for any more than 1% of the occupied time (CIBSE, 2006a). Although mechanical forms of cooling reduce a building’s internal temperatures, waste heat is emitted to the surrounding environment (Smith and Levermore, 2008), increasing the UHI. Additionally, increased air-conditioning use conflicts with government policies to curb CO$_2$ emissions (Levermore et al., 2004). Despite implementation of policies in European countries to curb energy waste in buildings, the IPCC notes that, globally, CO$_2$ emissions from buildings increased 2.7% per year from 1999-2004 (Levine et al., 2007). Figure 2-10 shows that the global emissions for the building sector were approximately 33% of the global total. Future projections to 2030 are based on the Special Report on Emissions (SRES) scenario A1B (Nakićenović et al., 2000).

![Figure 2-10 - Global CO$_2$ Emissions by Sector](image)

Based on historical data to 2000 and projected to 2030 by the SRES A1B scenario. (Source: de la Rue du Can and Price (2008) as modified by Levermore (2008a)).
Akbari et al. (1992), in a study of five major U.S. cities, found that peak electricity demand rises by 2-4% for each 1°C rise in temperature above 15-20°C. By estimating urban air temperature to be 2.5°C warmer than rural areas, this translates into additional air-conditioning use that accounts for 5-10% of peak urban demand (the time period, usually a half-hour of the daily cycle, when consumer demand for energy is highest). Figure 2-11 is an illustration of electrical load in relation to temperature for New Orleans, Louisiana. It provides a somewhat different picture of the comfortable range of temperatures. It demonstrates a very steep rise in demand for temperatures exceeding 25 °C and shows a comfort range of about 20-25 °C.

![Figure 2-11 – Electrical Load and Temperature](image)

As shown in this example from New Orleans, electrical load can increase steadily once temperatures begin to exceed about 68–77°F (20–25°C). Other areas of the USA show similar demand curves as temperature increases. (Source: (Sailor, 2002) Data courtesy Entergy Corporation)

Potential savings in building energy usage can be distinguished primarily as direct or indirect (Akbari and Konopacki, 2005). Examples of direct savings include reflective roofing, tree shading (Akbari and Konopacki, 2005), awnings (Smith and Levermore, 2008), and design of the building envelope to accept or reject heat as needed (Levermore, 2008b). Indirect effects include the lowering of ambient temperature through urban reforestation or reflective pavements (Akbari and Konopacki, 2005), and changing the behaviour of the building’s occupants (Levermore, 2008b). Furthermore, the IPCC Report Four on mitigation options for residential and commercial buildings notes that an Integrated Design Process (IDP), which allows for iterative design by a
full team of architects, engineers, and planners can save as much as 50% of total energy usage (Todesco, 2004).

A number of researchers have conducted studies on the relationship between the UHI and the summer cooling load of buildings (Huang et al., 1987; Kolokotroni et al., 2007; Santamouris et al., 2001; Taha et al., 1999). Taha et al (1999) estimated that a 1-2 °C reduction in space-averaged air temperatures through surface modifications led to a decrease of up to 10% in peak electricity demand. Kolokotroni et al. (2007) investigated the relationship between the London UHI and energy demand and found a 25% increase in cooling loads in urban areas, but a 22% decrease in heating loads. As pointed out by Davies et al. (2008), the decrease in heating is outweighed by the increased cooling demand for this particular set of buildings and while net energy savings would result for buildings without air-conditioning, the occupants may be subjected to uncomfortably high summer temperatures. Santamouris et al. (2001) performed similar investigations in Athens, where the mean summer daytime UHI is 10 °C, and found that the cooling load in urban areas may be doubled, while the peak load may even be tripled, and heating loads reduced by approximately 30%. The findings from these studies suggest that overall energy savings may be achieved by reducing the UHI effect, but the findings are solely based on air temperature differences, with no analysis of measures that might be taken to achieve UHI reductions. Also, the studies do not make clear whether the trade-offs between heating and cooling have been analysed in terms of carbon emissions. Table 2-3 presents a compilation of data on heating degree-days (HDD) and cooling degree-days (CDD) (discussed in section 2.2.4) initially published by Landsberg (1981), modified by Taha (1997), with recent data from London added by Davies et al. (2008). Both HDD and CDD data in the table are calculated from a base of 18.3 °C (HDD are typically calculated to a base of 18.3 °C or 15.5 °C, based on ANSI/ASHRAE Standard 90.1). In absolute terms, the urban locations exhibit a markedly lower number of HDD than airport (semi-rural) locations. CDD are higher for urban locations, but the overall difference favours reduced heating loads for most locations, especially for more northerly locations.
Table 2.3 – Heating and cooling degree days for selected cities
Source: Davies et al. (2008) as adapted from Taha (1997)

<table>
<thead>
<tr>
<th>Location</th>
<th>Heating degree days</th>
<th>Cooling degree days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Urban</td>
<td>Airport</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>384</td>
<td>562</td>
</tr>
<tr>
<td>Washington DC</td>
<td>1300</td>
<td>1370</td>
</tr>
<tr>
<td>St. Louis</td>
<td>1384</td>
<td>1466</td>
</tr>
<tr>
<td>New York</td>
<td>1496</td>
<td>1600</td>
</tr>
<tr>
<td>Baltimore</td>
<td>1266</td>
<td>1459</td>
</tr>
<tr>
<td>London</td>
<td>2419</td>
<td>2779</td>
</tr>
<tr>
<td>Seattle</td>
<td>2493</td>
<td>2881</td>
</tr>
<tr>
<td>Detroit</td>
<td>3460</td>
<td>3556</td>
</tr>
<tr>
<td>Chicago</td>
<td>3371</td>
<td>3609</td>
</tr>
<tr>
<td>Denver</td>
<td>3058</td>
<td>3342</td>
</tr>
</tbody>
</table>

In the UK, a number of recent research projects have explored various components of the relationship between climate change predictions, the UHI effect, and the potential impacts on urban areas and the built environment. An EPSRC-sponsored project known as LUCID (‘The Development of a Local Urban Climate Model and its Application to the Intelligent Design of Cities’) was conducted from 2007-2010, with a primary aim of developing innovative methods of modelling local temperature and air quality and its relation to energy, health, and comfort in the urban environment (Davies et al., 2008). Project partners note the potential strategy of passive cooling of buildings for responding to climate change. Through this method, heat is stored in the building fabric during the day and released through ventilation at night. However, it is also noted that the method depends on lower nighttime temperatures, a point which requires new methods and tools for understanding microclimate. The project further proposes that practical methods are needed for integrating and assessing the finer details of urban planning, such as building layout, orientation, and design of open spaces with regard to microclimate. SCORCHIO (Sustainable Cities: Options for Responding to Climate Change Impacts and Outcomes), a sister project to LUCID, conducted similar research in Manchester, with a focus on anthropogenic heat and adaptation strategies for urban areas (Smith et al., 2009). COPSE (Coincident Probabilistic climate change weather data for a Sustainable built Environment), another Manchester-based investigation, developed a methodology for generating future weather data for use in building design and planning scenarios (Watkins et al., 2011).
2.4 Conclusions

While the literature reviewed in this chapter supports the need for adaptation strategies that will respond to the increased temperatures expected from climate change and the UHI effect and it is clear that a great deal of research is ongoing in this area worldwide, a number of gaps in the research can be identified. These include: 1) methods to incorporate and quantify greening strategies at the building or neighbourhood scale; 2) quantification of the specific types and amounts of greenspace that might be effective; and 3) methods to estimate energy consumption changes at the neighbourhood or city level where a particular adaptation strategy is being considered. The following chapter will explore previous research and knowledge on the connections between these three elements.
Chapter 3

3  Greenspace and Relationship to Urban Microclimate and Building Energy

In developing a foundation for this research, it was essential to place the primary research questions and objectives into the wider context of the literature on urban microclimate, particularly as it relates to greenspace functions and energy usage in urban areas. As one of the critical points of the research is to provide evidence for the impact of differing types of greenspace on building energy consumption, the relationship between these two elements was examined in order to find appropriate methods for analysis. The literature reviewed in Chapter 2 suggests that changes in surface materials, land cover and building geometries are drivers of the UHI and microscale differences in temperature within cities. As one of many surface materials, vegetation contributes to the microclimate of urban areas. The effects of vegetation will be further explored in this chapter, including changes in:

1. Evapotranspiration and relative humidity,
2. Shading, and
3. Wind speed and direction.

These microclimatic effects may, in turn, alter the energy consumption of buildings (Akbari et al., 2001) by altering the heating and cooling requirements (Dimoudi and Nikolopoulou, 2003), or by increasing lighting requirements due to shading.

The general urban climatic conditions can also be related to energy usage. While certain factors such as wind and surface temperatures can be highly variable at the microscale, some typical patterns of energy consumption in urban areas can be observed, such as increased use of air conditioning in summer, reduced use of heating in winter, and higher rates of electricity used for lighting (Santamouris et al., 2001). Overall, impacts on urban populations include thermal discomfort in summer, wind tunnel effects and wind turbulence from high-rise buildings with poorly planned positions (Karatsou et al., 2006; Bitan, 1992).
3.1 Greenspace Definitions and Functions

Greenspace and, more generally, green infrastructure, has been noted for a wide range of benefits, including temperature moderation, air pollution control, biodiversity and wildlife enhancement, recreation, environmental education, and community farming. Various countries, including the United States of America (USA), UK, Canada and Australia, have developed definitions and frameworks for greenspace or green infrastructure and are beginning to include these in planning policies (Benedict and McMahon, 2002; Department for Communities and Local Government, 2002).

In the USA, for instance, a Green Infrastructure Work Group comprising local, state, and federal governments and NGO’s began working in August 1999 to develop training and planning guidelines for green infrastructure. The definition arrived at from this group was:

“Green infrastructure is our nation’s natural life support system — an interconnected network of waterways, wetlands, woodlands, wildlife habitats, and other natural areas; greenways, parks and other conservation lands; working farms, ranches and forests; and wilderness and other open spaces that support native species, maintain natural ecological processes, sustain air and water resources and contribute to the health and quality of life.” (Benedict and McMahon, 2002, p.12)

In the UK, the National Planning Policy Framework (Department for Communities and Local Government, 2012b, p.52) states that green infrastructure is

“A network of multi-functional green space, urban and rural, which is capable of delivering a wide range of environmental and quality of life benefits for local communities.”

Prior to the National Planning Policy Framework, Planning Policy Guidance 17 – Planning for Open Spaces, Sport and Recreation (2002) provided a framework of greenspace types and definitions. Based on this guidance, councils across the UK began undertaking audits of greenspace.

Table 3-1 provides a summary of the types, definitions, and purposes of each greenspace.
<table>
<thead>
<tr>
<th>Type</th>
<th>Definition</th>
<th>Primary Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parks and Gardens</td>
<td>Includes urban parks, formal gardens and country parks</td>
<td>• informal recreation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• community events</td>
</tr>
<tr>
<td>Natural and Seminatural Greenspaces</td>
<td>Includes woodlands, urban forestry, scrub, grasslands (e.g. downlands, commons, meadows), wetlands, open and running water and wastelands</td>
<td>• wildlife conservation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• biodiversity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• environmental education and awareness</td>
</tr>
<tr>
<td>Green Corridors</td>
<td>Includes towpaths along canals and riverbanks, cycleways, rights of way and disused railway lines</td>
<td>• walking, cycling or horse riding</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• leisure purposes or travel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• opportunities for wildlife migration</td>
</tr>
<tr>
<td>Amenity Greenspace</td>
<td>Most commonly but not exclusively found in housing areas. Includes informal recreation spaces, greenspaces in and around housing and village greens</td>
<td>• informal activities close to home or work</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• enhancement of the appearance of residential or other areas</td>
</tr>
<tr>
<td>Provision for children and young people</td>
<td>Areas designed primarily for play and social interaction involving children and young people</td>
<td>• equipped play areas</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• ball courts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• outdoor basketball hoop areas</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• skateboarding areas</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• teenage shelters and ‘hangouts’</td>
</tr>
<tr>
<td>Outdoor Sports Facilities</td>
<td>Natural or artificial surfaces either publicly or privately owned used for sport and recreation. Includes school playing fields.</td>
<td>• outdoor sports pitches</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• tennis and bowls</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• golf courses</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• athletics</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• playing fields (including school playing fields)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• water sports</td>
</tr>
<tr>
<td>Allotments and Community Gardens</td>
<td>Opportunities for those people who wish to do so to grow their own produce as part of the long term promotion of sustainability, health and social inclusion. May also include urban farms.</td>
<td>• growing vegetables and other root crops</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• N.B. does not include private gardens</td>
</tr>
<tr>
<td>Cemeteries &amp; Churchyards</td>
<td>Cemeteries and churchyards including disused churchyards and other burial grounds</td>
<td>• quiet contemplation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• burial of the dead</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• wildlife conservation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• promotion of biodiversity</td>
</tr>
<tr>
<td>Accessible countryside in urban fringe areas</td>
<td>Open countryside outside of the main urban centre</td>
<td>• recreation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• walking, cycling</td>
</tr>
<tr>
<td>Civic spaces</td>
<td>Includes civic and market squares, and other hard surfaced areas designed for pedestrians</td>
<td>• urban regeneration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• informal meeting or relaxation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• visual amenity</td>
</tr>
</tbody>
</table>

Source: Modified based on Maidstone Borough Council, Green Spaces for Maidstone Strategy, January 2005 and PPS17

This framework is echoed in a number of local and regional green infrastructure plans, such as the Northwest Green Infrastructure Guide (North West Green Infrastructure Think Tank, 2008), which also recommends a Data Audit and Resource Mapping in order to generate a GIS-based map of an area showing the greenspace types and
locations. The Manchester City Council Local Authority has performed such an audit, with details provided in Section 4.5.2.

3.2 Greenspace as Adaptation and Mitigation for Climate Change

With increasing urbanisation and predictions of increasing frequency of heat waves, it is possible that extreme events will place ever larger populations at risk. In response, one adaptation and mitigation strategy that has been suggested for urban areas is the addition of greenspace (Gill et al., 2007; Lindley et al., 2006; McEvoy, 2007; Wilby, 2007), such as parks, gardens, green roofs, and street tree plantings.

Akbari (2002) notes that vegetation has both direct and indirect effects in terms of altering CO\(_2\) emissions and potentially impacting on climate. The direct effects include carbon sequestration as vegetation uptakes CO\(_2\) in the process of photosynthesis. Indirectly, the vegetation alters microclimate, potentially leading to lower temperatures and thereby altering the building energy consumption, also leading to lower CO\(_2\) emissions. Figure 3-1 provides a conceptual framework for the vegetative effects.

![Conceptual Framework for Estimating Vegetation Effects on Energy and CO\(_2\)](image)

A meta-analysis by Bowler, et al. (2010) found that the air temperature of parks is 0.94 °C cooler, on average, than surrounding areas. However, the analysis also noted that most of the evidence was based on empirical studies from small numbers of sites, rather than wider, systematic approaches that could generate guidelines for planning of greenspace.
In addition to effects on air temperature, green areas allow better infiltration of runoff, and potentially reduce the risk of flood events, which are expected to increase in the UK with predictions of warmer, wetter winters (Hall et al., 2005).

3.3 Parameters Associated with Urban Greenspace, Microclimate and Building Energy

The research questions concerned require an understanding of the numerous variables and scales at which they are operating. On a city or regional scale, the main variables are related to the meteorological conditions, including solar radiation, air and surface temperatures, wind, precipitation, and humidity (Rotach et al., 2003), as well as the general urban form, including urban morphology, building density and orientation, and canyon geometry. At a localised scale are key variables which influence microclimate, including surface albedo, surface roughness length, thermal properties of the various urban fabrics, soil moisture, and surface cover. The following sections discuss the greenspace, building energy, and microclimate parameters relevant to the research with a brief discussion of thermal comfort as related to building energy demand.

3.3.1 Greenspace Parameters

Greenspace can be characterised by a number of parameters that contribute to its microclimatic effects. To explore the effects of differing types of greenspace through modelling, parameters frequently noted in the literature (Chen and Black, 1992; Kirkham, 2005; Kvet and Marshall, 1971; Larcher, 2003; Schulze et al., 2005; Deardorff, 1978) include:

- Leaf Area Index (LAI), generally defined as one-side leaf area (total of all leaves) divided by area covered by the tree canopy for deciduous trees, or alternatively using the hemi-surface area for cylindrical needles;
- Leaf Area Density (LAD), total leaf area in m$^2$/m$^3$ of air (measured at set intervals from base to top of tree), defined as LAI/h, where LAI is leaf are index and h is the total height of foliage, usually taken as the height of the crown for trees;
- Root Area Density (RAD), total root area in m$^2$/m$^3$ of air, measured at set intervals from the base of a plant to the total depth of the root zone;
- Vegetation type or species, often characterised by the type of photosynthesis - C3, C4, or CAM, where C3 plants convert CO$_2$ first to a 3-carbon compound, C4 convert CO$_2$ to a 4-carbon compound, and CAM (Crassulacean Acid Metabolism) store carbon in the form of an acid before photosynthesis. Most plants are C3, corn and some annuals are C4, while CAM includes succulents such as cactuses and some orchids and bromeliads;
- Canopy area, total area covered by the tree crown;
- Total height, measured from base to top;
- Height-to-crown, measured from base to the base of the crown;
- Leaf diameter and aerodynamic properties (sometimes generalised according to deciduous, coniferous, grass, etc.);
- Stomatal resistance ($r_s$) (or stomatal conductance ($g_s$)) – resistances (or conductances) of water-vapour transport; includes epidermal resistance (stomatal and cuticular) and boundary layer resistance. Water vapour diffuses through two resistances acting in series: stomatal aperture and boundary layer (air) (see Figure 3-2 for an illustration of resistances);
- Soil moisture or soil relative humidity;
- Short-wave albedo of the plant leaf - the reflected portion of incoming solar radiation with wavelengths in the range of 0.3-4.0 μm.

![Figure 3-2 – Illustration of Resistances in Soil-Plant-Atmosphere Exchanges](http://www.geog.ucsb.edu/ideas/SoilWaterBalance.html)  
Access date: 14/10/2012

For microclimate modelling, the majority of models include LAI or LAD, vegetation species (either built-in or the ability to characterise vegetation as C3 or C4 in combination with other parameters), vegetation height, and albedo of leaves (Baklanov et al., 2009). LAD can be used to model the shape of a plant by specifying different values at different heights along the plant’s central axis (e.g., a plant with a conical shape may have nearly equal LAD’s, while a tree with a distinct crown will have small
LAD’s towards the bottom and large LAD’s towards the top). Recent research in Manchester found that the LAI of trees is strongly related to cooling due to evapotranspiration, as measured by correlation with surface and globe temperatures (Armson, 2012). Closely related to LAI are the canopy area, total height, and leaf diameter, variables which taken together will largely define the tree species for modelling purposes. RAD impacts the uptake of available water from the root zone if the model includes a soil moisture component. The albedo of leaves is an important component of the leaf energy budget, affecting the amount of short-wave radiation absorbed by leaves. While these parameters characterise vegetation and contribute to its localised interactions with microclimate, a range of additional variables operating at different scales are interlinked and will also contribute to the overall microclimate and thermal comfort of a local area.

3.3.2 Microclimate Parameters

In any small area or neighbourhood, a localised microclimate can develop based on site-specific characteristics. The main factors contributing to microclimate in urban areas include:

- Topography and aerodynamic roughness, expressed as roughness length \((z_0)\) and zero-plane displacement \((z_d)\) (Arnfield, 2003; Rotach et al., 2003);
- Wind speeds (Karatsou et al., 2006);
- Relative humidity;
- Urban morphology, urban canyon geometry, and sky-view factor (ibid.),
- Thermal properties of urban fabrics, such as surface albedo (Taha, 1997) and emissivity (Voogt and Oke, 2003); and
- Human activity, such as vehicles and waste heat from buildings (Smith et al., 2009).

3.3.2.1 Canopy Layer Variability

A review of urban climatology research by Arnfield (2003) highlights the importance of scale when investigating urban surface and atmospheric interactions. Differences in energy exchange and meteorological measurements are observed as the scale of observation is varied from the individual building, to an entire street, city block, or neighbourhood. Figure 3-3 illustrates the concept of the roughness sublayer and canopy layer in relation to previously discussed concepts (Chapter 2.2.1) of urban boundary layer meteorology. This roughness sublayer contains the non-uniform mix of roughness elements, such as tall buildings, trees, streets, etc. which contribute to the
highly variable flow of heat, humidity, and pollutants (ibid.) in this layer. At a height of approximately 2-3 times the average building height (shown as $z=3h$ in Figure 3-3), the turbulent mixing of air will lead to a layer of more uniform and stable air, described as the inertial sublayer (Rotach, 2003).

![Figure 3-3 - Lowest Layers of Atmosphere Over a Rough Surface](image)

Figure 3-3 - Lowest Layers of Atmosphere Over a Rough Surface

* $z_i$ is the boundary layer height and $h$ is average height of roughness elements.
* (Source: Rotach, 2003)

Geiger (Atkinson, 2003) observed the interdependence of temperature and moisture (of air, soil, and vegetation) and found that temperature readings are less stable when taken closer to the ground. Researchers and meteorologists find it difficult to determine representative sites for climatic observations due to the structures and surfaces in urban areas which cause high spatial variation at near-surface level. In response to this, Oke (2006) has developed guidance and criteria for making climatic observations in urban areas. Using the concept of Urban Climate Zones (UCZ) based on classification of urban forms, climate stations can be located according to purpose, spatial surveys revealing areas of interest, and avoidance of microclimatic anomalies. For purposes of this research, these considerations of high spatial variation led to an approach that selected study areas and monitoring sites based on the specific building types and arrangement in relation to greenspace characteristics, later discussed in Chapter 4.

### 3.3.2.2 Urban Canyon Geometry and Temperature Measurements

One central question in research with regard to the impact of microclimate on building energy is the relative roles of surface and air temperatures. While both are deemed to
be important, it is often surface temperature that takes priority in measurement due to the availability of remote sensing and thermal imaging that are more easily obtained at fine scales.

Karatsou et al. (2006) provide a very thorough discussion of variation of surface and air temperatures with building height and the impacts of canyon geometry as well as thermal transfer. The surface temperature is affected by incoming solar (shortwave) radiation as well as emitted thermal (longwave) radiation. In general, the temperature profile increases with increasing height due to additional solar radiation in moving up the building. However, the lower building surfaces may also experience high temperatures due to thermal transfer between urban canyon surfaces.

Air temperature distribution is also complex in urban canyons and is influenced by surface temperature due to energy transfer by convection. Measurements in summer show surface temperatures are usually higher than air temperature (by up to 13°C) (ibid.) and that air temperature inside a canyon is higher than that above in undisturbed air. Canyon geometry, particularly the sky-view factor (SVF) and height to width (H/W) ratio (Ali-Toudert and Mayer, 2006) are found to have a significant impact on both types of temperature (Rotach et al., 2003).

In general, it is difficult to find direct correlations between surface and air temperatures. While air temperatures over a small area may be quite consistent due to air mixing through advection and convection, surface temperatures have been found to be more variable (Lowry, 1998) and more related to microscale site characteristics, such as SVF (Brown and Gillespie, 1995; Eliasson, 1996; Gill, 2006). While some studies have used air temperature to model urban areas, many have preferred land surface temperature (LST) because it is less dependent on wind speed and direction (Whitford et al., 2001). Research by Schwarz et al. (2012) for Leipzig, Germany successfully integrated the air and surface temperature measurements and found good correlations between the point measurements of air temperature and the averaged neighbouring LST measurements of a traverse. This indicates that it is perhaps the methods of data collection that need to be integrated from the start of a study.

### 3.3.2.3 Albedo and Emissivity

The surface albedo of building materials, vegetation, and other surfaces also strongly influences air and surface temperatures. Albedo can be defined as the proportion of incident solar radiation (shortwave) which is reflected outward from an object (Briney, 2013). High albedo is usually associated with light-coloured surfaces (i.e., most incoming solar radiation is reflected back to space), whereas low albedo corresponds to dark surfaces. In some materials, a light-coloured surface will absorb large amounts of radiation in the near-infrared range, causing it to have low albedo. Other surfaces
may appear dark, such as green grass, but reflect a large proportion of infrared radiation, causing a higher albedo (Berdahl and Bretz, 1997). Texture also contributes to the overall albedo, with bumpy or rough surfaces having a lower albedo than a smooth surface for a given material. Taha (1997) notes that urban albedos are usually in the range of 0.15 to 0.20, particularly for North American and European cities, while many African cities are good examples of higher albedo materials, in the range of 0.3 to 0.45. Figure 3-4 illustrates surface albedo values for typical urban surfaces.

![Figure 3-4 – Typical Albedos for Urban Surfaces](image)

Source: (Akbari et al., 1992)

While albedo characterises materials according to shortwave radiation, emissivity is the parameter associated with longwave radiation. Emissivity ($\xi$) is the ratio of heat emitted by a material as compared to heat emitted by a black body at the same temperature (for a black body, $\xi=1$). In the urban environment, emissivities of typical materials are: red brick (rough) = 0.94, concrete = 0.85, and white paint = 0.89 (Adler, 1999).

### 3.3.3 Thermal Comfort Parameters

While thermal comfort is a large and important field of study and is beyond the scope of this research, it is often noted as being important to both microclimate and building energy performance (Gan, 2001) and therefore, it is important to have an understanding of how it can be measured.
One key parameter governing thermal comfort is the mean radiant temperature (MRT) (Armson et al., 2012), which has the strongest influence on comfort indices such as PET (Physiologically Equivalent Temperature) and PMV (Predicted Mean Vote). It is technically defined as the uniform temperature of an imaginary black enclosure which results in an equivalent radiation energy gain on a human body as the actual radiation fluxes in the surrounding environment. More simply, it is the area weighted mean temperature of all the objects surrounding a body. Measurement of MRT is with a globe thermometer, a dry bulb thermometer placed inside a matte-black copper sphere.

Because MRT is often difficult to measure, models such as Outdoor Effective Temperature (ET*), or indices based on ISO standards, such as PMV or PPD (Predicted Percentage of Dissatisfied) are frequently used to estimate thermal comfort. The PMV predicts the mean value of the votes of a large group of people on the ISO thermal sensation scale (+3=hot; +2=warm; +1=slightly warm; 0=neutral; −1=slightly cool; −2=cool; −3=cold). The PPD predicts the percentage of a large group of people likely to feel ‘too warm’ or ‘too cool’. This was defined as those voting +3, +2, −2, or −3 on the scale (Olesen and Parsons, 2002, p.539). Recently, an analysis of a database of world-wide thermal comfort research using methodological standards of ASHRAE (American Society of Heating, Refrigeration, and Air-Conditioning Engineers), developed a thermal comfort model by showing a “clear dependence” of indoor comfort on outdoor air temperatures, especially for naturally ventilated or hybrid buildings (de Dear and Brager, 2001, p.100). Additionally, the study found a broader range of comfortable temperatures than the rather rigid suggestions of Standard 55-92 (ASHRAE, 1992 & 1995) and ISO 7730 (1994). The model allows for adaptation based on human perceptions of comfort, which are more relative to outdoor temperatures than building standards suggest.

### 3.4 Vegetation Modifications in Urban Environments

Givoni (1991) states that plants can have significant impacts around buildings and reduce the cooling loads (and, in some cases, heating loads), by:

- Providing shade and reducing solar heat gain at the ground surface;
- Reducing solar gain and wind speeds at walls in the case of vines and high shrubs;
- Lowering air temperatures at the building’s skin;
- Reducing the reflected longwave radiation in the vicinity of the building; and
- Acting as insulation in winter by lowering wind speeds and reducing heat losses from buildings (Gartland, 2008).
This section examines, in greater detail, some of the modifications that can take place due to vegetation in the built environment.

### 3.4.1 Vegetation Influence on Air and Surface Temperatures

Lowering of temperatures in a small, localised area have been noted even from a single tree (Jáuregui, 1975). Furthermore, a number of studies worldwide have noted the cooling effect of larger greenspaces, such as parks, on their immediate and surrounding environments. At the macro level, Kawashima (1990-1991) in Japan, and Nichol in Singapore (1996) used remotely sensed images to investigate cooling effects of green areas in and around urban areas. While both studies found notable temperature differences between vegetated and non-vegetated areas, the Kawashima (1990-1991) study found that the cooling effect of vegetation was less in the urban area than in the suburban area.

Similar approaches by Jauregui (1990/1991) and Spronken-Smith (1998) found that the microclimates in urban parks also influence temperature in surrounding land uses. Upmanis et al. (1998) reported that this influence is due to the size of the park and found that cooling extends to 1km for a park of 1,250 m in width and 30-40 m for a park of 3.6 ha.

Research with similar aims to that proposed here was conducted in Singapore by Yu and Hien (2006). Using simulation programs, for building energy and surface energy balance, the authors conducted research in and around a city natural reserve and a neighbourhood park. Their research found “remarkable” cooling effects not only in and around the parks themselves, but also significant impacts on the built environment based on scenarios that were at 100 m increments from the parks. The research also noted that the standard deviation of temperature measurements for the parks was less than that observed for the built environment, in agreement with observations of Oke (1999) and Geiger (Atkinson, 2003). This potentially indicates a stabilising effect on temperature due to the vegetation.

Other studies have found cooling effects extending to four times the park area (Barradas, 1991), equal width with the park (Spronken-Smith, 1994), or as little as 20 metres (Bacci, 2002).

A more recent project includes urban greenspace as one potential measure for adaptation to climate change in urban areas (Gill et al., 2007). One aspect of the project was to perform modelling, using a surface energy balance model developed by Tso et al. (1990, 1991) which demonstrated the effect of greenspace on the urban infrastructure. Models were run for a baseline climate generated for the years 1961-1990, and also for the UKCIP02 Low and High Emissions scenarios for 2020s, 2050s,
2080s (Hulme et al., 2002). The models were used to explore the impacts of development trends and to understand temperature changes under various greening scenarios, such as increasing or decreasing green cover in residential and town centres by 10%, adding green roofs, or increasing tree cover. Under a scenario of adding as little as 10% green to densely built areas, such as town centres, the modelling predicted surface temperatures could be kept at (or below) the 1961-1990 baseline. This held true for all emissions scenarios except the 2080’s high emissions scenario.

In contrast to these findings, Potchter et al. (2006) found that some types of greenspace intensify urban heat. In this study, medium-sized trees, although effective at reducing temperatures by up to 2.5 °C in the day, led to uncomfortable climatic conditions at night. This was attributed to increases in relative humidity and reduced wind velocity, as compared to larger trees with a high, wide canopy.

Chang et al. (2007) notes that little research has been performed to develop criteria for the design of greenspace in relation to urban heat mitigation. Bowler et al. (2010) in a systematic review of empirical research on urban greening and cooling effects notes that most studies have been performed on small numbers of sites and are unable to develop greening strategies based on the limited observations. While many studies (both empirical and modelling) have been able to demonstrate the cooling effect of parks and other types of greenspace, much more research is needed on the fine scale understanding of types, amounts, and placement of vegetation and the interactions with other microclimate parameters in order to inform planning and policy decisions. While Bowler et al. (2010) argues for more systematic empirical approaches, it could also be argued that modelling can provide such a systematic approach and better understanding of the dynamic relationships between the large number of variables found in the fine-scale urban environment.

### 3.4.2 Evapotranspiration and Partitioning of Latent and Sensible Heat Flux

Evaporation is water vapourisation from soils and other surfaces, while transpiration is water vapour transferred to the air from plant tissues (Allen et al., 1998). The two processes are difficult to distinguish in practice and are referred to together as evapotranspiration. This process alters the partitioning of sensible and latent heat and can significantly affect the localised climate.

Surface energy balance for an evapotranspiring area can be written as:

\[ R_n = G + \lambda \text{ET} + H \]

\[ \text{Equation 3-1} \]

where \( R_n \) is the net radiation, \( H \) the sensible heat, \( G \) the soil heat flux and \( \lambda \text{ET} \) the latent heat flux (Allen et al., 1998). Incoming radiation (solar and thermal) is partitioned...
in three forms: 1) ground storage; 2) heating of air near the ground surface (sensible heat); or 3) used to evaporate water from the ground, water bodies, or through vegetation (latent heat).

The Bowen ratio ($\beta$) is a ratio of sensible to latent heat and will vary widely in urban environments, depending on the amount and types of vegetation. On average, $\beta$ will be in the range of 0.5 to 2.0 with lower ratios for rural, vegetated areas and higher ratios (4 or greater) for densely built, urban areas with little vegetation (Oke, 1982; Taha, 1997). In urban areas, the high proportion of impervious surfaces, such as concrete, asphalt, and brick, coupled with the lack of vegetation and higher runoff rates leave less available water for evapotranspiration. As compared to rural, heavily vegetated areas, a greater portion of urban energy is transformed into sensible heat.

Grimmond and Oke (1995), in one of the few studies to measure both latent and sensible heat fluxes, studied the energy balance of four suburbs of the North American metropolitan areas: Los Angeles, California; Sacramento, California; Tucson, Arizona; and Chicago, Illinois. Although the cities cannot represent the great many possible combinations of morphology, climate, and building patterns, the study does give some general indications regarding the Bowen ratio. For instance, they found a summer value of 1.5 for $\beta$ in Tucson, where precipitation is infrequent, but irrigation is used, while the value is more likely to be 0.8-1.0 for cities with regular summer precipitation. The study also highlights the possibility of an inverse relationship between $\beta$ and the area under irrigation. An earlier study by Oke et al. (1992) for Mexico City found lower than expected $\beta$ for a tropical city, typically about 1.12 and seemed to be attributed to a higher portion of energy going into storage in the urban fabric as well as evapotranspiration due to irrigation and other water usage during the dry season.

Taha (1997) notes that a lack of vegetation in urban areas is a “major factor” in higher daytime temperatures, and goes on to discuss specific studies showing higher temperatures in urban areas with less vegetation. However, the discussion does not distinguish whether the increased temperature is strictly due to less evapotranspiration, or whether it might also be attributed to shading (change in incoming shortwave and outgoing longwave) or wind.

The rate of evapotranspiration is controlled by a number of factors, including air temperature, humidity, wind, soil water content, and the particular crop or type of vegetation. A number of models have been developed for estimating evapotranspiration and are considered important because of limitations to measurement. Perhaps the best known models for ET are the Penman-Monteith model and the Shuttleworth-Wallace model.
Penman-Monteith calculates ET through a complex formula based on solar radiation, daily average temperature, wind speed, and relative humidity. It is a standard method for modelling evapotranspiration for the United Nations Food and Agriculture Organisation (Allen et al., 1998). Problems with Penman-Monteith are that it requires several measurements and a number of assumptions, which are often invalid. Additionally, because Penman-Monteith is a single layer model that treats soil evaporation and plant transpiration as one process, Shuttleworth and Wallace developed a two-layer model to estimate these processes separately. The result is that Shuttleworth-Wallace produces a better estimate under low leaf area index, when soil evaporation is important (Zhang et al., 2008). By comparison to these and other ET equations, the Bowen ratio simplifies the calculation by allowing for measurement of $\beta$ and then calculation of latent heat based on net radiation and soil heat flux.

### 3.4.3 Wind and Turbulence

The effect of wind in the urban environment is arguably the most complex of all design elements, requiring careful consideration by architects, planners and urban climatologists (Santamouris et al., 2001; Smith and Levermore, 2008). Wind in the urban environment has significant effects on both indoor and outdoor human comfort, as well as heat transfer at the building envelope and potential for natural ventilation.

As discussed in section 2.2.1, the planetary boundary layer (PBL) (or Atmospheric Boundary Layer (ABL)) is the lowest portion of the atmosphere, in which the frictional drag of the surface affects the flow of air. In this layer, air approaching an urban area from a rural, open area meets more resistance due to the urban roughness elements such as buildings and infrastructure of varying heights and orientations. The flow is reduced within the urban canopy layer (UCL), creating turbulence, and further impacting flow in the urban boundary layer (UBL), which extends from the top of the canopy layer up to the bottom of the subsidence inversion (Kerschgens and Kraus, 1990). Factors affecting the flow include building heights and geometry, street orientation, vegetation, and topography.

Wind speed in the PBL increase with height above the surface according to a power law:

$$u_z = V_G(z/z_G)^\alpha$$  \hspace{1cm} \text{Equation 3-2}

where, $u_z$ is wind speed at height $z$, $V_G$ is the geostrophic wind, $z_G$ is the height of the geostrophic wind, and $z$ is the height at which $u_z$ is calculated and $\alpha$ is the exponent, which usually varies from 0.1 to 0.4, depending on roughness and atmospheric stability (smooth/stable =0.1 and 0.4 for rough/unstable).
The increased turbulence of the UCL complicates any prediction of wind speeds in urban areas. Nakamura and Oke (1988) studied wind flow and temperature profiles in an east-west oriented urban canyon in Japan and found a linear relationship between wind speeds above and within the canyon, with a typical reduction by two-thirds for within-canyon speeds. Also, the air remained unstable or near neutral at all times. A study by Santamouris (2001) found that canyon wind speeds were reduced by up to ten times that of ambient speeds, seriously reducing the potential for natural ventilation in such locations.

In terms of building energy, a few studies suggest that vegetation reduces wind speeds, which leads to reduced infiltration at the building envelope and lower energy consumption. Infiltration occurs when exterior air, which will be colder and denser in winter, seeps into a building through cracks or gaps around windows and doors at lower levels of the building. The warmer interior air rises and seeps out through exterior walls and roof space. In summer, the reverse occurs, with warmer exterior air entering through upper floors and colder interior air going out through lower level window and door frames (Mattingly and Peters, 1977). Research by Mattingly and Peters (ibid.) on the sheltering and building energy effects of fences, adjacent houses, and tall evergreen trees found that a straight row of evergreen trees was the most effective scenario tested, reducing infiltration by up to 40%. Parker (1983) supports this finding, stating that, for the warm, humid climate of south Florida, careful placement of trees and shrubs in relation to prevailing winds reduces infiltration during summer.

3.4.4 Vegetation and Building Energy Changes

One of the primary functions of vegetation in urban environments is the provision of shade. Trees and low vegetation will shade the ground surface, while taller trees, vines, and green roofs can reduce the heat transferred through the building envelope. Shade trees can be particularly effective at reducing solar gain through windows. Only a few studies have attempted to include the effects of vegetation in urban environments and their subsequent impacts on building energy consumption. Of those that have included vegetation, most have concentrated on building energy (and/or CO₂ emissions) solely as function of one variable, either air temperature or shading effects.

A study of two residential buildings in Sacramento, California estimated seasonal cooling energy savings of 29% solely through the use of sixteen shade trees (Akbari et al., 1997). Huang et al. (1987) used a modelling approach to investigate meso- and microclimates and their relationship to building energy. Using a climate model in conjunction with the DOE 2.1 model, along with hourly weather tapes for climate input,
modelling was performed on effects of temperature, wind speed, humidity, and solar gain from the use of vegetation. Scenarios tested include reduced solar gain through shading (by increasing tree canopy and placement on the South or West side of a building); wind speed reduction as a function of tree canopy density; evapotranspiration as a function of dry bulb temperature and solar radiation (after Jensen and Haise, 1963). The building prototype was single story residence of wood-frame construction. The study found that a 25% increase in tree cover can save 40% on residential cooling energy for Sacramento, and 25% in Phoenix and Lake Charles. The cooling energy savings increased to 50% and 33% respectively when optimizing for shading. A number of issues are raised in the discussion regarding assumptions in the modelling process. The authors note that the following need further investigation: evapotranspiration rates, mixing heights, adiabatic mixing, and localised effects. Huang et al. (1987) also note the potential for increased latent air conditioning load if moisture is added to the air through evapotranspiration.

In perhaps the most comprehensive study of this type, Akbari and Konopacki (2005) developed summary tables of energy savings based on simulations employing a selection of UHI reduction strategies, including solar-reflective roofs, shade trees, and ambient cooling. The analysis looked at buildings that were profiled according to usage (residences, offices, and retail stores), age (Pre-1980 (old) or 1980+ (new)), and fuel (natural gas or electricity). Simulations estimated cooling and heating energy use and peak power demand using the DOE-2.1E model and weather data for about 240 locations in the United States. Energy use and savings per 1000 ft² of roof area were integrated to provide results tables sorted by heating and cooling degree-days. Savings were greatest for residential buildings at 12% to 25%, and for office buildings, the electricity savings ranged from 5% to 18%, depending on the age and climatic location (as characterised by HDD) of the building. In this study, the shading was estimated by placing a building element (block) next to the building with the estimated height and volume of a tree and assigning a transmittance (0.1 for summer, 0.9 for winter). One difficulty in exploring this study is with regard to the methods used to estimate ambient cooling.

In a study near Tokyo, Japan, Ca et al., (1998) examined the influence of a nearby park during August and September by measuring air temperature, relative humidity, wind, foliage temperature and several surface temperatures. Through modelling, the study estimated a 15% reduction in cooling energy requirements at noon with approximately 1.5 °C air temperature reduction.

In a similar study, Yu & Hien (2006) studied the effects of a park on air temperature and cooling energy requirements in Singapore. The study found that the cooling effect
of the park extended into the areas surrounding the park with a maximum temperature difference of 1.3°C between the park and surroundings, with savings of up to 10% on cooling energy for an 8-storey office building. The study considered energy savings due to air temperature cooling, but not the effects of shading or changes to relative humidity or wind.

Kikegawa et al. (2006) classified urban areas or canopies according to SVF – using a numerical model, investigated the effects of several different UHI countermeasures, including albedo increases, urban greening (ground, walls, or roof), and reducing waste heat, and conservation of cooling energy. In the residential canopies, the study estimated 0.7 °C reduction in air temperature and 20% reduction in building energy due to green walls, while the office canopies were shown to have the greatest reductions (0.5 °C air temperature and 5% energy savings) due to the elimination of waste heat discharge.

While this section has identified and discussed several studies on the impacts of vegetation on building energy, no single study addresses all components of vegetation modifications in urban environments and the studies do show a wide range in energy reductions, from 5% up to 50%, depending on level of shading and estimated air temperature reductions. This topic is still in need of additional research, especially in verifying modelling studies for specific locations.

### 3.5 Conclusions

Chapter 3 has explored a range of greenspace functions and the effects of vegetation with regard to evapotranspiration, relative humidity, shading, and changes in wind speed and wind direction. The chapter reviewed each of these effects and their related potential impacts on building energy consumption.

The chapter began by looking in detail at a range of greenspace and microclimate parameters, and how they can be applied to measured and modelled changes in the urban canopy layer. Finally, the chapter reviewed the specific air and surface temperature, wind, and heat flux changes due to vegetation in urban environments and linked these effects to changes in building energy consumption.

The chapter revealed a wide range in estimates of building energy changes, and the need for additional research in this area. The research presented in the following chapters of this thesis relies on a modelling approach, but with the addition of empirical air temperature results. Through modelled and observed changes in microclimate (air temperature, wind speed, and RH), the research develops estimates of building energy changes for commercial buildings in a UK city.
Chapter 4

4 Methods

4.1 Potential Methods

A review of research on the relationship between greenspace and building energy usage found that such studies generally attempt to analyse the ability of green areas to reduce temperatures and then, based on temperature reductions, make estimates of electricity savings. Potential approaches for investigating and linking the microclimate influences of greenspace and building energy changes include descriptive case studies (Huang et al., 1987; Wilmers, 1990/91), mathematical modelling (Dimoudi and Nikolopoulou, 2003), analytical modelling (Bruse and Fleer, 1998; Jesionek and Bruse, 2003; Taha, 1997; Tso et al., 1990; Tso et al., 1991), empirical modelling, and remote sensing (Hardin and Jensen, 2007).

Karatsou et al. (2006) state that meteorological models are of limited use to urban designers because the parameters defined in the models are not strongly influenced by structures in the urban canopy layer. Issues of scale and the simplification of morphological characteristics do not allow the local-scale investigations needed by designers and planners. The implication is that modelling for urban design should be scaled down to a block or neighbourhood level and focused on detailed urban morphological characteristics such as canyon geometry, surface cover, and parameters affecting surface energy balance.

Investigations into microclimatic effects of vegetation by Dimoudi and Nikolopoulou (2003) provide some direction and insight using a modelling approach. The research first characterised vegetation as planar or three-dimensional and then used parameters of evapotranspiration, albedo, permeability, and transmission in a transpiration model developed by Terence Murphy of University of California, Davis (Murphy and Bestman, 1999). Further parametric studies using CFD (Computational Fluid Dynamics) analysis employed in a 3D mathematical model also estimated changes in air temperature and wind speed in relation to vegetation type, size of the green area, changes in urban texture, SVF, and distance from the green area. In a grid analysis, replacing a central building with a park led to temperature reductions between 2K and 6K, depending on the area analysed. Increasing the size of green area, up to triple the original size, showed the greatest temperature reduction (3.5K to 9K) as compared to a base case with no green areas. As the H/W ratio of a street increases, the park effect is more localised and increases the wind speed while decreasing the effect of vegetation. A small investigation of the replacement of park trees with a different species (such as a more tropical type) showed only a small change of less than 0.5 K. While this is a very insightful study, it is limited to investigating each parameter in relation to temperature...
and wind speed, but does not estimate impacts to building energy or impacts of different types and configurations of vegetation.

A study by Hardin and Jensen (2007) used remote sensing and field surveys to demonstrate the relationship between urban leaf area (using LAI as a measure) and urban temperatures. For the urban area of Terre Haute, Indiana, USA, surface temperature from ASTER imagery was analysed by regression with LAI measured in field surveys to derive a statistical relationship with LAI. The regression equation for predicting surface temperature based on LAI demonstrates that 62% of variation in surface temperature is accounted for by LAI. While the study shows that this single variable is significant in predicting urban surface temperatures, it does not attempt to relate the temperature to other important urban surface characteristics, such as SVF or height-to-width ratios.

Sebba et al. (1984), in an empirical study, measured dry and wet-bulb temperatures in and around a number of green and open space configurations (ie., open grass-covered space, open area but surrounded by trees and shrubs, completely tree-covered) in the hot, arid climate of Israel. Their measurements in residential neighbourhoods demonstrated that air temperature near trees was 0.5 to 1.0 °C cooler than near houses. More recent empirical studies in the same geographic area by Potchter et al. (2006, 2008) utilised Campbell weather stations fitted with temperature, humidity, wind speed, and wind direction monitors as well as unaspirated radiation shields. Measurements suggest that different types of park configurations, such as parks with small trees compared to densely planted parks with larger trees, have different temperature patterns throughout the day and night, with some configurations showing a warmer, more humid nighttime pattern than surrounding areas.

Using a model developed by Bruse & Fleer (1998) specifically for surface-plant-air interactions in urban environments, Jesionek & Bruse (2003) investigated the impacts of different levels of greening in relation to the microclimate of buildings. The research first developed a classification scheme for typical European urban building types and then used ENVI-met to simulate varying levels of greening and design parameters, such as canyon geometries or sealing rates. Results are analysed in terms of thermal changes due to increased green and effects on pollution dispersion and accumulation. The authors conclude that, especially in densely built block structures, greening with trees leads to higher pollution concentration, but in more open structures, thermal advantages can be used for microclimate improvement.

A recent study by Heiple and Sailor (2008) provides insight into approaches for modelling the energy consumption of buildings. The authors first discuss differences between top-down and bottom-up approaches to estimating energy consumption at fine
scales. The top-down approaches involve the use of city or regional scale aggregate data on electricity loads that is disaggregated by some method, such as diurnal variation in population densities (Sailor and Lu, 2004). In contrast, the bottom-up approaches start from the individual building consumption and build up an estimate to a local area or city-level. Because this study investigates the relationship between building energy and greenspace at a fine scale, the latter approach is most relevant.

4.2 Methods Selected for the Current Research

The previous section provides evidence for a number of potential approaches and reveals that both empirical studies and modelling are frequently utilised for this type of investigation. However, a number of impracticalities are involved in performing a strictly empirical study. As discussed in Chapter 3, a large number of variables influence the microclimate interactions between buildings and greenspace. In an empirical study, each greenspace selected for measurement would be in a different location with different surroundings and the greenspace itself may be influenced by other factors such as its location in the UHI, the building geometry, and surface characteristics surrounding it, thus making it difficult to determine whether the greenspace is influencing the built environment or vice versa.

Additionally, in this research it would be problematic to compare energy usage data for different buildings because the building mix in Greater Manchester is diverse in terms of age, size, construction materials, HVAC (heating, ventilation, and air conditioning) characteristics and occupancy rates. For residential buildings, the energy usage behaviour of individuals is very likely to cause significant variation even without consideration of other variables. Due to these limitations in empirical data, modelling is determined to be an important tool for assessing changes in building energy consumption due to different types and arrangements of greenspace.

Modelling in this research took place in two stages: microclimate modelling to assess differences in microclimate resulting from different greenspace types and arrangements; and building energy modelling to assess impacts to building energy. Temperature, humidity and several other climatic variables output from the microclimate model were used to alter weather file inputs for the building energy modelling.

In addition to modelling as the primary investigative tool, the use of at least one or two empirical parameters were necessary for calibrating and validating the microclimate element of the modelling. Due to the lack of model validation in the literature, it was important to compare model results to real-world data. For this part of the research, air temperature data were collected using iButton temperature sensors that were placed
on lampposts within selected study areas. Further details of the monitoring are provided in Section 4.6.

4.3 Modelling Software

This section reviews a number of existing models for their suitability in the proposed research. At present, no single software package is available that can model both the microclimatic effects of vegetation and the changes in building energy usage that might result from localised temperature changes. However, a number of separate models can be found to perform one or the other function, which has led to the use of one model for changes in microclimate, with the outputs used to alter weather files as inputs for building energy modelling.

4.3.1 Urban Microclimate Modelling

The first requirement in the modelling process is a suitable energy balance model in order to investigate energy balance changes due to changing the type of greenspace. A growing number of numerical models have been developed for investigations of urban canyons and neighbourhoods. These models are based on the physical processes encountered in urban environments, including radiative exchanges, turbulence, and evaporation and vary considerably depending on the scale, temporal resolution, processes and boundary conditions. These differences are clearly summarized by Ali-Toudert & Mayer (2006) and an excellent comparison of recent models is provided by Baklanov, et al. (2009).

A number of models were initially considered, including Canyon Air Temperature (CAT) (Erell and Williamson, 2006), the Soil Model for Submesoscales, Urbanized Version (SM2U) (Dupont et al., 2006), and Simple Urban Neighbourhood Boundary Energy Exchange Model (SUNBEEM) (Arnfield, 2000). However, these models are either slab or single-layer, which do not allow detailed modelling of the canopy, or in the case of the multi-layer model SUNBEEM, they do not have sufficient detail for detecting differences in vegetation. Another model that was considered as a follow-on from previous work on greenspace and climate change (Gill, 2006) was an energy balance model, developed by Whitford et al. (2001) based on research performed by Tso et al. (1990; Tso et al., 1991). However, that model is based on land-use type and only suitable for surface temperature estimations. Therefore, it is more useful for regional-scale modelling rather than the fine-scale block and neighbourhood microclimate simulations needed in this particular research.

One tool which meets the objectives of the microclimate modelling is the model ENVI-met, developed by the Research Group Climatology at Ruhr-University Bochum in
Germany (Bruse & Fleer, 1998; Bruse, 2004) for modelling surface-plant-air interactions in the urban environment. ENVI-met is a free package developed on the Microsoft Windows platform and is specifically designed for investigations of changes to landscape and the built environment in urban areas. It is aimed at planners and architects who need to understand the thermal and pollution-related impacts of various design parameters, such as building geometry, surface coverings, and vegetation in urban design. ENVI-met was selected for its additional level of detail in handling multilayer vegetation, the ability to develop site-specific vegetation profiles and its inclusion of latent heat and soil moisture. The model uses computational fluid dynamics (CFD) and thermodynamic processes, employing the non-hydrostatic incompressible Navier Stokes equations for the wind field, the k-epsilon turbulence model and a combined advection-diffusion equation with the Alternating Directly Implicit (ADI) solution technique (Bruse, 2011) to model the interaction between microclimate and urban surfaces, such as walls, pavements, and vegetation. Spatial resolution can be in the range of 0.5 to 10 m.

The model version used in this research (v3.1 Beta V) is limited in some aspects. Although the model is 3D, all components are placed on flat ground, leading to better simulation of study areas that are on level terrain. The model does not allow for variation of the building envelope, U-values (the coefficient for heat transfer across the building envelope), or internal temperatures for individual buildings (Emmanuel and Fernando, 2007) and does not incorporate forcing of weather variables after initialisation. Also, long model running times coupled with typical research time constraints limit the number of total simulation hours.

4.3.2 Building Energy Modelling

A large number of software packages are available for the building energy modelling element of the research. In the UK, AECOM oversees a Building Energy Calculation Software Approval Scheme on behalf of Communities and Local Government (CLG) (Lim, 2009). Software is classified as domestic or non-domestic, with the latter further classified according to one of three types:

- Operational Rating Calculation, which produces a display consumption certificate base on annual utility consumption data;
- Front-end interface for the simplified building energy modelling engine (FI-SBEM), which primarily provides a user-friendly interface for the CLG SBEM engine and produces an Energy Performance Certificate; and
Dynamic Simulation Modelling (DSM), which can model the thermal dynamic response of buildings and demonstrate compliance with Part L of the Building Regulations (HM Government, 2010).

Twelve programs are on the approved list for FI-SBEM, while only two, TAS and Virtual Environment by IES, are on the approved list for DSM.

One of the DSM programs, Virtual Environment (VE), was assessed as a suitable option for this research. IES-VE software was previously used on other research projects in the University of Manchester and has the advantages of being user-friendly as well as low cost to students and academic researchers. Hourly weather data required for simulations are available for Manchester from CIBSE and custom weather files can be created for testing the effects of changing weather patterns.

Modelling in IES-VE is achieved using the Model-It Module to size, place, and orient 3-D blocks to design the building’s structure, as in Figure 4-1.

The blocks can be modified in thickness and volume to provide realistic building elements, while surface coverings, construction elements, thermal profiles, HVAC and lighting schemes can also be adjusted to investigate a multitude of building designs. Importantly, for this research, the SunCast module is included for determining the effects of shading due to elements on or around the building.

The ApacheSim module controls the thermal dynamic simulation, including the modelling of conductive, convective, and radiative heat exchanges and integrating these with internal gains, air exchanges, and plant processes. Full descriptions of equations and solution methods are found in the ApacheSim Calculation Methods document (Integrated Environmental Solutions Limited, 2011). Additionally, the methods have been tested and verified by CIBSE, as documented in TM33 (CIBSE, 2006b).
Although TAS is an approved DSM known to be used by some local private companies, the cost is somewhat high at £1000 for a three-year academic license and £100 per USB dongle key.

Appendix A summarises the main characteristics of a selection of the modelling software considered for this research.

4.4 Modelling Requirements and Processes

As a guide to selection of study areas, a detailed look at both ENVI-met and IES-VE identified data inputs and parameters required for creating modelling scenarios. ENVI-met consists primarily of two input files. The first file is a configuration file, which allows input of file locations and initialisation parameters, such as locations of input and output folders, start time, interval for saving data, initial wind speeds and other initial values. The second file is an area file, which allows input of a detailed layout of the site, including buildings with heights, locations and heights of trees and other vegetation, and soil types.

Areas to be modelled are input on a rectangular grid which can range from small areas less than 20 x 20 cells up to a maximum of 250 x 250 cells, with each cell having a resolution of 0.5 m up to 10 m. Example models loaded with ENVI-met range from 30 x 30 up to 150 x 150 cells, with typical cell resolutions of 3 to 5 m. Larger model areas and/or higher resolution models require significantly longer running times, so it was important to select a model size and resolution that was manageable within the timeframe of this research project.
The top of the model is fixed at 2500 m, with the user specifying the height of the near-surface layer. Guidance for model set-up states that this last layer should be about twice the height of the tallest structure with a minimum height of 30 m.

Data are input on a cell-by-cell basis, by selecting from a list of soils, vegetation types, and specifying a building height for those areas covered by a building. Points that are of interest for careful examination (e.g., for corresponding field measurements) can be specified as receptor points.

Timing of model runs is set by the user, with a typical model running from early morning for a period of 24 hours and saving data once per hour. Due to the extensive calculations and numerous outputs (detailed in Appendix B), the time it takes to complete one simulation hour can be 4-6 hours or upwards depending on the size of the model area and level of detail in the model.

On completion of the microclimate modelling, the second modelling stage was to estimate energy changes due to additional greenspace by using IES-VE 2012. For this stage, a set of buildings were designed with suitable constructions for walls, floors, windows, and roof. According to the N-DEEM (non-domestic energy and emissions) model (Pout, 2000; Steadman et al., 2000) developed by the Building Research Establishment (BRE), energy end usage (cooling, heating, lighting, hot water) is estimated according to building characteristics, including: activity group (office, retail, hotels), construction type, and size.

Although residential (or domestic) and commercial buildings were both considered initially, it was found that the two are very different in terms of structural, ventilation, and HVAC characteristics. Residential can be difficult to model due to widely differing occupancy rates and timings, and unpredictable usage of heating, lighting, and electronics. Additionally, a report on climate change impacts for London notes that residential buildings are less of a problem in terms of UHI and climate change because less heat is gained from equipment and individuals have more control over windows, doors, and other comfort measures (Clarke et al., 2002). Recognizing that the usage will vary by the building’s primary activity, it was decided to focus the research and modelling on commercial buildings.

Data outputs from ENVI-met and iButton data were used to inform the changes to weather inputs in IES-VE. Tree elements were added to models to test the effects of shading. The building models and related greenspace scenarios are described in detail in Chapter 8, as many parameters are based on the results of the iButton data analysis and microclimate modelling presented in Chapters 5 and 7, respectively.
Table 4-1 provides a summary of variables associated with urban greenspace, microclimate and energy consumption of buildings, together with the operational scale, (i.e., point, parcel/plot, or neighbourhood) and the sources of data for this research.

<table>
<thead>
<tr>
<th>Parameter Type/Description</th>
<th>Scale</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Meteorological</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind Speed</td>
<td>Point</td>
<td>BADC</td>
</tr>
<tr>
<td>Cloud Cover</td>
<td>City/region</td>
<td>BADC</td>
</tr>
<tr>
<td>Temperature (Air and Surface)</td>
<td>Point</td>
<td>Field survey</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>Point</td>
<td>BADC</td>
</tr>
<tr>
<td><strong>Urban Microclimate</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>City Size</td>
<td>City/region</td>
<td>GIS</td>
</tr>
<tr>
<td>Building Density</td>
<td>City block</td>
<td>GIS/Cities Revealed</td>
</tr>
<tr>
<td>Urban Canyon Geometry - H/W or L/H ratios</td>
<td>City block</td>
<td>GIS/Cities Revealed and/or field survey</td>
</tr>
<tr>
<td>Urban morphology</td>
<td>City/region</td>
<td>For Manchester, ASCCUE</td>
</tr>
<tr>
<td><strong>Buildings and Pavings</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height</td>
<td>Plot</td>
<td>Cities Revealed, OS MasterMap</td>
</tr>
<tr>
<td>Age</td>
<td>Plot</td>
<td>Literature</td>
</tr>
<tr>
<td>Materials</td>
<td>Plot</td>
<td>Building modelling database</td>
</tr>
<tr>
<td>HVAC characteristics</td>
<td>Plot</td>
<td>Building modelling database</td>
</tr>
<tr>
<td>General Layout</td>
<td>Plot</td>
<td>Field Survey/Google Earth</td>
</tr>
<tr>
<td><strong>Greenspace</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>Plot</td>
<td>Manchester City Council</td>
</tr>
<tr>
<td>Species</td>
<td>Point/Plot</td>
<td>Field Survey</td>
</tr>
<tr>
<td>Leaf Area Index</td>
<td>Point</td>
<td>(Scurlock et al., 2001)</td>
</tr>
<tr>
<td>Leaf Area Density</td>
<td>Point</td>
<td>(Lalic and Mihailovic, 2004)</td>
</tr>
<tr>
<td>Canopy height</td>
<td>Point</td>
<td>Field Survey</td>
</tr>
<tr>
<td>Canopy area</td>
<td>Point/Plot</td>
<td>(Savage, 2008)</td>
</tr>
<tr>
<td>Albedo (short-wave)</td>
<td>Point</td>
<td>(Adler, 1999)</td>
</tr>
</tbody>
</table>

### 4.5 Site Selection

#### 4.5.1 Research Location

The city-region of Greater Manchester covers around 1300 km² with a population of 2.5 million people. It is governed by 10 local authorities, a number of which are supportive of research related to greenspace and climate change issues, including Manchester, Salford, and Rochdale. These local authorities allow access to areas and lampposts suitable for placement of monitoring equipment.

Manchester City Council Local Authority is the largest in terms of population. Its administrative zone stretches from the city core to the urban periphery North to South across a largely flat area. As stated in Section 4.3.1, one limitation of ENVI-met is the inability to vary the terrain elevation in different parts of the model; as the central part of Manchester is relatively flat, lying primarily between 35-78 m above sea level (LANDMAP, 2001) this problem is avoided. Additionally, it provides a good basis for a transect of modelling study sites across an urban gradient. While Manchester city centre has a mix of densely developed tall office, retail, and residential buildings with
low green cover (3-4%), the suburban areas allow investigation of lower density office, retail, industrial, and residential areas with approximately 25% green (Richardson and Mitchell, 2010). In addition, Manchester City Council has performed a greenspace audit, which is available in GIS format and categorises greenspace according to activity types.

By using Greater Manchester as the study area, the research benefits from links and inter-disciplinary support through several other Manchester based projects:

- EPSRC Sustainable Cities: Options for Responding to Climate Change Impacts and Outcomes (SCORCHIO) (which ran from 2007-2010),
- EPSRC COincident Probabilistic climate change weather data for a Sustainable built Environment (COPSE) (2008-2011),
- EPSRC Adaptation Strategies for Climate Change in the Urban Environment (ASCCUE) project (completed in 2006), and
- i-trees, a project coordinated between Corridor Manchester (a partnership of Manchester City Council, the University of Manchester, Manchester Metropolitan University and the Central Manchester University Hospitals NHS Foundation Trust) and Red Rose Forest, which is establishing and monitoring green infrastructure and microclimate in the Oxford Rd corridor, an area starting in St. Peter’s square in central Manchester and travelling south to Whitworth Park.

4.5.2 GIS Processing for Greenspace and Building Characteristics

For ENVI-met modelling scenarios, several different combinations of greenspace and building types were developed. Modelling scenarios are based on case study areas selected for their mix of building types, as well as surface and greenspace characteristics.

A GIS analysis was undertaken using ArcGIS 9.3 in order to identify the greenspace and building characteristics that might be suitable for further investigation and modelling. GIS files were derived from several sources, as shown in Table 4-2.
Table 4-2 – GIS Data Files and Sources

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Data Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban morphology types</td>
<td>Adaptation Strategies for Climate Change in the Urban Environment (ASCCUE) project (Lindley et al., 2006; Gill et al., 2008)</td>
</tr>
<tr>
<td>Building heights</td>
<td>Cities Revealed (2008)</td>
</tr>
<tr>
<td>Building activity types for commercial buildings</td>
<td>Sustainable Cities Options for Responding to Climate Change Impacts and Outcomes (SCORCHIO) project (EPSRC Grant Ref EP/E017428/1)</td>
</tr>
<tr>
<td>Surface temperature (originally 60 m grid, reprocessed to 30 m)</td>
<td>Landsat 7 ETM for 5th June 2007 (NASA, 2007)</td>
</tr>
<tr>
<td>Greenspace types for the Manchester Local Authority</td>
<td>Manchester City Council City Wide Open Spaces, Sport &amp; Recreation Study (PMP, 2009)</td>
</tr>
<tr>
<td>Tree canopy cover for the Manchester Local Authority</td>
<td>Red Rose Forest (2009), based on aerial photography from 2005-2006 and OS MasterMap, with methods detailed in Senior (2007)</td>
</tr>
</tbody>
</table>

4.5.2.1 Tree Canopy Cover
Because trees are found to be a good indicator of ecological performance (Whitford et al., 2001), including effects on air, surface and globe temperatures (Akbari et al., 1997; Armson et al., 2012; Levinson, 1997; Shashua-Bar and Hoffman, 2000) and reducing building energy consumption (Akbari, 2002; Akbari et al., 1997; Donovan and Butry, 2009; McPherson and Simpson, 2003) the amount of tree cover was selected as the initial greenspace criteria for selection of study areas.

The tree canopy cover (Savage, 2008), derived from aerial photographs, was received as a single shape file with polygons drawn to represent either individual trees or groups of trees, resulting in a file with more than one hundred thousand polygons. To make the data easier to analyse additional processing was performed to determine total amount of tree cover by area (processing details are in Appendix C). The final output is a raster grid of cell size 30 m x 30 m, with each cell’s value being the total area of tree cover for that cell. The result is shown in Figure 4-2.
Figure 4-2 – Map of Tree Cover Density for Manchester Local Authority
4.5.2.2 Building Height
The building height data was received as a single shapefile dataset from Cities Revealed. On close inspection of the dataset, a few questionable areas emerged, including areas of buildings with zero or very low (<3m) height and areas showing up as tall buildings that were known to be in park or tree-covered areas. As the research needed to clearly identify both the area covered by tree canopy and the area covered by buildings, as well as building height, it was necessary to correct these issues. To clean the dataset, a second buildings dataset was downloaded from OS MasterMap for comparison. Buildings in the Cities Revealed dataset were matched to buildings in MasterMap by selecting polygons that have their centroids in a polygon from MasterMap. When tested for the Manchester local authority, this method was able to assign heights to 84% of buildings, leaving only 16% with no match for height. The buildings with a match were rasterized to a 30 m x 30 m grid (additional processing notes in Appendix C), with each cell’s value being the average building height for that area, shown in Figure 4-3.
Figure 4-3 – Average Building Height for Manchester
©Crown Copyright/database right 2010. An Ordnance Survey/EDINA supplied service. (The gap in buildings going from NW to SE in the southern third of the map is due to a series of golf courses that are north of the M60 motorway.)
Further analysis of building heights was undertaken to create a classification of low, medium, and tall buildings. Figure 4-4 and Figure 4-5 show the building count by height for all buildings and non-dwellings, respectively. If looking at all buildings together, as in Figure 4-4, it appears that nearly all buildings are in the range of 9-10m in height. However, this figure is overwhelmingly dominated by dwellings. If these are removed from the analysis, it becomes clear that non-dwellings have greater variation in height, still dominated by a large cluster of buildings around 10m in height, but with many more buildings in the higher range of 12-18m.

Appendix D shows the calculations, using the Percentile module in Microsoft Access, for determining the low, medium, and tall height classes. A final reclassification was
performed in ArcGIS based on these height classes. The result is shown in Figure 4-6, which allows quick identification of areas of low or tall buildings.

![Figure 4-6 - Map of Building Heights for Manchester Local Authority](image)

### 4.5.2.3 Building Type

Analysis of building activity types in Greater Manchester was undertaken as a means of focusing the research on a particular set of buildings. A dataset of buildings and their activity types was available through the SCORCHIO project (EPSRC Grant Ref EP/E017428/1). The data cover an area larger than Greater Manchester, and therefore, an extract was created for the Manchester Local Authority. A count of buildings by activity type shows that dwellings far outnumber all other building uses. When dwellings are removed from the analysis (Figure 4-7), retail is most common with offices being the second most common. Following these, in nearly equal numbers, are manufacturing, storage and trade distribution, and schools. As previously discussed in Section 4.4, commercial buildings were determined to be the focus for modelling, so this processing narrowed the selection further to office or retail.
Energy usage patterns were compared in IES-VE by using a three-story building design for the month of July for different building activities. This was found to be helpful in understanding the sensitivity of the modelling software to activity type. Results for four different building types are discussed below, with related figures in Appendix D.

Comparison of energy usage patterns between four building activities (education, hospital, domestic, and office) shows somewhat different patterns between building types. For instance, the education building modelled uses the most electricity for lighting during the day, while the hospital uses a constant level throughout day and night. Hospitals show the highest usage for chillers with offices second highest and both showing similar patterns of equipment usage. Schools show about half of the equipment usage as compared to office and hospital. This analysis confirms that building activity type will have a measurable impact on the different types and amounts of energy being used, confirming the need to focus on one or two building types.

One last point for building energy modelling is regarding the issue of deep plan versus shallow plan buildings. Deep plan generally have a depth greater than about 13m and require air conditioning or an atrium (Santamouris and Geros, 2006), whereas shallow plan buildings are less than 13m deep and can be naturally ventilated. This design element impacts significantly on the energy requirements for a building, making it important to consider when selecting buildings for modelling.

![Figure 4-7 – Count of Non-residential Buildings by Activity Type](image-url)
4.5.2.4 Surface Temperature

Using ArcGIS 9.3, an extract of the surface temperature dataset, Landsat 7 ETM for 5th June 2007 (NASA, 2007) was created for Greater Manchester. The dataset was previously converted from ENVI format to Arc GRID format by the GIS Data Officer for School of Environment and Development, University of Manchester. The file showed a wide range of temperatures, from -20.1°C to 35.3°C, which needed further investigation before reclassing the data into low, medium, and high temperature categories. A histogram of the data found that the over 96% of pixels were in the range of 14.3°C to 29.7°C, so these values were chosen as lower and upper limits for the data and the remaining pixels were set to a value of “no data” in order to exclude them from further analysis. The remaining pixels, when viewed as a histogram, reveal a bimodal dataset, with peaks at approximately 19.6°C and 24.1°C and a mean of 21.1°C.

The dataset was further reclassed into low, medium, and high temperatures using standard deviations (std dev) – the mean +/- 1 std dev representing the medium range of temperatures (18.1°C-24.1°C), temperatures <1 std dev (<18.1°C) being low, and temperatures >1 std dev (>24.1°C) being high. The result is shown below in Figure 4-8.

![Map of Surface Temperatures in Greater Manchester for 5th June 2007](image)

Figure 4-8 – Map of Surface Temperatures in Greater Manchester for 5th June 2007
4.5.3 GIS Processing for Site Selection

Following the initial preparation of datasets, a series of overlays and calculations using the datasets were used to generate potential study areas based on building and surrounding characteristics. A matrix of greenspace, surface and building characteristics (Table 4-3) was developed and datasets were combined or overlaid in order to find areas that matched the selected criteria.

Table 4-3 – Criteria for Selecting Case Study Areas

<table>
<thead>
<tr>
<th>Amount of Tree Canopy Cover</th>
<th>Building Classification Type and (Height)</th>
<th>Surface Temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Low</td>
<td>• Retail and Office (Low)</td>
<td>• Low</td>
</tr>
<tr>
<td>• Medium</td>
<td>• Retail and Office (Medium)</td>
<td>• Medium</td>
</tr>
<tr>
<td>• High</td>
<td>• Retail and Office (Tall)</td>
<td>• High</td>
</tr>
<tr>
<td></td>
<td>• Residential (Low)</td>
<td></td>
</tr>
</tbody>
</table>

First, areas were selected by level of tree cover (low, medium, or high), and were then overlaid with each category of surface temperature, in turn (again, low, medium, then high). The result was a series of boolean (0 and 1 values) rasters, with a value of 1 for areas that met the selected tree cover and temperature combination. An example of this process is shown in Figure 4-9.

Figure 4-9 – Areas of Low Tree Cover and High Surface Temperature in Manchester

The second step was to select the desired building types (first retail and then office) and overlay these with the generalized building height raster in order to select areas with the desired building type and height. This again resulted in a raster grid showing
areas of the correct building type together with height class. An example is shown in Figure 4-10.

A matrix of greenspace, surface and building characteristics was developed in order to classify areas by a neighbourhood typology. Datasets were then overlaid in order to find areas that matched the selected criteria. Table 4-4 shows the resulting typologies and estimated area for each. Although other combinations of tree cover and surface temperature were investigated, such as high tree cover and low surface temperature, they were either not found, or only in very small areas, in combination with the selected buildings.

<table>
<thead>
<tr>
<th>Surface Characteristics</th>
<th>Building Classification (Type and Height)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tree Cover</td>
<td>Surface Temperature</td>
</tr>
<tr>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Medium</td>
<td>Medium</td>
</tr>
</tbody>
</table>

After digitising candidate areas representing the required combination of characteristics, five study areas were selected that comprise a combination of retail, office, and residential buildings surrounded by differing tree cover and surface
temperature characteristics from remote sensing. Locations of selected study sites are shown in Figure 4-11. The combination of typologies (from Table 4-4) for all sites is:

1. Manchester CBD – Type II and Type IV;
2. Manchester University/Brunswick – Type III and Type VII;
3. Fallowfield – Type I and Type VI;
4. Sharston – Type I; and
5. Wythenshawe – Type V and Type VIII.

![Figure 4-11 –Study Areas Resulting from GIS Analysis](image-url)
The main limitation of the analysis conducted is that the tree canopy cover is for the Manchester Local Authority only, which has limited the bulk of the analysis to this area. A number of sites in Salford were also selected initially based on the mix of buildings and surface temperatures but were reconsidered after assessing the amount of tree cover. The analysis did not yield areas of high tree cover in relation to the selected building types, as would be expected, considering that areas of high tree cover are most likely to be parks or completely natural spaces.

Following the selection of the five study areas described above, the list was further narrowed to select two areas for detailed microclimate modelling in ENVI-met. The Manchester CBD was selected for its mix of medium and tall retail and commercial buildings combined with low tree cover and relatively high surface temperatures. This area was selected as being most lacking in greenspace, and therefore, a useful modelling study for greenspace additions. In contrast, the Wythenshawe area, with its mix of retail, commercial, and residential buildings combined with medium tree cover and medium surface temperatures, was selected as the most suburban area with the most existing greenspace.

Figure 4-12 shows an overhead view of the Manchester CBD area from Google Earth and Figure 4-13 shows an ArcMap 9.3 graphic image that was used for digitizing the area in ENVI-met. Percentages of buildings and tree canopy for the areas were estimated in ArcMap 9.3, while total greenspace for the area was estimated using colour pixel analysis in Adobe Photoshop®CS2.

Building and greenspace percentages for Manchester CBD are estimated as:

- Buildings – 36%;
- Greenspace – 3% (tree canopy cover is 1% of this);
- Roads, Pavements, Parking – 61%.
Figure 4-12 – Google Image of City Centre Study Area

Figure 4-13 – Manchester CBD Study Area

Figure 4-14 is a Google image of the Wythenshawe study area, while Figure 4-15 is the ArcMap image used for digitising the study area in ENVI-met. Building and greenspace percentages for Wythenshawe are estimated as:

- Buildings – 23%;
- Greenspace – 20% (tree canopy cover is 8% of this);
- Roads, Pavements, and Parking – 57%.
Figure 4-14– Google Image of Wythenshawe Study Area
(iButton 31 – 16 Poundswick; iButton 32 – 64 Simonsway, iButton 33 – 8 Rowlands Way; iButton 34 – 56 Brownley Rd)

Figure 4-15 – South Manchester Suburban Study Area (Wythenshawe)
Comparing the composition of the two study areas it can be see that, while they are similar in their percentages of flat paved areas (roads, parking, and pavements), they are quite different in their ratio of buildings to greenspace.

### 4.5.4 Selection of Greenspace Scenarios

After selecting sites for investigation, analysis was undertaken to identify greenspace types and scenarios for modelling.

Table 4-5 provides a summary of the greenspace audit undertaken by Manchester City Council, with a total of 216 plots designated as greenspace and categorised according to the Planning Policy Guidance (PPG17) (Department for Communities and Local Government, 2002) statement.

<table>
<thead>
<tr>
<th>Greenspace Type (PPG17)</th>
<th>Number of Plots</th>
<th>Minimum Area</th>
<th>Maximum Area</th>
<th>Average Area per Plot</th>
<th>Total Area for all Plots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allotments</td>
<td>40</td>
<td>0.05</td>
<td>6.78</td>
<td>1.46</td>
<td>58.69</td>
</tr>
<tr>
<td>Indoor sports facilities</td>
<td>19</td>
<td>0.08</td>
<td>1.05</td>
<td>0.32</td>
<td>6.26</td>
</tr>
<tr>
<td>Natural and semi-natural</td>
<td>30</td>
<td>0.26</td>
<td>52.68</td>
<td>10.80</td>
<td>324.28</td>
</tr>
<tr>
<td>Outdoor sports facilities</td>
<td>13</td>
<td>0.86</td>
<td>33.57</td>
<td>7.59</td>
<td>98.66</td>
</tr>
<tr>
<td>Parks and gardens</td>
<td>107</td>
<td>0.08</td>
<td>248.46</td>
<td>7.80</td>
<td>834.14</td>
</tr>
<tr>
<td>Provision for children</td>
<td>6</td>
<td>0.01</td>
<td>0.08</td>
<td>0.06</td>
<td>0.35</td>
</tr>
<tr>
<td>Provision for teenagers</td>
<td>1</td>
<td>5.54</td>
<td>5.54</td>
<td>5.54</td>
<td>5.54</td>
</tr>
</tbody>
</table>

The greenspace audit shows that parks and gardens are the most prevalent type of greenspace, with allotments and natural/semi-natural spaces as second and third most common. Although less numerous, the natural/semi-natural spaces have a larger average area (by about 30,000 square metres) per plot than parks and gardens, but the total area of all parks and gardens is more than double that of natural/semi-natural.

While these type of data are helpful as a first step in understanding the area covered and uses of greenspace, they do not provide an understanding of the green structures that are an integral part of the urban fabric. Therefore, the research required additional detail on the types, sizes, and characteristics of greenspace.

One important development for this research was a separate “Plants” database tailored to the Manchester area. On examining the standard plants and Leaf Area Density (LAD) profiles supplied with ENVI-met, they were found not to be very comparable to
local plants and trees. Given that a major aim of this research is to compare the microclimatic effects of differing types of vegetation, the plant profiles are considered to be very important and should be as realistic as possible. A useful starting point is to look carefully at the vegetation that is currently in use or planned for use in the study areas. This is helpful for constructing a set of appropriate greenspace characteristics to use as the basis for designing greenspace scenarios and providing the ENVI-Met vegetation profile inputs. While trees are not the only greenspace being investigated, they are a good ecological indicator (Whitford et al., 2001) and provide a starting point for characterising vegetation. For Manchester, a list of species recently planted was supplied by Red Rose Forest (Stringer, 2010). This was especially useful as it describes a portion of the future tree canopy for Manchester.

Additionally, field surveys were undertaken in study areas to identify the most common types of trees and shrubs currently growing. The two sources were then generalised into categories of vegetation based on the height, shape, leaf type, and leafing period. This categorisation is similar to previous research that has investigated the microclimate effects of trees (McPherson and Simpson, 1995). Based on these characteristics, greenspace categories were defined as shown in Table 4-6. These categories also correspond to the new vegetation profiles developed in ENVI-met.
**Table 4-6 – Greenspace Categories for Microclimate Modelling**

<table>
<thead>
<tr>
<th>Greenspace Type</th>
<th>Max Height</th>
<th>Shape</th>
<th>Example Species Recently Planted by Red Rose Forest&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Example Species from Field Surveys</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newly Planted (small) Trees - Deciduous</td>
<td>5 m</td>
<td>Rounded/ Broadly Rounded</td>
<td>Prunus subhirtella autumnalis (Autumn Cherry)</td>
<td>Acer campestre (Field Maple)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Robinia pseudo umbraculifera (False Acacia)</td>
<td>Aesculus hippocastanum (Horse-chestnut)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Tilia mongolica (Mongolian Lime)</td>
<td>Tilia mongolica (Mongolian Lime)</td>
</tr>
<tr>
<td>Medium Trees - Deciduous</td>
<td>10-15 m</td>
<td>Narrow or Conical</td>
<td>Betula albosinensis Fascination (Chinese Red Birch)</td>
<td>Betula pendula (Silver Birch)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sorbus aucuparia Cardinal Royal (Cardinal Royal/Rowan)</td>
<td>Prunus padus (Bird Cherry)</td>
</tr>
<tr>
<td>Mature Trees (large) - Deciduous</td>
<td>20 m+</td>
<td>Rounded/ Broadly Rounded</td>
<td>Acer campestre (Field Maple)</td>
<td>Acer campestre (Field Maple)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Acer platanoides Globosum (Norway Maple)</td>
<td>Acer pseudoplatanus (Sycamore)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Norway Maple)</td>
<td>Quercus robur (English Oak)</td>
</tr>
<tr>
<td>Shrubs/Hedges</td>
<td>15 m</td>
<td>Open spreading</td>
<td>Crataegus monogyna Stricta (Hawthorn)</td>
<td>Crataegus monogyna (Hawthorn)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Crataegus laevigata Pauls Scarlet (Midland Hawthorn)</td>
<td>Ligustrum japonicum (Privet)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ligustrum japonicum (Privet)</td>
<td></td>
</tr>
<tr>
<td>Grass, mown</td>
<td>0.1 m</td>
<td>Low/Flat</td>
<td>n/a</td>
<td>Varied</td>
</tr>
<tr>
<td>Green Roof</td>
<td>Varied</td>
<td>Low/Flat</td>
<td>n/a</td>
<td>Varied</td>
</tr>
</tbody>
</table>

Considering the species identified, research on LAI values found a very useful database for comparison (Scurlock et al., 2001) and new LAD profiles were calculated based on the empirical relationship developed by Lalic and Mihailovic (2004). Additions to the ENVI-met plants database included the following plant types and heights:

Mown grass (10 cm), Silver birch (20 m), Pine (10 m), Scots pine (20 m), English oak (2m, 10m, 20m), Maple Sycamore (2m, 10m, 20m, 30m), and Hawthorn Hedge (4m).

<sup>1</sup> Other trees planted but not included in the table were: Juneberry, Erman’s Birch, Cornelian
For similar reasons, a new soil profile of Loam/Clay was added to the Soils Database as this is the dominant soil type for the area, based on the Land Information System, Soilscape Database developed by Cranfield University (Farewell, 2010).

Following the categorisation of greenspace, modelling scenarios were developed in which only the greenspace type and amount were changed. As a control scenario, each study area was initially modelled with existing tree and other vegetative cover as a base case. Then the following scenarios compared the effects of using differing amounts and types of greenspace:

1. Existing greenspace configuration as a base model (Base), calibrated with field data (discussed in 4.6);
2. No greenspace, in which all greenspace is replaced with asphalt, to determine the most extreme non-green case;
3. All existing greenspace replaced with grass only;
4. Base +5% newly planted trees;
5. Base +5% mature trees (mix of oak, maple, and silver birch);
6. Base +5% shrubs/hedges; and
7. Base + largest building fitted with green roof.

These modelling scenarios were selected based on realistic and achievable greening interventions that could be applied to all study areas. The percentage of greenspace added in these scenarios is a proportion of the total land surface area (not as a percentage of existing greenspace). This method allows a more straightforward comparison between study areas as it does not rely on making a calculation from the existing percentage of green cover.

While a recent study on greening in the Oxford Road Corridor proposed increasing total greenspace to 34% (Cavan and Kazmierczak, 2011), the scenario was described as a “deep green” option, covering a much larger area than the study areas in this research and greening all flat roofs in addition to 50% of car parks and 30% of roads. The addition of 5% selected here was determined to be a realistic addition that would cause little disruption to the existing urban fabric of buildings, roads, and paths and could be applied across study areas, high green (Wythenshawe) and low green (Manchester CBD), for comparison.

4.6 Monitoring for Model Validation

As discussed in section 4.5.2, study areas were selected based on the combination of building type and tree cover. The selected areas also served as field study areas for monitoring and in-depth characterisation of the existing greenspace. iButton air temperature sensors and radiation shields (Cheung et al., 2010) were placed at a
height of 4m in selected locations on the 13th July, 2010 (except in the CBD, where five sensors were already in place from related research projects). Figures 4-16 and 4-17 show the radiation shield and the placement of the iButton onto a metal hook that hangs inside the shield. The iButton sensors selected were the Maxim DS1922L temperature logging devices. Sensors were calibrated against a certified sensor (following procedures described in Cheung (2011)) and set to take readings every half hour, at a resolution of 0.0625 °C. iButton data were collected approximately once per quarter for a period of one year.

The iButton data served two purposes. First, the sensors provided empirical data for comparing air temperatures in areas with differing amounts of greenspace. And, most importantly, the data allowed calibration of the ENVI-met model, as setting receptors in the model that corresponded to monitoring points allowed validation of the modelling results. iButton results and their use for model calibration are discussed in detail in Chapters 5 and 6, while limitations to iButton measurement are discussed in Appendix F.

4.7 Conclusions

Chapter 4 began with a discussion of potential methods and approaches for determining impacts of greenspace on building energy consumption. It presented a rationale for selecting modelling as the primary means of investigation, along with the reasons for selection of ENVI-met and IES-VE as the specific software tools.

The second half of the chapter provided the detailed methods for selecting case study areas. The method for selecting study areas was a thorough GIS analysis in ArcGIS 9.3, selecting neighbourhoods based on classification of tree cover, building type and
height, and surface temperature. The chapter also presented a rationale for classifying greenspace types to be studied. The final result was a selection of five study areas for monitoring and further narrowed to two study areas for detailed modelling.
5 Analysis of iButton Air Temperature Data

While the previous chapter provided details of the methods used in the research, this chapter explores the data collected from iButtons as mentioned in Chapter 4.6. While the iButtons were initially envisaged solely as a tool for validation and calibration of the micro-climate model ENVI-met, the data acquired were further explored for the relationship between air temperatures, greenspace, and building energy consumption. This served three purposes:

1. to select an appropriate summer modelling day based on iButton data results;
2. to utilise the data for model calibration and validation (further discussed in Chapter 6); and
3. to explore the iButton data to gain an understanding of selected air temperature indices and possible relationships to building energy demand.

This chapter will attempt to answer the questions:

- Which day/days might yield the most useful modelling scenarios for microclimate; and
- Which is the most appropriate air temperature indicator for building energy performance?

5.1 iButton Data Analysis for July and August (Summer) 2010

For the study areas selected for this research, as shown in Figure 5-1, iButton temperature sensors (Table 5-1) were placed in selected locations on the 13th July, 2010 (discussed in section 4.5.4). The first round of data collection took place on 26th August, 2010, approximately 6 weeks after the sensors were installed. Generally, the sensors were checked about once every three months in order to prevent overwriting of data. This section summarizes the results from the initial summer data collection and provides the methods of analysis for later rounds of data collection. Winter data analysis is treated separately in Section 5.2 in order to compare summer and winter seasonal differences.
### Table 5-1 – iButton Numbers and Description of Location

<table>
<thead>
<tr>
<th>Study Area</th>
<th>iButton Number</th>
<th>Location Description</th>
<th>Existing Greenspace Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wythenshawe</td>
<td>31, 32, 33, 34</td>
<td>Suburban area of retail, commercial, and community services with surrounding residential</td>
<td>20</td>
</tr>
<tr>
<td>Sharston</td>
<td>35, 36, 37, 38</td>
<td>Industrial estate of low, medium industrial, commercial buildings, but very near to large golf courses</td>
<td>7</td>
</tr>
<tr>
<td>Fallowfield</td>
<td>30, 39, 41, 42</td>
<td>Mixed retail and residential area, approximately midway between City Centre and the suburban Wythenshawe site</td>
<td>25</td>
</tr>
<tr>
<td>University/Brunswick</td>
<td>14, 15, 43, 44</td>
<td>University campus with medium height buildings, low tree cover and residential area of Brunswick</td>
<td>16</td>
</tr>
<tr>
<td>City Centre (CBD)</td>
<td>6, 7, 11, 32C, 64</td>
<td>Manchester City Centre with tall retail and commercial buildings, low tree cover</td>
<td>3</td>
</tr>
</tbody>
</table>

2 Sensor 31 had not started at the time of the August data collection; was reset during this initial collection.
3 Sensor 36 was found near the selected site, but had been removed and crushed.
4 iButton data for sensors 6, 7, 11, 14, 15, 32C, and 64 from CoPSE project, courtesy of Henry Cheung
5.1.1 Average Daily Temperatures

Initially, average daily temperatures were investigated in order to identify warm days. Warm days, defined as days with a daily average of 2°C or more above the mean July/August typical daily average of 16.5°C (based on 1981-2010 averages for
Manchester Airport weather station) (MetOffice, 2011a), were selected as an indicator of days when discomfort within buildings is likely to be greatest. As shown in Figure 5-2 and Figure 5-3, temperatures for July and August varied widely from day to day. Overall, a minimum half-hourly temperature of 8.08 °C was recorded on 27th August with a maximum half-hourly temperature of 25.75 °C on 19th July. Within a two-day period in mid-July (17th-19th), the average daily temperature increased from approximately 14.5 to 19.5 °C, falling again to 15 °C over the following three days. August average temperatures show a similar variability between the 13th and 21st. Overall, July was wetter than normal with nearly 166 mm of rain (192% above average for Northwest England and Northern Wales) and air temperature at 0.7 °C above average. August was wetter than normal (83 mm, 75% above average), but also 0.4 °C cooler, which was the coolest since 1993 (Met Office, 2010).

![Average Daily Temperature by Sensor for July](image)

**Figure 5-2 – Average Daily Temperature by Sensor for July**
5.1.2 Maximum Temperatures and Date Selected for Modelling

While daily average temperature indicates July 19th as the warmest day for the July and August monitoring, it is also important to identify a day with good UHI conditions, leading to higher variability between sensor locations. While average temperatures are important for considering energy consumption over the whole day, maximum temperatures are important for analysing peak demand and potential for air conditioning usage. In analysing the temperature records, it is more likely that days of higher maximum temperature with clear and calm conditions would reveal greater temperature differences, as these are the conditions under which the UHI effect is greatest (Oke, 1982). Daily maximum iButton recordings show 15 days with a standard deviation higher than 0.5. Dates of highest maxima which also show high variability between iButton locations include: 19th-20th July, 15th and 20th August.

Figures 5.4-5.6 highlight the differing conditions for the dates of highest maximums and variability between sensors. In selecting a date for modelling, the wind speed and solar radiation were also considered. Given that July and August wind speeds for Manchester are typically 4-5 m/s and that completely cloud-free days are rare (MetOffice, 2011a), the 19th July was selected as a date which is warm but is also typical in terms of wind speed and incoming solar radiation. Cloud cover on 19th July was low for the morning and early afternoon, but increasing after 3 pm.
Figure 5-4 – Maximum Temperatures for Selected Warm Days

Figure 5-5 – Wind Speed for Selected Warm Days
5.1.3 Area of Tree Canopy and Relationship with Air Temperature Indices

In addition to selecting a day for modelling comparison, the iButton data allowed analysis of various air temperature indices and the potential relationship to tree canopy cover. Although a detailed GIS dataset of vegetation types was not available, a high quality dataset for tree canopy cover (described in 4.5.2.1), was available as an indicator of greenspace. Of the greenspace configurations tested, (Section 4.5.4) it is expected that the mature trees scenario will have the strongest correlation with air and surface temperatures. Total area of tree canopy cover was calculated for five different distances (10m, 20m, 25m, 50m, and 100m) from each sensor. Distances were selected starting from the largest distance (100m) (Shashua-Bar and Hoffman, 2000) that might reasonably have an effect on air temperature at a particular point and then testing half of that distance (50m) and so forth down to 10m. The 20m distance was tested after some results found a relationship at 25m, but not at 10m. While some studies have found air temperature effects at larger distances, for instance 1.5 times the width of the nearest park, or up to 1100 m (Upmanis et al., 1998), such studies are investigating cooling effects of parks. Given that none of the sensors in this study are located near to a large urban park, it was decided to investigate more localised effects. Table 5-2 shows the amount of greenspace within the given radius of each sensor while Figure 5-7 shows an example of GIS processing for area of tree canopy.
Table 5-2 – Area of Tree Canopy within the Vicinity of Each Sensor

<table>
<thead>
<tr>
<th>Study Area</th>
<th>iButton No</th>
<th>10m</th>
<th>20m</th>
<th>25m</th>
<th>50m</th>
<th>100m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wythenshawe</td>
<td>30</td>
<td>0</td>
<td>193</td>
<td>369</td>
<td>908</td>
<td>2250</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>0</td>
<td>37</td>
<td>116</td>
<td>431</td>
<td>3825</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>8</td>
<td>180</td>
<td>273</td>
<td>744</td>
<td>1564</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>182</td>
<td>475</td>
<td>576</td>
<td>1542</td>
<td>4198</td>
</tr>
<tr>
<td>Fallowfield</td>
<td>35</td>
<td>190</td>
<td>488</td>
<td>599</td>
<td>1285</td>
<td>2693</td>
</tr>
<tr>
<td></td>
<td>37</td>
<td>45</td>
<td>165</td>
<td>185</td>
<td>235</td>
<td>1360</td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>1</td>
<td>175</td>
<td>289</td>
<td>600</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>39</td>
<td>119</td>
<td>354</td>
<td>515</td>
<td>1341</td>
<td>2516</td>
</tr>
<tr>
<td></td>
<td>41</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>608</td>
<td>400</td>
</tr>
<tr>
<td>University/ Brunswick</td>
<td>42</td>
<td>7</td>
<td>15</td>
<td>15</td>
<td>74</td>
<td>3693</td>
</tr>
<tr>
<td></td>
<td>43</td>
<td>0</td>
<td>57</td>
<td>68</td>
<td>519</td>
<td>5154</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>65</td>
<td>277</td>
<td>496</td>
<td>2228</td>
<td>4778</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>1</td>
<td>108</td>
<td>186</td>
<td>736</td>
<td>2448</td>
</tr>
<tr>
<td>City Centre</td>
<td>64</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>157</td>
<td>685</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>822</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>536</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>21</td>
<td>268</td>
</tr>
<tr>
<td></td>
<td>32C</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>267</td>
<td>1635</td>
</tr>
</tbody>
</table>

Figure 5-7 – Example of GIS Analysis to Calculate Area of Tree Canopy around Each Sensor (at 10, 20, 25, 50 and 100 m)
First, average daily temperatures were calculated for each iButton. For a few selected days that showed higher than average variance among iButtons, the daily average was tested by linear regression for correlation with area of tree canopy cover at each of the distances noted above. No correlations were identified for either the selected daily average temperatures or July and August monthly average temperatures. However, this is expected as the daily or monthly average masks variability that might occur at particular times of day.

Likewise, selected days of maximum temperatures and monthly average maximums for July and August were tested for correlation with tree canopy cover at all distances. Again, no correlations were identified.

A third index, the Urban Heat Island Index (UHII) and its relationship with tree canopy cover was also investigated. UHII is calculated as the temperature difference between each iButton and a rural reference (Woodford station, in this study, approximately 18 km South of Manchester city centre, Latitude: 53.333 °N, Longitude, -2.15 °W). Analysis of the UHII shows that some locations are consistently warmer than others, with a relatively larger number of hours with temperatures above the rural reference.

UHII was calculated for each half-hourly reading in July and August and analysis was undertaken to determine whether temperature variations are correlated with the amount of greenspace in the vicinity of each sensor.

For each iButton, a total count of half-hourly UHII within a given interval was calculated (eg, number of times that the UHII was >1 and up to 2 °C). The results were then grouped by study area, with a percentage of total readings calculated per study area. The results are shown below in Figure 5-8, with study areas arranged from most suburban (Wythenshawe) to most urban (City Centre). The analysis demonstrates that the more suburban areas have a greater frequency of readings in the range of 0-1°C, while the most urban area (City Centre) most frequently records UHII in the 1-2°C and also shows nearly twice as many readings as Wythenshawe in the 2-3 °C range. While the order here does not strictly correlate with green cover (Sharston, Fallowfield, and University have similar percentages of tree cover), the areas do follow a pattern of increasing urbanisation in terms of building density and height.
Following the grouping by study area, a linear regression analysis then determined whether or not area of tree cover is a predictor for UHII exceeding a given threshold. For this analysis, a total count of half-hourly UHII exceeding a certain threshold was calculated (e.g. number of times that the sensor exceeded a UHII of 2 °C) for each iButton. The table of resulting regression values ($R^2$) and a graph (Figure 5-9) for each combination of canopy area and UHII threshold are shown below.

**Table 5-3 – Regression Values ($R^2$) for Tree Canopy within Given Distance and UHII**

(Shaded cells are significant relationships, $p<0.05$)

<table>
<thead>
<tr>
<th>UHII Threshold</th>
<th>Distance for Calculating Area of Tree Cover (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>UHII&gt;2</td>
<td>0.1781</td>
</tr>
<tr>
<td>UHII&gt;3</td>
<td>0.2471</td>
</tr>
<tr>
<td>UHII&gt;4</td>
<td>0.2496</td>
</tr>
<tr>
<td>UHII&gt;5</td>
<td>0.1671</td>
</tr>
</tbody>
</table>
Figure 5-9 – Regression Results for Area of Tree Canopy Cover as Predictor of UHII Frequency

While these results show that area of tree canopy cover is not a strong predictor of UHII, they also reveal that the $R^2$ value differs by more than two-fold, depending on the distance at which tree cover is calculated and the threshold value used for measuring UHII. The results demonstrate that the strongest relationship can be found when the area of tree canopy is calculated at a distance of 20-25m and for UHII thresholds exceeding 3 or 4 ($p<0.05$). Calculating area of tree cover too near to the sensor (10m) often does not show enough tree cover to be measurable, while calculating too far (>100m) (Shashua-Bar and Hoffman, 2000) includes tree cover that probably has no effect on the point in question. Also, using a UHII that is too high above the average UHII (average UHII for July and August is 1.0-1.25, in this research) does not reveal a relationship. This result highlights the importance of considering the distance from which greenspace is measured when analysing greenspace and air temperature relationships.

5.1.3.1 Grouping by Urban Morphology Type
Given the rather weak relationships found in using the entire dataset, one idea that occurred was to group the iButton results by urban morphology characteristics. In doing this, many of the confounding factors, such as building heights, building density, and traffic patterns can be reduced, possibly revealing stronger relationships between area of green cover and UHII frequency. First, the five iButtons in the City Centre were grouped and regressions were again tested for each combination of tree cover and UHII threshold. In this case, the strongest relationship ($R^2=0.80$, $p<0.05$) was found for the frequency of UHII>4 and the area of tree canopy within 100m (Figure 5-10). Using
this relationship, it is estimated that a 5% increase in canopy cover leads to 10 fewer hours per month with UHII>4.

![Regression Results for City Centre](image)

**Figure 5-10 – Summer Regression Results for City Centre, UHII>4 and Tree Canopy within 100 m**

Secondly, iButtons for the study areas of Fallowfield and Wythenshawe were grouped into one “suburban” group (n=7) as they are of similar morphology and either group alone did not contain enough points for generating significant results. For this suburban group, the strongest relationship found was for UHII>3 and tree cover within 50 m (R²=0.6162, p<0.05). Using this relationship, it is estimated that each 5% increase in canopy cover leads to 3 fewer hours with UHII>3 per month. For building energy, this translates to 3 fewer cooling degree hours, or 2.1% savings.

These results highlight the role of urban morphology in determining the particular relationship that might exist between greenspace and air temperatures. The results imply that greenspace has a role in lowering the number of hours that a location experiences more extreme values of UHI Intensity. It is reasonable that a City Centre might show stronger correlations for area of green within a larger distance (100m) as there is so little green overall (only 3% average) in this area. In contrast, suburban areas will have more tree canopy within a shorter distance (50m) and also generally experience lower overall values of UHII, thus the stronger correlation with UHII>3 for suburban.
5.2 iButton Data Analysis for December (Winter) 2010

For the study areas selected for this research, iButton data were collected again in early December and then a third time in late March in order to investigate seasonal differences. This section analyses the December data and assesses differences between summer and winter. The analysis follows on from the methods used in the August data analysis in Section 5.1. Table 5-4 summarizes the status of iButtons that were checked in December, with data for the City Centre (iButtons 6, 7, 11, 14, 15, 32C and 64) provided through research by Henry Cheung (Cheung, 2011).
Table 5-4 – iButton Numbers and Description of Location

<table>
<thead>
<tr>
<th>Study Area</th>
<th>iButton Number</th>
<th>Location Description</th>
<th>Lamppost Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wythenshawe</td>
<td>31°</td>
<td>Simonsway</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>32°</td>
<td>Poundswick, Wythenshawe</td>
<td></td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>Rowlands Way</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>Brownley Rd near Crawley Ave</td>
<td>55</td>
</tr>
<tr>
<td>Sharston</td>
<td>35°</td>
<td>Leestone Rd</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>36°</td>
<td>Leestone Rd</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>37</td>
<td>Harper Rd</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>Harper Rd</td>
<td>8</td>
</tr>
<tr>
<td>Fallowfield</td>
<td>30°</td>
<td>Intersection Birchfields Rd/Moseley Rd</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>39</td>
<td>Birchfields Rd</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>41</td>
<td>Kingsway Ave</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>42°</td>
<td>Moseley Rd</td>
<td>21</td>
</tr>
<tr>
<td>University/Brunswick</td>
<td>43</td>
<td>Whitekirk Close</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>44</td>
<td>Brunswick St</td>
<td>25</td>
</tr>
</tbody>
</table>

5.2.1 Average Daily Temperatures September 2010 – March 2011

Initially, average daily temperatures were compared across sensors to investigate temperature patterns for September 2010 – March 2011. As shown in Figure 5-12, temperatures for September - March, while often consistent across sensors, varied widely from day to day. A strong cooling trend occurred in November, with temperatures falling from approximately 15 °C on the 4th November to -4°C by the 28th. Temperatures remained cold throughout December with approximately half the days showing an average temperature below freezing. January and February are highly variable, while March shows a warming trend. Data collected during this period between July 2010 and March 2011 reflect the unusually cold winter conditions reported throughout the UK from December through February, with December, in particular, being the coldest for 100 years (MetOffice, 2011c). This was also followed by an unusually warm and dry spring, with an average temperature of 10.2 °C, equally warm to 1893, the warmest on record (MetOffice, 2011b).

---

5 Sensor 31 had not started at the time of the August data collection; was reset during the initial collection. Data was collected in December, but the sensor was missing in March. Shield and hook were in place and the bottom door of the shield was closed, so it may have been blown out by high winds.

6 Data was collected for December, but the sensor was found on the ground under the shield. Based on temperature readings, it appears to have fallen out in early February.

7 Sensor 35 was collected in December, but wedged into the shield and could not be removed for the March collection.

8 Sensor 36, in the August collection was found near the selected site, but had been removed and crushed. It was replaced at that time, but missing again in the December collection; not replaced.

9 Sensor 30 was missing both the iButton and hook

10 Sensor 42 was missing
Throughout the 6-month period, some large temperature changes occurred over a period of a few days. For instance, in just 3 days in September (22<sup>nd</sup> – 25<sup>th</sup>), the daily average dropped from 16.5 °C to 9.5 °C. A similar drop occurs again between the 10<sup>th</sup> and 13<sup>th</sup> October. Similar strong warming and cooling periods occurred throughout December, January, and February. December was selected for further investigation as the coldest month during the winter collection period.

5.2.2 Area of Tree Canopy and UHII Variation

During December, a few days were found to have high UHI indices for portions of the day. These days (3<sup>rd</sup>, 19<sup>th</sup>, 20<sup>th</sup>, 23<sup>rd</sup>, and 24<sup>th</sup> December) show unusually cold rural reference temperatures, as low as -14.6 °C on 20<sup>th</sup> December, and UHII up to 11.2 °C. Figure 5-13 explores the pattern of UHII for the 19<sup>th</sup> and 20<sup>th</sup> December, comparing the most suburban site to the most urban site, and also showing the cloud cover for the same period. The data shows a general pattern of very high UHII for low cloud cover (BADC, 2010) and lowest UHII for both sites when cloud cover is at a maximum.
Following the methods outlined in section 5.1.3, linear regression was again used to test area of canopy cover as a predictor of UHII above a particular threshold. While it is recognized that most of the tree canopy in the study area is deciduous, the area that would be covered by tree canopy in summer can still be used as an indicator of the greenspace surrounding each sensor because it will still be an area of unpaved, natural surfaces. For winter (December), regression results show that area of tree canopy has some correlation with UHII, but at a much shorter distance. For December, the strongest relationships were found for amount of tree canopy measured at 10m and UHII>3 or UHII>5 ($R^2=0.46$ and 0.45, respectively, $p<0.01$) (Figure 5-14 and Figure 5-15).
As with the summer data, the winter analysis was further analysed for correlations within sub-groupings based on urban morphology. Figure 5-16 again shows a general trend towards higher percentages of readings in the upper ranges of UHII with
increasing urbanisation. However, when the results are according to urban and suburban, no significant correlations were found for winter. On first analysis, it appeared that the urban case had a strong correlation for UHII>7 and canopy cover at 100m. However, the statistical analysis did not find the relationship to be significant.

Figure 5-16 – Winter (December) Half-hourly Recordings by Study Area

The December winter data shows a higher maximum UHII of 11.2 °C, compared to 8.7 °C for the July-August period. This is of particular interest for microclimate and building energy comparisons and leads to later analysis (Chapter 8) regarding the trade-offs between additional summer cooling requirements and reduced winter heating requirements for urban areas.

5.3 Conclusions

Chapter 5 analysed air temperature measurements for five study areas in the Manchester local authority, using data collected through iButton temperature sensors from 19 locations. While the majority of studies investigating temperature relationships with greenspace have focused on surface or air temperature in absolute terms, this study investigated several different air temperature indices that might be derived from high temporal resolution datasets. The study also investigated the effect of grouping data by season and by urban morphology.

Based on the results presented in this research, significant correlations could not be found between tree canopy cover and daily average air temperature, maximum temperature, or minimum temperature in summer or winter. However, when analysing the data with respect to the UHII, correlations were found in both seasons.
In summer, the strongest significant correlation for the whole dataset was found for UHII>4 and area of greenspace within 20 m² ($R^2=0.35$, $p<0.05$). When grouping summer data by urban morphology, a strong negative linear relationship was found for the urban case with UHII>5 and area of greenspace within 100 m² ($R^2=0.80$, $p<0.05$). In the summer suburban case, UHII>3 is significantly correlated with area of greenspace within 50 m².

For winter, the strongest correlations were found for the entire dataset, but at a much smaller distance than in the summer case, measured at 10 m and UHII>3 or UHII>5 ($R^2=0.46$ and 0.45, respectively, $p<0.01$). In contrast to summer, when the strongest correlations were found for grouping by urban morphology, no significant correlations were found based on urban morphology in winter.

The results in this chapter demonstrate the importance of selecting an appropriate air temperature indicator (UHII, in this study) and also demonstrate the influence of distance at which canopy area is measured, urban morphology, and season in detecting a relationship between air temperature and area of tree canopy cover. When considering the UHI effect in urban areas, the results demonstrate a reduction in the number of hours at peak summertime UHII, particularly in the urban case, but less influence on winter UHII, thus moderating negative impacts of UHI in the summer while maintaining wintertime benefits.
6 ENVI-met Model Sensitivity and Calibration

6.1 Envi-met Model Sensitivity Testing

The chapter presents the results of model runs that were performed for testing the model’s sensitivity to selected parameters. Due to the long model running times, it was not possible to test all initialisation parameters. However, those parameters that could be changed to meet the specific conditions of the site and day selected for this research were tested. These parameters (discussed in Chapters 3.3.1 and 3.3.2) include wind speed, relative humidity, soil relative humidity, and albedo of walls and roofs, and grid resolution. A testing model was set up with the configuration shown in Figure 6-1 with a total area of 400 m x 400 m, and grid resolution of 4 m x 4 m. Buildings (grey) are 20 m in height and all greenspace is mown grass. Each model was tested for a period of 24 hours modelled time with a starting time of 6 am.

![Model Configuration for Sensitivity Testing](image)

6.1.1 Wind Speed Sensitivity

Figure 6-2 shows the model results for wind speed. The results show that low wind speed (1 m/s) leads to temperatures (modelled as potential temperature, defined as the temperature of an air parcel if compressed or expanded adiabatically to a standard...
pressure, usually 1000 millibars (100 kiloPascals) that are warmer by nearly 2 °C at 6pm, and a slower rate of cooling in the afternoon hours as compared to the base model wind speed of 5 m/s. This difference remains at approximately 2 °C throughout the night. High wind leads to temperatures that are cooler by about 1 °C in the early part of the day, but show smaller differences of approximately 0.5 °C in the 3-6 pm time period, and almost no difference after 9 pm.

![ENVI-met Sensitivity Testing Wind Speed](image)

**Figure 6-2 – ENVI-met Sensitivity to Wind Speed**

### 6.1.2 Relative Humidity Sensitivity

Figure 6-3 shows the results of changing the relative humidity (RH) by +/- 10% from the base model value of 75%. These results show very little effect on temperature for a change of 10% RH. A very small decrease in temperature occurred in the morning and evening for a decrease of 10% RH, and likewise, a very small increase in temperature was found in the morning hours for an increase of 10% RH.
6.1.3 Soil Relative Humidity Sensitivity

As shown in Figure 6-4, changing the soil relative humidity by +/- 20% from the base model value of 50% (50% RH for the upper soil layer, 60% RH for the middle soil layer, and 70% RH for the deeper soil layer) has little effect on temperature. In this particular model, the effect might not be measurable because the only greenspace in the model is mown grass of 10 cm, whereas other types of vegetation with greater evapotranspiration might lead to temperature differences based on availability of soil moisture.

Figure 6-3 – ENVI-met Sensitivity to Relative Humidity
Figure 6.4 – ENVI-met Sensitivity to Soil Relative Humidity

6.1.4 Albedo Sensitivity

As shown in Figure 6-5, the model sensitivity of potential temperature to albedo of walls and roofs is quite low. For the lower albedo of 0.1, the model shows only minor changes from the base model. Interestingly, it shows slighter higher temperatures between 12 pm and 6 pm in the high albedo case.
6.1.5 Grid Size Sensitivity, 4m vs. 8m Grid Resolution

The model’s sensitivity to the grid resolution was compared using a 4 m grid (base model) with an 8 m grid. As shown in Figure 6-6 the model shows somewhat lower temperatures between the hours of 12 pm and 12 am for the lower resolution (8m grid size) model. The temperature differences are very small, around 0.1 °C, in the earlier and later parts of the day, but increase to about 0.3 °C between 7 pm and 10 pm.

![Figure 6-6 – ENVI-met Sensitivity to Grid Resolution](image)

6.1.6 Conclusions on Model Sensitivity

For the parameters tested, the wind speed has the most significant impact on the overall temperatures (higher or lower pattern) and the range of temperatures, with a reduced range of temperatures (less nighttime cooling) at low temperatures. Next, the lower grid resolution has effect of lowering temperatures from about 3:00 pm to midnight, demonstrating that the model should be used in terms of relative comparisons between different scenarios of a base model, but not taken to produce absolute temperatures. The results for RH suggest that small changes in RH (<10%) are unlikely to affect temperature, a result which can be useful when interpreting microclimate changes for use in building energy modelling. One unusual result is that for albedo, which should be investigated further.
6.2 ENVI-met Calibration with iButtons

In this research, it was important to calibrate ENVI-met with field data, as only a few papers are available in the literature (Ali-Toudert and Mayer, 2006; Ali-Toudert et al., 2005; Samaali et al., 2007) to confirm its suitability for comparison with real-world applications. For this research, a total of five areas were selected (see 4.5.3 and Figure 4-11), starting from Manchester city centre and following generally southwards approximately 14 km to an area near Manchester Airport at the urban periphery. The first area in the study to be modelled was Wythenshawe Forum, the most suburban of the five study areas shown in Figure 4-11 (Section 4.6.3). As it is one of the larger areas with approximately 15% retail and office, 8% residential, and 20% greenspace (remaining 57% for roads, parking, and pavements) with a consistent set of iButton sensor data for the 2010 summer, it was chosen for the first modelling area and is presented here as a calibration example (refer to Figure 4-14 and Figure 4-15 for images of the study area).

6.2.1 Model Parameters

Initially, the study area was digitized in ENVI-met with the current configuration of buildings and greenspace. This current configuration was chosen as a starting point in order to calibrate the model as closely as possible to observed air temperatures as determined from the iButton data collection. While the model outputs a large number of parameters – e.g., wind speed, relative humidity, surface temperatures, mean radiant temperature - air temperature is one parameter that is investigated in this research and can be easily monitored throughout the year. Also, surface temperatures can be estimated using total solar radiation data and surface properties such as absorptivity and emissivity. While the main focus of the research is to compare differing greenspace configurations through modelling, this initial comparison to measured air temperatures and calculated surface temperatures provides an important check on the validity of modelling results.

The model date was set to 19\textsuperscript{th} July 2010 as it was not only the warmest study day (maximum daily air temperature of 25.7 °C) for July and August, but also a day with a relatively high UHII, with a difference of 2.48 °C between highest and lowest recorded maximums (as determined in the iButton datasets, Section 5.1.2). For the model date of 19\textsuperscript{th} July, Manchester Ringway recorded a maximum of 24 °C.

Table 6-1 compares the parameters that were changed from the initial run to the final run (only showing parameters that were changed from default values supplied with ENVI-met sample models). Initially, many parameters (e.g., Timing, Dynamical Timesteps and Turbulence) were initialised based on sample model configurations.
provided with ENVI-met, but after further investigation, parameters were chosen based on the site-specific conditions for the study area.

| Table 6-1 - ENVI-met settings, Comparison of Initial to Final Values for Manchester-Wythenshawe Base Model |
|---|---|---|
| Envi-met Model Section | Parameter | Initial Value | Final Value |
| Main Data | Wind Speed | 5 | 5 |
| | Wind Direction | 180: South | 180: South |
| | Roughness Length | 0.1 | 0.5 |
| | Initial Temperature of Atmosphere | 286 | 292 |
| | Relative Humidity | 50 | 75 |
| Timing | Update Surface Data, interval in seconds | 60 | 30 |
| | Update Wind and Turbulence, interval in seconds | 1800 | 900 |
| | Update Radiation and Shadows interval in seconds | 900 | 600 |
| | Update Plant Data, interval in seconds | 600 | 600 |
| LBC Types | LBC for T and q | 1, open | 1, open |
| | LBC for TKE | 2, forced | 1, open |
| Building | Albedo Walls | 0.2 | 0.4 |
| | Albedo Roofs | 0.3 | 0.5 |
| Soil Data | Initial Temperature Upper Layer (0-20 cm) [K] | 286 | 283 |
| | Initial Temperature Middle Layer (20-50 cm) [K] | 288 | 284 |
| | Initial Temperature Deep Layer (> 50 cm) [K] | 290 | 285 |
| | Relative Humidity Upper Layer (0-20 cm) | 50 | 50 |
| | Relative Humidity Middle Layer (20-50 cm) | 60 | 60 |
| | Relative Humidity Deep Layer (below 50 cm) | 60 | 70 |
| Timesteps | Sun height for switching dt(0) | 40 | 30 |
| | Sun height for switching dt(1) | 50 | 50 |
| | Time step (s) for interval 1 dt(0) | 20 | 5 |
| | Time step (s) for interval 2 dt(1) | 10 | 2 |
| | Time step (s) for interval 3 dt(2) | 5 | 1 |

6.2.2 Modelling Calibration Results

6.2.2.1 Air Temperature

Figure 6-7 shows the results of the first model run for the Wythenshawe study area, while Table 6-2 summarizes the air temperature differences and calculates the average temperature difference (absolute values) for the hours shown. In the graph below, hourly differences range from 0.68 °C up to 9.5 °C with the largest difference seen between iButton 33 and its modelled receptor. While this is likely to be in one of the relatively warm areas due to the surrounding buildings and pavings, the modelled point is significantly overestimating the temperature in this area. Moreover, when the modelled air temperatures are compared to the iButton hourly average, the linear regression shows some correlation ($R^2=0.56$), but not a very close agreement.
Figure 6-7 – Graph of Modelled and Measured Air Temperatures for First Iteration in ENVI-met
(Modelled Receptor 2 corresponds to iButton 32, Receptor 3 corresponds to iButton 33 and Receptor 4 to iButton 34; refer to Figure 5-1 for locations)

Table 6-2 – Average Air Temperature Difference and Error between Modelled and Measured, 1st Model – July 19th 2010

<table>
<thead>
<tr>
<th>iButton ID</th>
<th>Temperature Difference (Modelled minus Measured)</th>
<th>Average of Absolute Temperature Differences (9 am – 9 pm)</th>
<th>Standard Error of Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>09:00</td>
<td>12:00</td>
<td>15:00</td>
</tr>
<tr>
<td>32</td>
<td>-1.28</td>
<td>0.16</td>
<td>1.01</td>
</tr>
<tr>
<td>33</td>
<td>0.25</td>
<td>5.93</td>
<td>7.89</td>
</tr>
<tr>
<td>34</td>
<td>-5.16</td>
<td>-4.71</td>
<td>-4.88</td>
</tr>
</tbody>
</table>

Minor changes were made to the configuration between the first and second iterations, mainly to test the effect of timing. The settings for Dynamical Timesteps were changed to 20, 10, and 5 seconds for intervals 1, 2, and 3, respectively. Due to the mix of dark and light-coloured buildings, Albedo of Walls and Roofs were changed to 0.4 and 0.5, respectively. Timing was altered to give longer times between updates (updating surface data every 300 seconds instead of every 60 seconds) in order to determine if the model could run faster, considering that running times for this area can be 4-5 hours per hour of simulation. Changing these timings decreased running time to approximately 3 hours per hour of simulation. However, in the final iteration, the Dynamical Timesteps were reset to 5, 2, and 1 (intervals 1, 2, and 3) as the model became unstable with larger timesteps.
Following the second iteration, additional research was undertaken to determine possible reasons for the large temperature differences between modelled and actual, particularly for iButton 33. A few causes were identified in the ENVI-met documentation (Bruse, 2006). Particularly for larger modelling domains, nesting grids surrounding the model area should be set to a minimum of 3 and empty grids within the model domain were set to 5. Soil humidity was changed from 80% to 70% and upper soil temperature was changed from 288K to 283K, with the middle and lower layers scaled up to 284 and 285, respectively, based on a summer average soil temperature of 10.75 °C, as noted by Gill (2007).

Following an improved temperature pattern, but overall low temperatures in the third iteration, the setting for Initial Temperature of the Atmosphere at 2500 m was investigated. It was found that temperatures will be distributed around this initial temperature, with approximately +5 to +6 °C for daytime and -3 to -5 °C at night (Bruse, 2006). For this simulation, this indicates that the initial temperature should be 290.5 K - 291 K (or 17.5 °C - 18 °C), rather than the 286 K that was used for Iterations 1-3. Sun height for switching from first to second dynamical timestep was set to 30°, compared to 40° for previous runs.

As a further calibration test, the model was run for a simulation period of three days in order to test the evolving temperature patterns in longer model running times. Results from the final set of modelling parameters are shown in Figure 6-8 and Table 6-3, with significant improvements from the previous iterations. Figure 6-8 shows the model temperatures as they evolve over the three-day modelling period, with temperatures converging very well toward measured values by the third day. Temperature differences in the final model average around 0.5 °C for the third day, a much more useful comparison if the model is to be used in making predictions about changes in real situations. Furthermore, comparing hourly average air temperature over the entire study area to average iButton temperatures for the third day, the model shows a very high correlation with measured air temperatures - $R^2$ of 0.94 (p<0.05), on forcing the regression line through the origin (Figure 6-9).
Figure 6-8 - Graph of Modelled and Measured Air Temperatures for Final Iteration of Base Model

Table 6-3 - Average Air Temperature Difference and Error Between Modelled and Measured, Final Iteration – July 19th 2010

<table>
<thead>
<tr>
<th>ib ID</th>
<th>Temperature Difference (Modelled minus Measured)</th>
<th>Average of Absolute Temperature Differences (9 am – 9 pm)</th>
<th>Standard Error of the Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>09:00</td>
<td>12:00</td>
<td>15:00</td>
</tr>
<tr>
<td>32</td>
<td>2.03</td>
<td>0.60</td>
<td>0.49</td>
</tr>
<tr>
<td>33</td>
<td>2.34</td>
<td>0.80</td>
<td>0.77</td>
</tr>
<tr>
<td>34</td>
<td>0.73</td>
<td>0.34</td>
<td>-0.18</td>
</tr>
</tbody>
</table>
Figure 6-9 – Linear Regression of iButton Average Air Temperature with Model Average Air Temperature

6.2.2.2 Surface Temperature
Analysis was also undertaken to validate the modelled surface temperatures against surface temperatures. An approximate measure of surface temperature can be calculated with the sol-air temperature (T_{sol-air}) equation, using data from the nearest weather station (Woodford) with available solar radiation data. The calculation (Equation 2) is solved by an iterative method to resolve the circular reference for T_{sol-air} (Barrett et al., 2002):  

\[ T_{sol-air} = t_0 + (\alpha E_t + \xi L_{sky})/h_c - \sigma T_{sol-air}^4/h_c, \]  

where (Equation 6-1)

- \( t_0 \) = outdoor ambient temperature (BADC, 2010), K
- \( \alpha \) = absorptivity of surface, estimated at 0.8 for weathered asphalt (Barrett et al., 2002)
- \( h_c \) = coefficient of heat transfer by long wave (LW) radiation and convection at outer surface, estimated as 4+4v, where \( v \) is wind speed (BADC, 2010); wind speed is adjusted to account for the differences in speed at the study site and those measured at the meteorological station, using \( v/v_r = kH \), where \( v \) is wind speed at height \( H \), \( v_r \) is wind speed at 10m, \( k \) and \( a \) are coefficients that depend on terrain (Littlefield, 2012), W m\(^{-2}\)K
- \( E_t \) = total solar incident on surface (BADC, 2010), W m\(^{-2}\)
- \( \xi \) = emissivity of surface, 0.9 (Littlefield, 2012)
- \( L_{sky} \) = downward LW incident on horizontal surface (Barrett et al., 2002), W m\(^{-2}\)
- \( \sigma \) = Stefan-Boltzmann constant (5.6697 x 10\(^{-8}\) Wm\(^{-2}\)K\(^{-4}\))
Figure 6-10 compares the modelled surface temperature and calculated sol-air temperatures. The comparison is made for an asphalt parking area, as $T_{\text{sol-air}}$ is not useful for evapotranspiring surfaces. Average differences between modelled and calculated are 7.3 °C (SEE of 8.5 °C) for the hours of 9 am – 2 pm. While the surface temperature validation reveals a large difference (7.3 °C, on average), it may be explained by the presence of two large buildings to the East and North sides of the parking area which, in reality, would keep the asphalt parking area partially shaded for morning and early afternoon hours. If this shading is accounted for in the sol-air temperature calculation and approximated as 25% for any hour up to 3 pm, the average difference is 1.1 °C (SEE of 1.9 °C). From 3 pm, the model diverges strongly from calculated temperatures. This is due to the fact that the meteorological data show increasing cloud cover and greatly reduced total solar radiation (nearly 50%) starting from 3 pm on this particular day, whereas the model is run under clear sky conditions. Based on these calculations, reasonable comparisons can only be made for the clear-sky portions of the day.

![Image: Comparison of ENVI-met Modelled Surface Temperatures with $T_{\text{sol-air}}$ in the Wythenshawe, Manchester Study Area 19th July 2010](image)

Figure 6-10 – Comparison of Modelled Surface Temperature (non-vegetated) with Calculated $T_{\text{sol-air}}$
6.3 Conclusions

The developers of ENVI-met do recognise the model is limited in terms of comparison to real-world measurements (Bruse, 2006), as is typically the case with numerical models. As previously mentioned, the model is limited in that only the starting temperature and wind conditions can be set (and are not forced at later times) and the properties of individual buildings cannot be changed. In comparison to previous research which compares measured and modelled values (Emmanuel and Fernando, 2007), the model fit is very acceptable and can be considered as valid for relative comparisons of urban dynamics. The comparisons to real-world air and surface temperatures performed here demonstrate that it is possible to get a base model that approximates a real day, especially when compared to clear-sky conditions. This provides a basis to move forward in changing one aspect - greenspace types and amounts in the case of this research – with confidence that the initial model configuration produces reasonable results.
7 Microclimate Modelling Results

This chapter presents the microclimate modelling results using ENVI-met to compare two case study areas - one urban commercial, and one suburban commercial-residential.

7.1 Urban Case Study Results

Using the same process as discussed in section 6.2, a base model was calibrated for the urban study area of Manchester City Centre. Once a suitable base model was obtained, a series of models were run in which only the greenspace type and amount were changed for each run. Following the base model, the scenarios tested were:

1. No greenspace, in which all greenspace is replaced with asphalt, to determine the most extreme non-green case;
2. All existing greenspace replaced with grass only;
3. Base +5% newly planted trees;
4. Base +5% mature trees (mix of oak, maple, and silver birch);
5. Base +5% shrubs/hedges; and
6. Base + largest building fitted with green roof.

The urban case study base model contains only about 3% existing greenspace (as compared to approximately 20% in the suburban case study, which follows).

7.1.1 Effect on Air Temperature

Figure 7-1 and Figure 7-2 show the most difference in air temperature\(^{11}\) change from the base model for the +5% mature trees scenario. For this scenario, air temperature reductions of up to 0.7 °C are modelled for the hours 3-6 pm. Other scenarios show small changes, with the change to all asphalt or all grass showing almost no difference from the base model.

\(^{11}\) ENVI-met outputs potential temperature. The air temperature here is calculated as Potential Temperature (K)-273. While a transformation from potential temperature to air temperature would take into account the pressure change if changing height, all temperatures are being compared at the same model height (and therefore, the same pressure).
Air Temperature for Differing Greenspace Configurations in the Manchester City Centre Study Area Modelled in ENVI-met for July 19, 2010

Figure 7-1 – Average Air (Potential) Temperature Over Study Area by Greenspace Type, Manchester City Centre (Urban) Study Area

Change in Air Temperature from Base Model Manchester City Centre

*Asphalt and Grass scenarios show very small (<0.01 °C) increases from Base Model
*Green Roof scenario is nearly the same as Hedges

Figure 7-2 – Air (Potential) Temperature Difference from Base Model, Manchester City Centre (Urban) Case Study
7.1.2 Effect on Surface Temperature

Using the same greenspace scenarios tested previously, the model results were analysed for changes in surface temperature. As shown in Figure 7-3 and Figure 7-4, the changes to surface temperature are much greater, as expected. For instance, the mature trees scenario shows a reduction of up to 1.6 °C at 3 pm, while the surface temperature increase due to all asphalt is up to 0.25 °C. New trees achieve a reduction of up to 0.5 °C and show a somewhat greater reduction than hedges, probably due to the additional shading created by the canopy shape. Temperature differences are most pronounced between the hours of 1 pm and 5 pm, with temperatures converging again after 6 pm. However, the mature trees scenario remains approximately 0.5 °C cooler, even at 9 pm.

Figure 7-3 - Average Surface Temperatures by Greenspace Type, Manchester City Centre (Urban) Study Area
7.1.3 Effect on Relative Humidity

As in the suburban case study, modelling results for the base model, all asphalt, and +5% mature trees scenarios were compared for changes in relative humidity. As shown in Figure 7-5, relative humidity is almost exactly the same for the base model and the scenario replacing all greenspace with asphalt, due to the fact that the base model in this case is already around 97% asphalt. However, in the case of adding 5% mature trees, relative humidity increases by about 2%, on average.
7.1.4 Effect on Mean Radiant Temperature

Mean radiant temperature ($T_{mrt}$) was examined as an indicator of the changes in thermal comfort that might be observed for outdoor areas in the model. For the City Centre, the mature trees scenario reduces the mean radiant temperature by about 5.5K during the day with a maximum reduction of 5.9K at 3 pm (Figure 7-6). In this case, the change to all asphalt results in very small changes from the base model because the proportion of asphalt is already very high in the base model.
7.1.5 Effect on Wind Speed

For the same reasons mentioned with regard to mean radiant temperature, the asphalt scenario shows very little change in wind speed from the base model (Figure 7-7). However, the addition of 5% mature trees leads to an average reduction in wind speed of approximately 0.5 m/s. This result may have implications for the UHI, given that lower wind speeds are a factor in enhancing the UHI effect.

![Wind Speed for Selected Scenarios](Manchester City Centre)

Figure 7-7 – Wind Speed (m/s) for Selected Urban Scenarios

7.2 Suburban Case Study Results

7.2.1 Effect on Air Temperature

After calibration of the base model, which represents the current field conditions, the greenspace scenarios were again tested in the suburban case study site. The base model contains approximately 20% greenspace consisting of new and mature trees, grass, and hedges.

Figure 7-8 shows a comparison of air temperatures for each greenspace scenario. Changing the amount of greenspace was shown to have only minor effects on air temperature, except in the extreme case of replacing all vegetation with asphalt, which shows an average increase of 2.4 °C. The change to all asphalt is interesting in that it shows that UHI may be worse during the day in the suburban case and perhaps shows the importance of maintaining existing vegetation, even in relatively green suburban areas.
Figure 7-9 shows the hourly differences in air temperature from the base model, which indicates virtually no difference in air temperature between modelled scenarios, except for a decreased cooling trend in late afternoon for the two scenarios with reduced amounts of greenspace (grass and asphalt scenarios).
Comparisons here are for a one-day modelling period. Although the three-day run of the base model shows a higher correlation with measured temperatures (discussed in Section 6.2.2), comparisons between models based on greenspace changes were determined to be suitable even for the one-day run. As a check on the potential changes of a one-day vs. three-day run, the two extreme cases of asphalt and mature trees were run for three modelling days (Figure 7-10). By the third modelled day, the mature trees scenario resulted in a marginally higher air temperature cooling effect of 0.1 °C – 0.2 °C for the hours of 1 pm to 4 pm, but virtually no change for other times. For the third day of the asphalt scenario, the pattern of warming had shifted to earlier hours so that more warming occurred in late morning and mid-day, but average overall differences were only warmer by 0.1 °C.
When considering these results for air temperature, it is important to note that this is the average temperature change over the whole study area, and that while changes are occurring (e.g. a small decrease in the areas with added greenspace), the amount of greenspace added is only 5%, which results in almost no detectable change when averaged over the entire study area. Regression analysis of canopy cover (total m$^2$ within buffer zones of 10, 50, and 100m and ward-level evapotranspiring cover) with average July maximum air temperature (29 iButton locations for buffer zones and 38 locations for ward-level data) found no significant relationship between air temperature and canopy cover for this suburban site. This is consistent with a recent PhD on the Manchester UHI intensity, as measured by air temperature difference from a rural reference point (Cheung, 2011), which found only a small effect on air temperature when compared to amount of evapotranspiring cover ($R^2=0.32$ for daytime and $R^2=0.35$ for nighttime, under clear and calm conditions). That research also found that the most significant factors affecting UHI were small sky-view factor (SVF$<0.65$) and low wind speed ($<10$ m/s).

For the green roof scenario, the air temperatures evaluated here were at the 4 m height, in keeping with the placement of iButton sensors, but it was found that air temperature decreases slightly, by up to 0.17 °C, at roof level on top and on the downwind side of the green roof. Although very few studies were found for impacts on air temperature due to green roofs, one modelling study comparing nine cities and
using a combination of green walls and green roofs found a reduction of 12.8 °C average daytime temperature (at 1 m above the green roof) for Riyadh and approximately 8 °C for London (Alexandri and Jones, 2008). However, recent experimental research for Manchester estimates a more modest cooling effect of 1.06 °C at 300 mm above an intensive green roof, with a maximum summer nighttime cooling of 1.58 °C (Speak et al., 2013). The latter result is more comparable in scale as the study is based on a single roof and, given that the research modelled here is for an extensive roof (relatively thin soil and substrate with little or no structural alterations to the roof), it would likely have a reduced cooling effect as compared to an intensive roof (relatively deep soil and substrate, usually requiring additional structural support and irrigation).

7.2.2 Effect on Surface Temperature

Again, using the greenspace scenarios stated previously, surface temperatures were compared (Figure 7-11). The first scenario was an extreme example in which all existing greenspace was replaced by asphalt. The results estimate that replacing all current vegetation (approximately 20% of the study area) with asphalt would lead to an average daytime increase of 4.7 °C over the study area, while increasing the amount of greenspace by adding 5% mature trees would decrease surface temperatures by 1.0 °C on average. Adding 5% greenspace cover as hedges or new trees was shown to decrease surface temperatures by approximately 0.5 °C on average, with new trees being slightly more effective at cooling than hedges, probably due to greater shading effects. Replacing all current vegetation with only grass would increase surface temperatures by about 0.6 °C and adding a green roof on the largest building, while reducing the building’s roof temperature, would have no result on overall surface temperatures. The results therefore demonstrate that greening strategies are an important determinant of temperatures even in suburban areas towards the periphery of cities.

These again are one-day comparisons, with three-day runs also conducted for asphalt and mature trees. By the third day, the mature trees show a slightly reduced surface temperature cooling effect of 0.85 °C, while asphalt shows reduced warming of about 3.7 °C (or 1.0 °C less than in the one-day run) on average.

These findings show a slightly larger impact than previous work by Gill (2006) which estimated a 1.5 °C decrease in surface temperature for each 10% increase in green cover (change from the 1961-1990 baseline emissions scenario in a medium-density residential area, which is comparable to the suburban area in this study). If the relationship between percentage of mature trees and surface temperature in this study...
should prove to be linear, it would indicate a 2.0 °C decrease in surface temperature for a 10% increase in mature trees. The current study adds to knowledge by quantifying the relative temperature differences that can be attributed to specific types and total percentage cover of vegetation. As concluded by Shashua-Bar and Hoffman (2000), the surface temperature differences can be attributed to the effects of shading provided by mature trees as compared to the non-shading vegetation, such as grass and shrubs. More specifically, as concluded by Hardin and Jensen (2007), the larger surface temperature reductions for mature trees can be attributed to the effects of increased LAI provided by mature trees as compared to the lower-LAI vegetation, such as new trees and hedges.

![Surface Temperatures for Differing Greenspace Configurations]

Figure 7-11 – Surface Temperatures by Greenspace Type, Wythenshawe, Manchester (Suburban) Case Study

Figure 7-12 shows the hourly change from the base model temperatures, with most differences seen in the middle part of the day from 10 am – 5 pm and temperatures beginning to converge again towards the evening.
Table 7-1 and Figure 7-13 compare the change in surface temperature against the change in total leaf area for the study area. Change in total leaf area was calculated by taking the average LAI for each greenspace scenario and multiplying by the area of vegetation added/removed (e.g. +5% total area for mature trees, -20% total area for change to grass only). The $R^2$ for the regression analysis is approximately 0.70, but this value increases to 0.97 (significant, $p<0.02$) when the asphalt scenario is removed. This increase in linearity is reasonable because the asphalt scenario not only reduces the vegetated surface but has the added effect of a somewhat reduced albedo and increased thermal capacity.
### Table 7-1 – Surface Temperature and Leaf Area Changes Compared to Base Model

<table>
<thead>
<tr>
<th>Greenspace Type</th>
<th>Average Surface Temperature Change (°C)</th>
<th>Change in Total Leaf Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+5% Mature Trees</td>
<td>-1.00</td>
<td>167,328</td>
</tr>
<tr>
<td>+5% New Trees</td>
<td>-0.51</td>
<td>114,912</td>
</tr>
<tr>
<td>+5% Hedges</td>
<td>-0.46</td>
<td>38,304</td>
</tr>
<tr>
<td>Grass only, replacing current vegetation</td>
<td>0.62</td>
<td>-258,048</td>
</tr>
<tr>
<td>Asphalt only, replacing current vegetation</td>
<td>4.69</td>
<td>-322,560</td>
</tr>
</tbody>
</table>

#### Figure 7-13 - Plot of Surface Temperature Change and Total Leaf Area Change with Linear Trend and Regression Statistics (excluding the change to Asphalt)

**7.2.3 Effect on Relative Humidity**

Given that relative humidity will be an important parameter for building energy modelling, effects on relative humidity were compared for the base model and the two scenarios that are most different - all asphalt and +5% mature trees. Results are shown in Figure 7-14. Given the already significant amount of greenspace present in the base case for the study area, the addition of 5% mature trees results in only a slight increase in relative humidity of about 0.4% on average. However, the extreme worst case of replacing all existing vegetation with asphalt shows a reduction in RH of about 15%, on average.
7.2.4 Effect on Mean Radiant Temperature

In the suburban, the mature trees scenario reduces mean radiant temperature by an average of approximately 1K during the day and up to a maximum of 1.5K at 6 pm (Figure 7-15). In contrast, the asphalt scenario increases the daytime mean radiant temperature by 6K, on average, with a maximum increase of 8K by 6 pm. As discussed in section 3.3.3, mean radiant temperature is a significant factor in calculations of thermal comfort, so this shows a potentially significant impact on levels of outdoor thermal comfort due to mature trees.
7.2.5 Effect on Wind Speed

Figure 7-16 shows the hourly wind speed for the base model, asphalt, and mature trees scenarios (at 4m height). The addition of mature trees leads to a wind speed reduction of 0.5 m/s on average, while the change to all asphalt leads to an increase in wind speed of 0.5 m/s on average, with a slightly larger difference between 9:00 pm and 6:00 am. All scenarios show reducing wind speeds from 9 pm, as expected.
7.3 Conclusions

The results presented in this chapter highlight some important differences between urban and suburban greenspace impacts. For air temperature, the urban scenario of adding 5% mature trees results in a maximum reduction of 0.6 °C, whereas the suburban scenario results in almost no difference. This is sensible in that an addition of 5% in the urban case brings the total greenspace to 8%, nearly tripling the greenspace percentage from the original 3%. However, in the suburban case, the area is already approximately 20% greenspace, so the addition of 5% only increases the greenspace by one-quarter of the existing amount, leading to reduced overall impacts. Also, many of the spaces available for planting trees in the suburban area are currently covered by grass, whereas tree planting in the city centre will most frequently replace areas of asphalt or concrete, another reason for greater impact in the city centre. In a dense urban centre that is mostly covered by asphalt and concrete, a small addition to greenspace can have a relatively larger impact on air and surface temperatures, as demonstrated here.

Figure 7-17 nicely demonstrates the UHI effect by comparing the urban and suburban cases side by side. It shows an average UHII of about 1.0 °C. In Figure 7-18, the worst case scenario of all asphalt in the suburban area shows an increase in air temperature that exceeds the urban case. This is perhaps due to the more open and
exposed surfaces found in the suburban area that would be exposed to solar radiation at all hours of the day.

Figure 7-17 – Comparison of Urban and Suburban Air Temperature Patterns

Figure 7-18 – Comparison of Urban and Suburban Air Temperatures for Asphalt and Mature Trees
Figure 7-19 – Comparison of Urban and Suburban Surface Temperature Results

Surface temperature results in Figure 7-19 are also interesting in that they show higher daytime temperatures for the suburban change to all asphalt, but this scenario cools more quickly than the urban case and achieves lower nighttime temperatures than the urban asphalt scenario.

It is worth noting that these modelling results are likely to be conservative, but perhaps represent the differences that would be achieved under the average UHI conditions. The wind speed of 5 m/s applied in the models is average for Manchester, but does not represent the lower wind speeds that would occur under high UHI conditions. The temperature increases from suburban to urban here are a maximum of 2.5 °C for surface temperature and 0.8 °C for air temperature, whereas recent work by Cheung (2011) documents a Manchester summer nighttime air temperature UHI intensity of up to 8 °C (most frequently it is 1.5 °C), and work by Smith et al. (2011) shows a summer daytime surface temperature UHI that can exceed 10 °C.
8 Building Energy Modelling - Detailed Methods and Results

Chapters 5 and 7 have explored the various microclimate effects of six different urban greenspace scenarios and used the results of iButton air temperature data to determine the best measures for developing correlations between air temperature and area of tree canopy cover. In this chapter, the results from the two methods of exploration will be used to inform the process of building energy modelling, developing a series of building energy calculations that will determine the potential impacts of greenspace on building energy performance.

As one of the main aims of this research is to estimate the impacts on building energy that might occur with urban greenspace changes, two different approaches were selected in achieving this aim. As a first estimate, the sol-air temperature was calculated and modified to estimate the potential impacts of shading. Secondly, for a more precise calculation, the building energy modelling programme, IES-VE 2012 was selected (as previously discussed in Chapter 4.3). This chapter presents the results of these two approaches and builds on the microclimate modelling results presented in the previous chapter, utilising the results from ENVI-met to inform key variables in the building energy modelling process.

8.1 Sol-air Temperature Calculations

Building energy consumption has been estimated for a summer month using the July Test Reference Year (TRY) weather data. The TRY is a set of data developed by CIBSE to represent a typical pattern of weather for 14 locations in the UK. Each month of data is selected separately, taken from the year in which that month is most representative of the 23-year average, usually from the years 1983-2005. The initial estimate uses the sol-air temperature. For a particular U-value of the construction and the building’s desired internal temperature, energy usage can be estimated as:

\[
\frac{Q}{A} = U_c (T_i - T_{\text{sol-air}})
\]

\[
\frac{Q}{A} \text{ (W/m}^2\text{)} = \text{heat transfer in/out of building}
\]

\[
U_c = U\text{-value for construction (W/m}^2\text{K)}
\]

\[
T_i = \text{indoor temperature (K)}
\]

The \( T_{\text{sol-air}} \) calculation can be adapted to account for some of the effects of vegetation, including shading and wind (Allen et al., 1998; Barrett et al., 2002). The following explains how to include the effects of vegetation in this equation:

\[
T_{\text{sol-air}} = T_0 + \left( a^\text{Tr} - \Delta Q_v \right) / h_0
\]
\[ T_0 = \text{outdoor air temperature (K)} \]
\[ a = \text{absorptivity of surface} \]
\[ I = \text{global solar irradiance (W/m}^2\text{)} \]
\[ \Delta Q_{ir} = \text{extra infrared radiation due to difference in external air Temp and apparent sky Temp} = \xi \Delta R, \text{ where} \]
\[ \xi = \text{emissivity} \]
\[ \Delta R = \text{difference between outside dry-bulb air and sky mean radiant temperature, estimated as} \]
\[ 21-17^\circ C, \text{ for vertical surfaces (Adler, 1999), where, } C = \text{cloudiness (oktas/8)} \]
\[ h_0 = \text{heat transfer coefficient for radiation (long wave) and convection} = 4 + 4v, \text{ where} \]
\[ v = \text{wind speed} \]

To determine the effects of shading and building density, I can be divided into direct and diffuse components. Then, Sky View Factor (SVF) is applied to the diffuse component to determine the amount of diffuse radiation falling on the building. A shading factor can be applied to the direct radiation component in the form of Partial Shaded Area (PSA) (Erell and Williamson, 2006), which is the area of building receiving shade (at a given hour) divided by total building surface area, so:

\[ I = R_{dir}*(1-PSA) + R_{dir}*SVF \]

Using the longwave losses as estimated by \( \Delta R \) above, the final model becomes:

\[ T_{\text{sol-air}} = T_0 + (a*(R_{dir}*(1-PSA) + R_{dir}*SVF) - \xi*(21-17^\circ C))/h_0 \]

Using the equations presented here and the July TRY data, estimates of vegetative effects can be developed using different values of PSA, vapour pressure and wind speed. Several combinations of SVF and PSA were investigated in order to estimate potential changes in energy consumption through shading and built form (ie., low and open sites, or tall, compact sites as represented by SVF) and vegetation represented by PSA. Figure 8.1 shows that an increase in shading of 10% may reduce cooling requirements by about 3.5% in a completely open area, whereas reducing the SVF to 0.8 (through denser building arrangements) and adding 25% shading could reduce cooling requirements by up to 15% (the latter calculation assumes only a small increase in absorptivity due to the additional built structures).
The estimates can be made for different building arrangements and constructions by using SVF and construction U-values. While $\Delta R$ is dependent on the vapour pressure, the equation is still limited with respect to evapotranspiration and the impact of heat storage in the urban fabric. Under low SVF, heat is radiated between buildings rather than back to the open sky and this component is difficult to estimate with this rather simplified calculation. Additionally, while higher vapour pressure and cloudy conditions will result in less long-wave heat loss than clear conditions coupled with low vapour pressure, the microscale effects of evapotranspiration are difficult to estimate by this method. This leads to a more detailed investigation using building energy modelling software, in which the weather files can be adjusted to account for several additional variables.

8.2 IES-VE Modelling

8.2.1 Description of Building Models

After estimating energy reductions using the sol-air temperature calculations, a more detailed analysis was undertaken using IES-VE 2012 building energy modelling software.

The simulation focuses on office buildings, as discussed in Chapter 4.5. A large number of variables can affect the simulation of the building energy usage, including building characteristics such as age, building construction, ratio of natural gas to
electricity consumption, occupancy rates, and HVAC characteristics (Heiple and Sailor, 2008). CIBSE and the BRE have identified four typical types of office buildings in the UK (CIBSE, 2000), shown in Figure 8-2:

1. Naturally ventilated, cellular;
2. Naturally ventilated, open plan;
3. Air conditioned, standard; and
4. Air conditioned, prestige.

![Figure 8-2 – Typical Office Building Types in the UK](source)

Source: (CIBSE, 2000)

As the research is interested in the energy trade-offs that might occur in air-conditioned buildings, modelling was based on the latter two types. A total of three buildings were tested:

- Two versions of Type 3, one shallow-plan three-storey, and one shallow-plan ten-storey; and
- Type 4, one deep-plan three-storey.
The buildings were sketched using the ModellIT module in IES-VE. To test the interaction of glazing ratios and shading, each building was first modelled with 20% glazing, then with 50% glazing. Table 8.1 provides the building details while Figures 8.2 to 8.4 show the three buildings as sketched in IES-VE. All buildings were modelled as a General Office and it is assumed that all buildings have been modernized in terms of windows, doors, light fittings and insulation.

Building constructions applied were:

- Roof – flat roof, 2002 regulations;
- Ceiling – carpeted 100 mm reinforced concrete ceiling;
- External wall – standard wall construction, 2002 regulations;
- Internal partition – 13mm plaster, 105mm brick, 13mm plaster;
- Ground floor – Standard floor construction; and
- Door – wooden

Key thermal template settings were:

- Timing – Office 8:00-6:00;
- Cooling Temperature – 23.0 °C;
- Heating Temperature – 19.0 °C;
- RH – 70% maximum;
- ACH – 0.250 Infiltration; and
- Internal Gains – Fluorescent lighting, 12 W/m²; Occupancy 14 m²/person; Equipment, 12 W/m².

Full constructions and thermal templates are detailed in Appendix G.

**Table 8.1 – Building Types and Descriptions**

<table>
<thead>
<tr>
<th>Building Type Designation</th>
<th>Plan Type</th>
<th>Glazing Ratios</th>
<th>Floor Area and Layout</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modern A</td>
<td>Shallow</td>
<td>20%, 50%</td>
<td>972 m² - 9 (6mx6m) rooms per floor</td>
<td>3 Floors</td>
</tr>
<tr>
<td>Modern B</td>
<td>Shallow</td>
<td>20%, 50%</td>
<td>3240 m² - same layout as building A</td>
<td>10 Floors</td>
</tr>
<tr>
<td>Modern C</td>
<td>Deep</td>
<td>20%, 50%</td>
<td>5418 m² - 84 (3mx3m) rooms, 4 open plan areas (10mx15 m), 18 larger offices (5mx5m)</td>
<td>3 Floors</td>
</tr>
</tbody>
</table>
Figure 8-3 – Building A - Three-Storey Shallow Plan

Figure 8-4 – Building B - Ten-Storey Shallow Plan

Figure 8-5 – Building C - Three-Storey Deep Plan
8.2.2 Summer Energy Scenarios

Each building was first modelled with the July TRY weather data for Manchester Airport without surrounding shading elements as a base estimate of cooling energy usage for summer. This base case was first compared with two models that incorporated tree shading; the first model added four trees on the North side of the building, while the second model added four trees on the South side of the building. A third scenario tested the effect of a green roof. Then, additional models tested UHI increases or reductions, and wind speed reductions. Trees of approximately 10 m were selected as the shading element given that mature trees were found to have the most effect in the microclimate modelling presented in Chapter 7. The model names and descriptions were:

- **Base** – Building in suburban conditions, without shading, modelled with July TRY weather data;

- **Shade – North** Four trees added as Topographic Shade, two on the North and one on each of the Northwest and Northeast corners of the building, shading approximately 20% of the building; and **South** - Four trees added as Topographic Shade, two on the South side and one on each Southwest and Southeast corners of the building, again shading approximately 20% of the building;

- **Urb_UHI** - To simulate each building's energy increase due to the UHI (ie, a building placed in urban conditions), a new weather file (UHI+6) was created using the EPW creator Excel spreadsheet from IES-VE. In this file daytime temperatures were increased by 1.5 °C, and nighttime by 3 °C. These values are based on a recent Manchester PhD (Cheung, 2011) showing average summer daytime/nighttime UHI. Additionally, in the TRY dataset, nearly two full days in July (16th-18th) are clear, calm and warm days, which are conditions for an intense UHI, so temperatures were increased strongly, +3 °C for daytime and +6 °C for nighttime;

- **Urb_UHI_green** - To test the effect of greening (shading plus reduced UHI peak hours), a new weather file (UHI+6_green) was created based on the TRY_UHI+6 file. The UHI on the peak days (16th-18th) was reduced by 1 °C, in effect taking off the peak of the UHI. In this weather file, the UHI for the peak days is +2 °C for daytime and +5 °C for nighttime. This reduction in UHI due to greening is based on the negative summer correlation between UHI and area of tree canopy that was presented in Chapter 5. The regression equation indicates a potential reduction of 10 cooling degree hours for each 5% increase
Chapter 8

in greenspace. The weather file changes here are scaled up, allowing for a total of 40 cooling degree hours due to the 20% shading around the shallow-plan three-storey building.

- **Urb_UHI_green_wind** – To test the effect of a reduced wind speed, a new weather file (UHI+6_green_wind) was created based on the TRY_UHI+6_green file. In addition to the changes in the two previous scenarios, this file also reduced the hourly wind speeds for July by 1 m/s. The reduction is based on the wind speed reductions for the mature trees scenario of the urban microclimate modelling presented in chapter 7.1.

- **Green Roof** – The green roof was constructed following as closely as possible (given available material settings in IES-VE) the diagram in Figure 8-6, with constructions as shown in Figure 8-7.

![Figure 8-6 – Example Green Roof Construction](Stoddard and Bissonnette, 2012)
The results show a maximum of 1.6% reduction in chiller energy as a combined result of four trees shading the south side of the building and the reduction of UHI peak hours on a shallow plan three-storey building. Total reductions for this same building with the combined effects of 4 trees on the North and 4 trees on the South are estimated at 2.7%.

The percentage savings is reduced for a deep plan building (0.7% for 4 trees on the south side and UHI peak hours reduction), primarily due to the fact that the same 4 trees in this scenario will not be shading an equivalent surface area (only 10% of the building’s surface in this model). However, if the model had achieved the 20% shading of the shallow-plan building, this would lead to 1.4% savings, slightly less than the reduction achieved in the shallow plan building. This is reasonable due to the larger internal building volume for a deep-plan building that would be unaffected by shading measures.

For the green roof scenario, the summer results show a very marginal increase in building energy consumption (0.3%). Therefore, it is anticipated that the particular construction of the green roof may play an important role in its functioning for building energy. Also, this result may be limited by the available construction materials in IES-VE.
While wind reductions are often cited as a thermal advantage due to lower infiltration rates, the results here show that lower wind speeds can be detrimental because of the reduction in heat transport away from the building envelope in summer. However, this is usually understood as a problem which would apply to poorly insulated buildings (Akbari, 2002).

The detailed analysis presented here indicates that the sol-air calculations used in the initial stages are likely to overestimate the energy reductions that can be achieved.
### Table 8-2 - Summer Table of Results, Chiller Energy Usage (MWh)

<table>
<thead>
<tr>
<th>Building</th>
<th>Tree Location</th>
<th>Base Energy, Chillers</th>
<th>Shade</th>
<th>Urb_UHI</th>
<th>Urb_UHI_green</th>
<th>Urb_UHI_green_wind</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Amount</td>
<td>% Change</td>
<td>Amount</td>
<td>% Change</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(MWh)</td>
<td></td>
<td>(MWh)</td>
<td>from Base</td>
</tr>
<tr>
<td>Modern A, 20% Glazing</td>
<td>North</td>
<td>3.6168</td>
<td>3.5833</td>
<td>-0.9%</td>
<td>4.0555</td>
<td>12.1%</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td></td>
<td>3.5628</td>
<td>-1.5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modern B, 20% Glazing</td>
<td>North</td>
<td>11.2775</td>
<td>11.2494</td>
<td>-0.3%</td>
<td>12.6552</td>
<td>12.2%</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td></td>
<td>11.2380</td>
<td>-0.4%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modern C, 20% Glazing</td>
<td>North</td>
<td>22.5894</td>
<td>22.4979</td>
<td>-0.4%</td>
<td>24.8123</td>
<td>9.8%</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td></td>
<td>22.4652</td>
<td>-0.6%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modern A, 50% Glazing</td>
<td>North</td>
<td>5.9342</td>
<td>5.8726</td>
<td>-1.0%</td>
<td>6.5604</td>
<td>10.6%</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td></td>
<td>5.8333</td>
<td>-1.7%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modern B, 50% Glazing</td>
<td>North</td>
<td>18.0455</td>
<td>17.9733</td>
<td>-0.4%</td>
<td>19.9219</td>
<td>10.4%</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td></td>
<td>17.9553</td>
<td>-0.5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modern C, 50% Glazing</td>
<td>North</td>
<td>29.1205</td>
<td>28.8875</td>
<td>-0.8%</td>
<td>31.8691</td>
<td>9.4%</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td></td>
<td>28.7745</td>
<td>-1.2%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
While the effect of tree shading and UHI reduction appear to be small when considered over the entire month, as presented in the previous table, the results can also be examined more closely for the effects during the peak UHI period. The following table (Table 8-3) shows the peak UHI conditions for the set of buildings with 20% glazing (as seen from the monthly results, the values for the 50% are not widely different). The results for this period show that shading by four trees on the South side of building A can reduce the cooling energy by 2.7% in a building located in the UHI. In this case, a reduction in wind speed is not considered as the peak UHI occurs on days of low wind. The 10-storey shallow plan building (B) and deep plan building (C) are similar to each other in reductions for this 3-day period of peak UHI conditions.

<table>
<thead>
<tr>
<th>Building</th>
<th>Tree Location</th>
<th>Urb_UHI Amount (kWh)</th>
<th>Urb_UHI green Amount (kWh)</th>
<th>% Change from Urb_UHI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modern A</td>
<td>North</td>
<td>572.0</td>
<td>560.2</td>
<td>-2.1%</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td></td>
<td>556.6</td>
<td>-2.7%</td>
</tr>
<tr>
<td>Modern B</td>
<td>North</td>
<td>1738.4</td>
<td>1711.7</td>
<td>-1.5%</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td></td>
<td>1705.4</td>
<td>-1.9%</td>
</tr>
<tr>
<td>Modern C</td>
<td>North</td>
<td>3209.6</td>
<td>3161.4</td>
<td>-1.5%</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td></td>
<td>3156.4</td>
<td>-1.7%</td>
</tr>
</tbody>
</table>

Figure 8-8 shows the patterns of dry-bulb temperature and chiller usage for the typical UHI and green UHI cases. In this figure, it is apparent that savings would be greater in air-conditioned buildings that are occupied during the nighttime, when UHII is greatest. As these buildings are modelled as office buildings, the air conditioning is switched off at night, masking the potential savings for buildings that are occupied at this time.
8.2.3 Summer Carbon Emissions

Table 8-4 shows the changes in carbon emissions (for the set of buildings with 20% glazing) due to the average summer UHI (+1.5 °C daytime and +3.0 °C nighttime). The results show the greatest increase for the 10-storey shallow plan building and the least increase for the deep plan building. While the deep plan building shows a higher overall usage and higher usage per square metre, the energy consumption does not increase as much under the UHI conditions.

Table 8-4 – Changes in Summer (July) Carbon Emissions due to UHI

<table>
<thead>
<tr>
<th>Building</th>
<th>Chiller CE Base (Electricity, kg CO₂)</th>
<th>Chiller CE Urb_UHI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amount</td>
<td>% Change</td>
</tr>
<tr>
<td>Modern A</td>
<td>6714</td>
<td>7020</td>
</tr>
<tr>
<td>Modern B</td>
<td>20323</td>
<td>21284</td>
</tr>
<tr>
<td>Modern C</td>
<td>46517</td>
<td>48068</td>
</tr>
</tbody>
</table>

If also considering the direct reduction in CO₂ emissions due to the carbon sequestered by each tree, the carbon savings due to tree planting in urban areas is marginally higher. Akbari (2002) estimated that each urban tree can reduce an average of 4.6-11.4 kg CO₂ per year (with older trees sequestering more carbon). This leads to an estimate of at least 1 kg CO₂ per tree for the month of July, considering that the most tree growth in the UK is during spring and summer. With four trees around each building, the reduction is 4kg CO₂ for July.
Chapter 8

8.2.4 Winter Energy Scenarios

For the winter investigation, a model using the December TRY weather data and a model under UHI conditions are compared. In winter, the daytime UHI average is 1.6 °C, while the nocturnal UHI is 3.1 °C. Under clear and calm, peak UHI, conditions, the UHI daytime mean is 2.0 °C and nighttime mean is 6.0 °C. The clear and calm conditions (defined as <3 m/s wind speed and <2 oktas of cloud cover) occurred on portions of several days (7th-9th, 12th and 14th December), totalling 39 hours in the month. Air temperature effects from greening are not considered for the winter because the data analysis in Chapter 5 did not find any correlations between area of tree canopy and the air temperature indices investigated for the month of December. Therefore, the analysis assumes a neutral air temperature effect from greening for winter months.

In comparing the energy changes for winter (Table 8-5 and Figure 8-9), large percentage reductions in boiler energy are found for all buildings located in the urban area under UHI conditions, as compared to the base case (suburban) location. However, while chiller usage is smaller in absolute terms, this shows substantial increases for the urban location. This is explained by the fact that, depending on the building construction and thermal profile, chillers may be required in winter to offset internal gains.
Table 8-5 – Winter (December) Table of Results, Boiler and Chiller Energy Usage

<table>
<thead>
<tr>
<th>Building</th>
<th>Base Energy, Boilers</th>
<th>Boiler Energy with Avg UHI</th>
<th>% Change</th>
<th>Base Energy, Chillers</th>
<th>Chiller Energy with Avg UHI</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modern A</td>
<td>1.6262</td>
<td>0.726</td>
<td>-55.4%</td>
<td>0.6631</td>
<td>0.8734</td>
<td>31.7%</td>
</tr>
<tr>
<td>Modern B</td>
<td>4.4010</td>
<td>1.7875</td>
<td>-59.4%</td>
<td>1.1761</td>
<td>1.8536</td>
<td>57.6%</td>
</tr>
<tr>
<td>Modern C</td>
<td>2.3309</td>
<td>0.8453</td>
<td>-63.7%</td>
<td>7.7157</td>
<td>9.824</td>
<td>27.3%</td>
</tr>
</tbody>
</table>

8.2.5 Winter Carbon Emissions

Following on from the changes to boiler and chiller energy discussed in the previous section, Table 8-6 summarises the changes in carbon emissions from these same scenarios. This was important to investigate as it is often argued that the benefit of a winter UHI is more important for energy savings than the detriment of a summer UHI. While it might be true that, in absolute terms, the reduction in boiler energy outweighs the increase in chiller energy, the results shown in Table 8-5 indicate only a very slight advantage to carbon emissions when investigating the trade-offs in boiler and chiller energy for December. The results show that carbon emissions due to chiller usage are far higher than that for boilers. Building A, for example, only has carbon emissions of 322 kg (suburban), and although reduced to 144 kg for the average UHI conditions, the
relatively small amount of chiller energy leads to 4652 kg CO\textsubscript{2} for the suburban and increases to 4799 kg for the urban UHI.

While it could be argued that a UK building is unlikely to use chiller energy in winter, the same comparison could also be made for summer to winter tradeoffs. Even if chillers were completely turned off in winter, the case is even more apparent for carbon emissions due to summer air conditioning usage. On balance, in terms of carbon emissions, any increase in summer air conditioning will far outweigh the reductions in winter heating.

### Table 8-6 – Changes in Winter (December) Carbon Emissions

<table>
<thead>
<tr>
<th>Building</th>
<th>Boiler CE (Natural Gas, kg CO\textsubscript{2})</th>
<th>Boiler CE with Avg UHI</th>
<th>Chiller CE (Electricity, kg CO\textsubscript{2})</th>
<th>Chiller CE with Avg UHI</th>
<th>Total System CE (Electricity, kg CO\textsubscript{2})</th>
<th>Total System CE with Avg UHI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modern A</td>
<td>322</td>
<td>144 (−55.3%)</td>
<td>4652</td>
<td>4799 (3.2%)</td>
<td>4974</td>
<td>4943 (−0.6%)</td>
</tr>
<tr>
<td>Modern B</td>
<td>871</td>
<td>354 (−59.4%)</td>
<td>13272</td>
<td>13745 (3.6%)</td>
<td>14144</td>
<td>14099 (−0.3%)</td>
</tr>
<tr>
<td>Modern C</td>
<td>462</td>
<td>167 (−63.9%)</td>
<td>36136</td>
<td>37607 (4.1%)</td>
<td>36597</td>
<td>37775 (3.2%)</td>
</tr>
</tbody>
</table>

### 8.2.6 Building Energy Consumption Conclusions

While it may appear that the benefits of a winter UHI far outweigh the summer detriment, it is worthwhile to further examine some of the causes for the large differences estimated here. One explanation is possibly in the methods used to develop the summer and winter UHI weather files. During the summer, the UHI analysis is more weighted to the daytime average of 1.5 °C because sunrise is typically around 5 am and sunset around 9 pm (16 daytime hours). During the winter, the UHI analysis is weighted toward the nighttime average of 3.1 °C because sunset is, on average, at 4 pm, and sunrise is not until 8 am (16 nighttime hours). In reality, this daytime/nighttime differentiation is likely to be less straightforward and more of a gradual increase or decrease in temperature differences than estimated here.

Also, the exact causes of a higher winter UHI require further investigation. Undoubtedly, some portion of the UHI is due to greater thermal mass and heat storage/release in urban areas, but it might be argued that an anthropogenic component enhances this (Smith et al., 2009). Another cause may be warm air leakage due to poorly sealed buildings. The latter case represents an excess of boiler energy in any initial calculation of energy consumption.
Chapter 9

9 Conclusions

Initial motivations for performing this study were to explore the use of greenspace as a potential adaptation for climate change (as explained and evidenced by UKCP09 (Jenkins et al., 2009)) and as a method of reducing the UHI effect in urban areas. The research has performed a fine-scale assessment of types and amount of vegetation, the potential microclimate impacts and the related impacts on building energy demand.

While the two previous chapters have presented the main results of the research, including the microclimate modelling and building energy modelling, this chapter will discuss and summarise the main findings throughout all components of the research. Included are recommendations for greenspace planning in the context of UK climate, a discussion of contributions to knowledge, and finally, recommendations for future research.

9.1 Conclusions to Research Questions and Hypotheses

The research first utilised the urban microclimate model ENVI-met to model two distinct study areas, estimating a number of microclimate parameters, including air and surface temperatures, relative humidity, mean radiant temperature, and wind.

These microclimate results and an analysis of iButton temperature sensors were then used to inform the building energy modelling performed in IES-VE for determining summer cooling and winter heating trade-offs that might be achieved through the addition of greenspace.

The research focused on the effect of vegetation on the energy performance of commercial buildings by assessing three factors – shading with mature trees, reduction in total number of hours at peak UHII conditions, and changes in wind speed.

The study concludes the following as related to the original research questions and hypotheses developed:

• What are the changes in microclimate (air temperature, surface temperature, wind and relative humidity) due to different types and total percentage cover of urban greenspace?
  
  o Hypothesis: Greenspace influence on microclimate depends on the specific type of greenspace as well as the urban morphology of the neighbourhood in which it is added;

While the largest air and surface temperature changes were found for the addition of mature trees, as might be expected, the urban case study also
estimated that temperature reductions due to new trees or hedges would be approximately half of that for mature trees. Whereas the impacts for new trees would increase over time to the level of the mature trees, the impact of hedges would likely remain static as they were modelled at a reasonably mature height of 4m.

While the green roof scenario found only small changes in air temperature at the 4m height evaluated, it did show small reductions at roof level (about 0.17 °C in the suburban case), on the downwind side. As expected, the green roof would not have any impact on ground surface temperatures, or mean radiant temperature at the 4m height evaluated here.

For a temperate maritime climate such as Manchester, realistic additions to vegetation (+5% mature trees) can reduce air temperatures by up to 0.7 °C and surface temperatures by up to 1.6 °C in highly urbanised areas. For the suburban case, the largest impacts are on surface temperatures (1°C reduction through shading), mean radiant temperature and wind, with little effect on air temperature except in the extreme worst case of replacing all existing vegetation (20% of the study area) with asphalt, leading to 3.2°C increase at mid-day.

While surface temperatures and mean radiant temperatures are reduced from the base case for scenarios with additional greenspace in both case studies, air temperatures were only found to be reduced in the urban case. This is likely due to the very different ratios of built area to greenspace – 23% buildings and 20% greenspace in the suburban case, but 36% buildings and 3% greenspace in the urban case. In the suburban case, many spaces available for tree planting are already covered by grass, whereas the urban case requires removal of asphalt or concrete in order to make additional space for trees. This changes not only the greenspace amount but changes the surface energy balance by decreasing thermal storage in the urban area.

The results demonstrate that greenspace additions in densely built urban areas will have a greater microclimate and building energy impact than in the suburban case. This is reasonable in that the changes applied in the urban area are larger in terms of changes to existing greenspace. Adding 5% in an urban area is a big change to the overall proportion of green cover, nearly tripling the total amount of greenspace from 3% existing to a total of 8%, whereas adding 5% in the suburban case is only one-quarter of the existing 20% greenspace.
• Is the area of greenspace as a proportion of total area correlated to air temperature indicators, considering the average, maximum, or minimum air temperature or Urban Heat Island Intensity?
  o Hypothesis: Area of greenspace as a proportion of the area under investigation will have a negative linear relationship with at least one indicator of air temperature;

The total area of tree canopy around each sensor within five different distances was analysed for correlation with maximum, minimum, and average air temperatures and UHII. For summer, no significant relationships were found for the first three indices. Summer correlations were found for area of tree canopy and UHII. No significant winter correlations were found.

The iButton data demonstrate that, for summer, a significant correlation can be found between hours of UHII>4 and area of tree canopy within 100 m for the urban case, whereas the suburban shows the strongest correlation between UHII>3 and tree canopy within 50 m. For the suburban area, it is estimated that each 5% increase in canopy cover leads to 3 fewer hours with UHII>3 per month. For building energy, this translates to 3 fewer cooling degree hours, or 2.1% savings.

• Which greenspace effects, such as shading, evapotranspiration, and changes to wind speed, have the most influence on building energy consumption?
  o Hypothesis: Considering shading, evapotranspiration, and wind, shading will have the most impact on building energy consumption;

Savings are slightly greater due to trees being placed on the South side of a building (1.5% for a shallow plan 3-storey office building). Reducing the number of hours at the peak UHII (as evidenced by the iButton analysis presented in Chapter 5) results in up to 1.6% savings. However, a reduced wind speed due to the presence of mature trees (by 1 m/s) leads to a slight increase (0.4 % at most) in chiller energy required, attributable to reductions in heat transport away from the building envelope through convection.

Under peak UHI conditions (when wind is low), the most benefits will arise through shading, with estimates of 3.2%-4.8%, depending on building type, with most savings achieved in the three-storey shallow plan building.

• What is the trade-off between summer cooling and winter heating energy consumption when considering the microclimatic influences of greenspace?
Hypothesis: The benefit of reduced summer cooling energy will outweigh any detriment to winter heating energy caused by additional greenspace.

Although it would appear that there is a large increase in winter heating savings due to a building being situated within an urban area with a winter UHI, the results show that chiller energy must also be considered in these assessments. For the climate under consideration (temperate maritime), an increase in winter UHI may also lead to an increase in chiller energy usage for air conditioned buildings. These results are especially interesting because the CO₂ emissions due to electricity usage (as from chillers) are far higher than that for boiler usage (6.9 kg CO₂ per square metre for July chillers compared to 0.33 kg CO₂ per square meter for December boilers).

Given the results presented, the summer UHI is a factor that must be accounted for in building energy performance. In terms of energy usage, there is a clear strong reduction in winter boiler energy due to the UHI. However, if the greater emphasis is placed on carbon emissions, a different picture emerges. It then becomes clear that the summer UHI has the greater potential for increases in carbon emissions due to increased chiller usage.

The results confirm the importance of wind as a major factor in energy performance of buildings. While it is well established that a higher UHI is strongly correlated with low wind speeds, the study considers the effect of lower wind speeds due to additional vegetation. This leads to the conclusion that consideration must be given to planting schemes that will provide shade and/or temperature reductions, but not impede wind flow at the building envelope during summer. In this case, the distance for planting should be considered in such a way that it is close enough to provide shade, but not so close as to impede wind flow. In winter, if planting deciduous trees, plantings should not have a detrimental effect on wind flow.

9.2 Recommendations for Greenspace Planning

Based on the results presented in this research, several recommendations can be made for greenspace planning in the context of UK climate. Looking at the microclimate results of the two case studies presented here, different greening strategies might be applied depending on the urban morphology and existing composition of surface cover. In the urban case, with highly compact built forms, the smaller types of vegetation (new trees and hedges) can be found to reduce surface
temperatures by 0.4-0.5 °C and may prove more suitable for the space available for planting. In the suburban case, it is primarily the addition of large trees that will lead to measurable microclimate impacts and adding shading elements that will lead to energy savings.

For commercial buildings, the larger building volume to envelope ratio is the determining factor in building energy usage with regard to vegetation impacts. Whereas residential studies have shown significant impacts from vegetation, up to 47% (Akbari et al., 1997) this study concludes that the larger building envelope and building volumes in commercial buildings reduces the potential impacts of vegetation. Vegetation would need more strategic placement (on the south side, for instance) in order to have noticeable benefits and attention is needed to the percentage of building area shaded in order to reduce building surface temperature.

Based on the microclimate results showing wind speed reductions due to vegetation, careful siting is needed for trees that have the potential to be large at maturity. Such trees should be planted close enough to buildings to provide shade, but at a distance that will not obstruct wind. Therefore, the mature crown size should be taken into account in the planning stage and a gap between building and tree crown should be allowed to permit wind flow across the building envelope.

In terms of targeting neighbourhoods for redevelopment or retrofitting, an initial assessment should target any areas with buildings having a high percentage of glazing. In the building energy results, large increases in chiller energy usage (up to 64%) occur for the simple change from 20% glazing to 50% glazing. Therefore, in terms of controlling energy usage and carbon emissions, greening programs should begin by targeting buildings that are highly glazed, providing shade on the south side of a building in Northern latitudes. Such targeted measures could have the largest impact, allowing time and resources to be devoted to the areas that would most benefit from thermal enhancement.

### 9.3 Contributions to Knowledge

While the research has utilised modelling tools developed by other organisations, a number of approaches and outcomes contribute to knowledge in the understanding of microclimate and impacts on building energy for a climate such as that of the Northwest region of the UK.

While numerous studies have utilised empirical methods to investigate microclimate and building energy, the modelling approach in this study has allowed exploration of key variables and dynamic relationships that are difficult to examine in an empirical approach, which is often limited to interactions of small numbers of variables (such as the relationship between air temperature and distance from a park or size of a park).
The modelling scenarios examined here make it clear that tradeoffs are inherent in altering the composition of both urban and suburban areas. While it is already known that vegetation is only one of many factors influencing microclimate in urban areas, the role of different vegetation types has been further developed through this study. In the microclimate modelling, careful attention to realistic greening scenarios, such as types and percentages of greenspace that can be applied in both urban and suburban areas and careful attention to LAI as a major parameter provide a level of detail not presented in other similar studies. Owing to this detail, the results presented are realistic in terms of impacts that might be achieved in the near-term, within a period of 5-10 years.

To the author’s knowledge, this is the first quantification of combined microclimate and building energy impacts due to different green structure types in a UK city. While several studies have performed similar research in arid or tropical climates, and Akbari and Kolokotroni (2005) present a compilation of data for a wide range of climates, this study presents detailed analysis for a temperate maritime climate. The estimations of energy demand tradeoffs for office buildings due to greenspace, in terms of summer cooling and winter heating loads and the estimations of carbon emissions tradeoffs are areas that fill a distinct gap in the literature on urban greenspace and building energy performance for the UK. While some estimations have been made, they are primarily for residential energy and largely based on air temperature changes, rather than incorporating shading and wind effects, as analysed here.

The research fully documents the need for careful calibration of the model ENVI-met prior to full modelling comparisons between changing parameters or scenarios. The results of calibration demonstrate that, while the model can be quite accurate and useful, it does require careful calibration and attention to input parameters.

The approach of using empirical data to calibrate the model proved to have additional benefits, in that the iButton results could be further analysed for correlations with amount of tree canopy cover at varying distances from the iButton sensor. Using the iButton data, the study presents new findings about effect of distance on correlations between tree canopy cover and air temperatures in different seasons. One important finding is that UHII and maximum temperatures are not solely a function of vegetative cover, but are more strongly linked to urban morphology, such as building density and average height. Therefore, by analysing air temperature measurements in groups according to urban morphology, some of the confounding factors are eliminated and the relationship between UHII and proportion of tree cover is more apparent.
9.4 Limitations of the Study

The methods used in this research, while having the previously discussed advantages of modelling (Section 4.2) do have a few limitations. A mathematical or analytical model is always a limited representation of dynamic processes taking place in the real world. A model relies on previous research into the physical processes represented in the model and frequently must choose from several different methods of representing a particular process, as in the case of evapotranspiration models discussed in Section 3.4.2. For urban canopy layer models, of which ENVI-met is one, the issues of scale, parameterisation, and degree of sophistication of processes make it difficult to compare results from research using different models (Baklanov et al., 2009). In the case of ENVI-met, while several studies have produced interesting results (Ali-Toudert and Mayer, 2006; Emmanuel and Fernando, 2007; Fahmy et al., 2010) with the model, little evidence is available in the literature for its validation. This study addressed this limitation by first calibrating the model with air temperature measurements.

Another issue in performing a modelling study is the quality of data inputs and choice of values for initialisation parameters. The selection of study areas and model setup relied on numerous datasets derived from different sources (BADC for weather, Cities Revealed and MasterMap for buildings, tree canopy developed through aerial photographs, as detailed in Section 4.5.2). Most datasets will contain errors of some type and these can follow through, leading to error in later stages of the research. While these datasets have been developed elsewhere and complete accuracy cannot be guaranteed, each set was evaluated at the receiving stage, and again verified through field inspection when developing the list of potential study areas.

One known data issue occurred with iButton data collection. Due to lost or inaccessible i-buttons, far less data is available for the Jan-Mar period, which is one reason for concentrating winter results on December. For future data collection, the iButtons will need to be placed in more secure clips and attached to the hook using a wire or tie-wrap. Also, differences in timing of iButton recordings, as detailed in Appendix F, are estimated to have a small impact on the regression analysis. Potential error associated with timing differences has been analysed and found to be less than 0.07 °C for the majority of readings.

An issue with both the microclimate and building energy modelling is the length of running times. The length of model running times, particularly for ENVI-met, is limiting in terms of the number of study areas and scenarios that can be completed and analysed within a reasonable timeframe. ENVI-met scenarios take 3-6 days,
depending on model size and timesteps. For IES-VE, the shading calculations are also lengthy when using any complex shading elements, such as the trees included in the building energy scenarios. These required approximately six days to run each shading calculation for each of these building and tree combinations (3 buildings x 2 tree orientations x 6 days) – 36 days on shading calculations alone, for each set of buildings run. Attempts were made to speed up the process (including investigations of model timing and an investment in faster computer hardware) but the nature of the models was ultimately beyond any practical attempts to control this aspect.

9.5 Future Research Recommendations

While this research employed two separate modelling tools and used the outputs of the microclimate modelling to inform certain input parameters of the building energy modelling, the process of setting up, running, and analysing two separate models is lengthy, slow, and requires knowledge of two, mainly distinct, types of modelling. Clearly there is a need for modelling tools to be improved and developed at the building or neighbourhood level that can incorporate both the building structure and energy consumption calculations with changes to surrounding land use and vegetation structures. Ideally, such tools should be developed and integrated with GIS systems in order to speed the process of model setup and data input.

For scaling up the results from this study, the work could be applied to city-level by developing additional models for different building types (those that represent the most common building usages, including retail, residential, and education). As in this study, a first step would be to analyse data on building types and heights to gain an estimate of the building stock for the city. Then, perform building energy modelling on the remaining building types and height classes, which could probably be narrowed down to 10-12 additional classes. Finally, the percentage savings (per m2) could be applied across the building stock categories to develop a city-level or urban core estimate.

One issue that appears to be particularly difficult is the effect of wind on building energy performance. While some research argues that vegetation has the effect of reducing outside air infiltration, other research (including this) indicates that lower wind speed reduces the turbulent mixing of air and may lead to greater heat gain through the building envelope on warm days. Perhaps the first result is true for poorly sealed or poorly pressurised buildings wherein vegetation may act as an additional insulation. However, wind may also reduce heat gain through convection, and therefore, higher wind speed in summer will reduce heat gain at the building envelope. This particular aspect needs further study to clarify the relationship between wind speed and vegetation at the building envelope.
# Appendix A - Modelling Software Summary

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Inputs</th>
<th>Outputs</th>
<th>Cost and Additional Notes</th>
</tr>
</thead>
</table>
| Design Builder | 3-D Building Design by positioning, stretching, cutting 3-D blocks  
Building construction  
Activity  
HVAC  
Lighting | Linked to energy plus software for simulation of heating and cooling loads.  
Environmental performance data such as CO₂ emissions  
Internal air, mean radiant and operative temperatures and humidity  
Comfort output including underheating and overheating hours distribution curves, ASHRAE 55 comfort criteria (unmet loads), Fanger PMV, Pierce PMV ET, Pierce PMV SET, Pierce Discomfort Index (DISC), Pierce Thermal Sens. Index (TSENS), Kansas Uni TSV.  
Site weather data  
Heat transmission through building fabric including walls, roofs, infiltration, ventilation etc.  
Visualisation and site shading analysis | Free 30 day trial, then can get 90% student discount on purchase price of £799  
If using CIBSE/Met Office hourly weather data for Manchester, would need to purchase these files for £150 |
| IES-VE       | 3-D Building Design by positioning, stretching, cutting 3-D blocks  
Building construction  
Building thermal profiles  
HVAC  
Airflow analysis  
Lighting analysis | Same as Design Builder | Yearly student license available for £50  
Hourly weather files available for purchase  
Well documented and supported |
<table>
<thead>
<tr>
<th>Model Name</th>
<th>Inputs</th>
<th>Outputs</th>
<th>Cost and Additional Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENVI-met</td>
<td>Initial Configuration: Wind Speed, Roughness Length, Wind Direction, Initial Temp, Atmosphere, Specific Humidity in 2500 m, Relative Humidity in 2 m. Area Inputs: position and height of buildings, position of plants, distribution of surface materials and soil types, position of sources, position of receptors, database links, geographic position of the location on earth. Databases: Soils, Profiles – based on vertical layers of differing soils, Plants, Sources – for emissions of gases and particles.</td>
<td>Simulates: Flow around and between buildings, Exchange processes of heat and vapour at the ground surface and at walls, Turbulence, Exchange at vegetation and vegetation parameters, Bioclimatology, Particle dispersion.</td>
<td>Free program which has been used in a number of papers on greenspace modelling. Suitable for modelling finescale greenspace and microclimate – high resolution (0.5-10 m) and small time-steps (down to 10 sec).</td>
</tr>
<tr>
<td>TAS building designer (EDSL)</td>
<td>Draw or import 3D building models, Weather data (energy plus)</td>
<td>Heating and Cooling Loads, Shading and daylight analysis, Evaluation of Ventilation Regimes</td>
<td>Similar to Design Builder. Free trial can last for up to 8 weeks. Gives access to data for 2500 recorded weather sites worldwide. Hourly values for solar radiation, temperature, humidity, windspeed, and direction. Does not appear to be as well supported and documented as Design Builder but is widely used.</td>
</tr>
<tr>
<td>PCRaster</td>
<td>Dynamic Modelling program specifically created for modelling of environmental problems. User is free to develop the variables, equations, and dynamics necessary to a specific problem. Inputs include raster maps, lookup tables, variable values, equations.</td>
<td>3D visualisations of environmental processes.</td>
<td>Uses the Python programming language which is very good at handling spatio-temporal variables. Has been used for modelling landslide, land degradation, ecology, hydrology, and geomorphology. So far, has been mainly used for land-based processes. May be only 2.5 D, not truly 3D, so needs investigation to determine if it’s suitable for surface-plant-air interaction.</td>
</tr>
</tbody>
</table>
Appendix B – Output Files from ENVI-met

Main Data Files
Contains the complete state of the 3D model, including the atmosphere, the surface and the soil. These files are stored in binary format.

Atmospheric Data

<table>
<thead>
<tr>
<th>FIELD</th>
<th>UNIT</th>
<th>MEANING</th>
</tr>
</thead>
<tbody>
<tr>
<td>z</td>
<td>m</td>
<td>Model height of data (Cartesian coordinates.)</td>
</tr>
<tr>
<td>Classed LAD</td>
<td>-</td>
<td>Classified LAD and ID for buildings (see remark)</td>
</tr>
<tr>
<td>Flow u</td>
<td>m/s</td>
<td>Wind speed u-component</td>
</tr>
<tr>
<td>Flow v</td>
<td>m/s</td>
<td>Wind speed v-component</td>
</tr>
<tr>
<td>Flow w</td>
<td>m/s</td>
<td>Wind speed w-component</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>m/s</td>
<td>Total wind speed</td>
</tr>
<tr>
<td>Wind Speed change</td>
<td>%</td>
<td>Change of wind speed comp. to inflow</td>
</tr>
<tr>
<td>Wind direction</td>
<td>deg</td>
<td>direction of the wind flow relative to geographic north</td>
</tr>
<tr>
<td>Pressure perturb</td>
<td>Pa</td>
<td>Relative Pressure Perturbation</td>
</tr>
<tr>
<td>Pot. Temperature</td>
<td>K</td>
<td>Potential Air temperature</td>
</tr>
<tr>
<td>Pot. Temperature (Diff K)</td>
<td>K</td>
<td>Potential Air temp. difference to inflow</td>
</tr>
<tr>
<td>Pot. Temperature Change</td>
<td>K/h</td>
<td>Change of Air Temperature with time</td>
</tr>
<tr>
<td>Spec. Humidity</td>
<td>g/kg</td>
<td>Specific Humidity Air</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>%</td>
<td>Relative Humidity of Air</td>
</tr>
<tr>
<td>TKE</td>
<td>m²/s²</td>
<td>Turbulent Kinetic Energy</td>
</tr>
<tr>
<td>Dissipation</td>
<td>m²/s²</td>
<td>Dissipation of TKE</td>
</tr>
<tr>
<td>Vertical Exchange Coef. I.</td>
<td>m²/s</td>
<td>Vertical Turbulent exchange coefficient Km</td>
</tr>
<tr>
<td>Horizontal Exchange Coef.</td>
<td>m²/s</td>
<td>Horizontal Turbulent exchange coefficient Km</td>
</tr>
<tr>
<td>Absolute LAD</td>
<td>m²/m³</td>
<td>Leaf Area Density</td>
</tr>
<tr>
<td>Direct SW Radiation</td>
<td>W/m²</td>
<td>Shortwave Direct Radiation (see remark)</td>
</tr>
<tr>
<td>Diffuse SW Radiation</td>
<td>W/m²</td>
<td>Shortwave Diffuse Radiation (see remark)</td>
</tr>
<tr>
<td>Reflected SW Radiation</td>
<td>W/m²</td>
<td>Shortwave Direct Radiation (see remark)</td>
</tr>
<tr>
<td>Longwave Rad. Environment</td>
<td>W/m²</td>
<td>Longwave Radiation received from the environment</td>
</tr>
<tr>
<td>Sky-View-Factor Buildings</td>
<td>-</td>
<td>Sky-View-Factor (only buildings considered)</td>
</tr>
<tr>
<td>Sky-View-Factor Bld+ Vegetation</td>
<td>-</td>
<td>Sky-View-Factor (buildings plus vegetation considered)</td>
</tr>
<tr>
<td>Temperature Flux</td>
<td>K*m/s</td>
<td>Temperature flux from vegetation per unit leaf area</td>
</tr>
<tr>
<td>Vapour Flux</td>
<td>g/kg*m/s</td>
<td>Vapour flux from vegetation per unit leaf area</td>
</tr>
<tr>
<td>Water on leaves</td>
<td>g/m²</td>
<td>Amount of liquid water on leaves</td>
</tr>
<tr>
<td>WallTemp Cellborder x</td>
<td>K</td>
<td>Wall Temperature Wall x-axis (see Knowledgebase 12)</td>
</tr>
<tr>
<td>WallTemp Cellborder y</td>
<td>K</td>
<td>Wall Temperature Wall y-axis (see remark)</td>
</tr>
<tr>
<td>FIELD</td>
<td>UNIT</td>
<td>MEANING</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>--------</td>
<td>-----------------------------------------------------------</td>
</tr>
<tr>
<td>Wall Temp Cellborder z</td>
<td>K</td>
<td>Wall Temperature Wall z-axis (see remark)</td>
</tr>
<tr>
<td>Leaf Temperature</td>
<td>K</td>
<td>Temperature of leaves in grid box</td>
</tr>
<tr>
<td>Local Mixing Length</td>
<td>m</td>
<td>Mixing length calculated from the TKE-Dissipation</td>
</tr>
<tr>
<td>PMV Value</td>
<td>-</td>
<td>PMV value (see [PMV] section)</td>
</tr>
<tr>
<td>PPD Value</td>
<td>%</td>
<td>Percentage People Dissatisfied (see [PMV] section)</td>
</tr>
<tr>
<td>Mean Radiant Temperature</td>
<td>K</td>
<td>Mean Radiative temperature</td>
</tr>
<tr>
<td>Gas/Particle concentration</td>
<td>µg/m³</td>
<td>Concentration of selected particle or gas in microgram</td>
</tr>
<tr>
<td>Gas/Particle source</td>
<td>µg/s</td>
<td>Emission rate of particle or gas source in microgram</td>
</tr>
<tr>
<td>Deposition velocity</td>
<td>mm/s</td>
<td>Deposition velocity (only at surfaces)</td>
</tr>
<tr>
<td>Total Deposited Mass</td>
<td>µg/m²</td>
<td>Total amount of mass deposited to ground or leaf surface unit area since start (*)</td>
</tr>
<tr>
<td>Deposited Mass time averaged</td>
<td>µg/(m²s)</td>
<td>Average Amount of mass deposited per hour (*)</td>
</tr>
<tr>
<td>TKE normalised 1D</td>
<td>-</td>
<td>TKE normalised with 1D profile (E/E_1D)</td>
</tr>
<tr>
<td>Dissipation normalised 1D</td>
<td>-</td>
<td>Dissipation normalised with 1D profile (Eps/eps_1d)</td>
</tr>
<tr>
<td>Km normalised 1D</td>
<td>-</td>
<td>Vertical Km norm. with 1D profile (Km/Km_1D)</td>
</tr>
<tr>
<td>TKE Mechanical Prod</td>
<td></td>
<td>Turbulence Production due to wind shear (tensor deformation)</td>
</tr>
<tr>
<td>Stomata Resistance</td>
<td>m/s</td>
<td>Stomata resistance of plant</td>
</tr>
<tr>
<td>CO₂</td>
<td>mg/m³</td>
<td>CO₂ concentration (if A-gs model used, see [PLANTMODEL] section)</td>
</tr>
<tr>
<td>CO₂</td>
<td>ppm</td>
<td>CO₂ concentration in ppm (*)</td>
</tr>
<tr>
<td>Plant CO₂ flux</td>
<td>mg/kg*m/s</td>
<td>CO₂ flux per unit leaf area (see remark)</td>
</tr>
<tr>
<td>Div Rlw Temp change</td>
<td>K/h</td>
<td>Air Temperature change due to longwave flux divergence</td>
</tr>
<tr>
<td>Local mass budget</td>
<td>µg/(s*m³)</td>
<td>Local pollutant mass budget of grid cell (: net deposition)</td>
</tr>
</tbody>
</table>
### Surface Flux

<table>
<thead>
<tr>
<th>FIELD</th>
<th>UNIT</th>
<th>MEANING</th>
</tr>
</thead>
<tbody>
<tr>
<td>z_topo</td>
<td>m</td>
<td>Absolute height of model ground surface (always 0 in recent version)</td>
</tr>
<tr>
<td>T Surface</td>
<td>K</td>
<td>Ground surface temperature</td>
</tr>
<tr>
<td>T Surface Diff</td>
<td>K</td>
<td>Difference of ground surface to reference surface</td>
</tr>
<tr>
<td>T Surface change</td>
<td>K/h</td>
<td>Change of ground surface temperature</td>
</tr>
<tr>
<td>q Surface</td>
<td>g/kg</td>
<td>Specific humidity of surface (available vapour)</td>
</tr>
<tr>
<td>uv above surface</td>
<td>m/s</td>
<td>Wind speed at the first grid level above ground surface</td>
</tr>
<tr>
<td>Sensible heat flux</td>
<td>W/m²</td>
<td>Sensible heat flux into the air (+: towards air)</td>
</tr>
<tr>
<td>Exchange coef. Heat</td>
<td>m²/s</td>
<td>Exchange coefficient for heat between surface and air</td>
</tr>
<tr>
<td>Latent heat flux</td>
<td>W/m²</td>
<td>Sensible heat flux into the air (+: towards air)</td>
</tr>
<tr>
<td>Soil heat flux</td>
<td>W/m²</td>
<td>Heat flux into soil (+: directed towards deeper layers)</td>
</tr>
<tr>
<td>Sw direct radiation</td>
<td>W/m²</td>
<td>Direct shortwave radiation reaching ground surface</td>
</tr>
<tr>
<td>Sw diffuse radiation</td>
<td>W/m²</td>
<td>Diffuse shortwave radiation reaching ground surface</td>
</tr>
<tr>
<td>Lambert factor</td>
<td>0..1</td>
<td>Value of Lambert's law for solar angle</td>
</tr>
<tr>
<td>Longwave radiation bud.</td>
<td>W/m²</td>
<td>Longwave radiation budget of ground surface</td>
</tr>
<tr>
<td>Longwave rad. from vegetation</td>
<td>W/m²</td>
<td>Longwave radiation received from vegetation layers above</td>
</tr>
<tr>
<td>Longwave rad. from environment</td>
<td>W/m²</td>
<td>Longwave radiation received from buildings</td>
</tr>
<tr>
<td>Water flux</td>
<td>g/(m²/s)</td>
<td>Water flux from/to the ground surface</td>
</tr>
<tr>
<td>Sky-View Factor</td>
<td>0...1</td>
<td>Sky View factor for z=0 (buildings only counted)</td>
</tr>
<tr>
<td>Building height</td>
<td>m</td>
<td>Height of building top (0 if no building assigned)</td>
</tr>
<tr>
<td>Surface albedo</td>
<td>0...1</td>
<td>Albedo of ground surface</td>
</tr>
<tr>
<td>Deposition speed</td>
<td>mm/s</td>
<td>Deposition flux of analysed pollutant component</td>
</tr>
<tr>
<td>Mass deposited</td>
<td>µg/m²</td>
<td>Mass deposited at ground surface in µg</td>
</tr>
</tbody>
</table>

### Soil

<table>
<thead>
<tr>
<th>FIELD</th>
<th>UNIT</th>
<th>MEANING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>K</td>
<td>Soil temperature</td>
</tr>
<tr>
<td>Volumetric water content</td>
<td>m³/m²</td>
<td>Water content of the soil matrix</td>
</tr>
<tr>
<td>Relative soil wetness</td>
<td>%</td>
<td>Relative wetness of soil compared to its saturation value</td>
</tr>
</tbody>
</table>
Appendix C – GIS Processing Logs

GIS Processing Details for Tree Canopy Cover

First, a 500-metre grid was used to sum the total area of tree canopy for each grid cell. Although helpful in getting an overall picture of areas with low and high tree cover, the grid was found to be too coarse for investigating building and block-level sites as criteria for selection.

In order to match the scale of some other datasets, such as surface temperature, the tree canopy polygons were reprocessed to a raster grid of 30 m. The tree canopy was reprocessed as follows: Using Conversion Tools – Feature to Raster, the tree canopy polygons were reprocessed to an output cell size of 3x3, with cells assigned a value based on the sum of Shape_Area (area of each polygon within the cell). This was then aggregated to a 30 m grid by using Spatial Analyst – Generalization – Aggregate with a cell factor of 10. The final output is a grid of cell size 30x30 with each cell’s value being the total area of tree cover for that cell.

GIS Processing Details for Buildings Dataset

To clean the dataset, a second buildings dataset was downloaded from OS MasterMap for comparison. Buildings in the Cities Revealed dataset were matched to buildings in MasterMap by selecting polygons that have their centroids in a polygon from MasterMap. When tested for the Manchester local authority, this method is able to assign heights to 84% of buildings, leaving only 16% with no match for height.

The buildings with a match in MasterMap were exported as a separate dataset and rasterized as a 3x3 grid using Conversion Tools – Polygon to Raster. Those cells with a height of zero were deemed to be unreliable and were then set to a value of ‘NoData’ using the SetNull tool. To be consistent with other datasets, this was then aggregated to a 30 m grid using the Spatial Analyst – Generalization with a cell factor of 10 and Aggregation Technique of Average. The result is a 30x30 grid with each cell’s value being the average building height for that area.
Appendix D - Building Energy Usage by Type

Figure D-1 – Energy Usage for Education – 15th July

Figure D-2 – Energy Usage for Domestic – 15th July

Figure D-3 – Energy Usage for Hospital – 15th July
Figure D-4 – Energy Usage for Office – 15th July
Appendix E - Calculations for Determining Building Height Classification

Table D-1 – Percentile Calculations for Building Height

<table>
<thead>
<tr>
<th>From Access, Percentile Module, All Buildings</th>
<th>From MS Access, Percentile Module, All Buildings 12</th>
<th>From MS Access, Percentile Module, All Buildings Except Dwellings 13 (7417 buildings)</th>
<th>From MS Access, Percentile Module, Dwellings Only (158,811)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Height</td>
<td>160</td>
<td>119</td>
<td>160</td>
</tr>
<tr>
<td>75th Percentile Height</td>
<td>9.9</td>
<td>14.6</td>
<td>9.9</td>
</tr>
<tr>
<td>Median Height</td>
<td>9.6</td>
<td>10.9</td>
<td>9.6</td>
</tr>
<tr>
<td>25th Percentile Height</td>
<td>9.4</td>
<td>9.7</td>
<td>9.4</td>
</tr>
<tr>
<td>Minimum Height</td>
<td>1.9</td>
<td>2.3</td>
<td>3.5</td>
</tr>
<tr>
<td>Fourth Spread</td>
<td>0.5</td>
<td>4.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Upper Outlier Boundary</td>
<td>10.35</td>
<td>18.25</td>
<td>10.35</td>
</tr>
<tr>
<td>Lower Outlier Boundary</td>
<td>8.85</td>
<td>3.55</td>
<td>8.85</td>
</tr>
<tr>
<td>New Std Dev</td>
<td>0.25</td>
<td>2.35</td>
<td>0.25</td>
</tr>
<tr>
<td>Low</td>
<td>9.1</td>
<td>6.2</td>
<td>9.1</td>
</tr>
<tr>
<td>Avg</td>
<td>9.6</td>
<td>11.3</td>
<td>9.6</td>
</tr>
<tr>
<td>Tall</td>
<td>10.1</td>
<td>15.6</td>
<td>10.1</td>
</tr>
</tbody>
</table>

12 Includes all buildings with height data, whether the function is known or not
13 This does not include buildings of unknown base function
Appendix F – Sources of Variation in iButton Readings

As mentioned previously, one point of variation in the readings that should be considered is the timing of the readings. Although calibrated against a certified iButton, the sensors were set running in sequence so that timings are not perfectly synchronised. Table F-1 shows the hourly reading times for each button, which varies from 13-past to 20-past each hour, so the timing difference between two sensors can be up to 7 minutes.

Table F-1 – iButton numbers and reading times

<table>
<thead>
<tr>
<th>i-button number</th>
<th>Reading Times</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>00:18, 00:48</td>
</tr>
<tr>
<td>32</td>
<td>00:13, 00:43</td>
</tr>
<tr>
<td>33</td>
<td>00:14, 00:44</td>
</tr>
<tr>
<td>34</td>
<td>00:14, 00:44</td>
</tr>
<tr>
<td>35</td>
<td>00:15, 00:45</td>
</tr>
<tr>
<td>36</td>
<td>00:16, 00:46</td>
</tr>
<tr>
<td>37</td>
<td>00:16, 00:46</td>
</tr>
<tr>
<td>38</td>
<td>00:17, 00:47</td>
</tr>
<tr>
<td>39</td>
<td>00:17, 00:47</td>
</tr>
<tr>
<td>41</td>
<td>00:18, 00:48</td>
</tr>
<tr>
<td>42</td>
<td>00:19, 00:49</td>
</tr>
<tr>
<td>43</td>
<td>00:20, 00:50</td>
</tr>
<tr>
<td>44</td>
<td>00:20, 00:50</td>
</tr>
</tbody>
</table>

In order to check possible temperature differences due to differences in timing, differences in half-hourly readings were analysed for all of July and August. This analysis showed that, for over 95% of readings the average temperature change between any two half hourly readings was 0.3 °C. If this is interpolated to a time difference of 7 minutes, the potential difference is reduced to 0.07 °C, very close to the overall accuracy of iButtons. In a very few cases, the half-hourly change was greater than 2 °C, but this occurred in less than 0.5% of readings.

Additionally, daily average temperatures were analysed for the 2-week period after calibration but before iButtons were placed in study areas. A daily average temperature was calculated for each iButton and then the maximum temperature difference between any two buttons was recorded. Over the two week period, the average difference between buttons was less than 0.06 °C with a maximum difference of 0.10 °C.

Table F-2 – Check on Average Daily Temperatures after Calibration but Prior to Placement in Study Areas

<table>
<thead>
<tr>
<th>Date</th>
<th>iButton recording for the Minimum Daily Average Temperature</th>
<th>iButton recording for the Maximum Daily Average Temperature</th>
<th>Temp Difference (Max-Min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29-Jun-10</td>
<td>25.0280</td>
<td>25.0832</td>
<td>0.0552</td>
</tr>
<tr>
<td>30-Jun-10</td>
<td>24.8669</td>
<td>24.9223</td>
<td>0.0554</td>
</tr>
<tr>
<td>Date</td>
<td>Min</td>
<td>Max</td>
<td>Difference</td>
</tr>
<tr>
<td>--------</td>
<td>-------</td>
<td>-------</td>
<td>------------</td>
</tr>
<tr>
<td>01-Jul-10</td>
<td>25.0587</td>
<td>25.0969</td>
<td>0.0383</td>
</tr>
<tr>
<td>02-Jul-10</td>
<td>24.0908</td>
<td>24.1279</td>
<td>0.0371</td>
</tr>
<tr>
<td>03-Jul-10</td>
<td>23.3275</td>
<td>23.3674</td>
<td>0.0399</td>
</tr>
<tr>
<td>04-Jul-10</td>
<td>22.9764</td>
<td>23.0139</td>
<td>0.0374</td>
</tr>
<tr>
<td>05-Jul-10</td>
<td>22.7071</td>
<td>22.7522</td>
<td>0.0451</td>
</tr>
<tr>
<td>06-Jul-10</td>
<td>22.9216</td>
<td>22.9992</td>
<td>0.0775</td>
</tr>
<tr>
<td>07-Jul-10</td>
<td>21.5784</td>
<td>21.6402</td>
<td>0.0619</td>
</tr>
<tr>
<td>08-Jul-10</td>
<td>21.8050</td>
<td>21.9009</td>
<td>0.0959</td>
</tr>
<tr>
<td>09-Jul-10</td>
<td>22.6990</td>
<td>22.7816</td>
<td>0.0826</td>
</tr>
<tr>
<td>10-Jul-10</td>
<td>23.9693</td>
<td>24.0414</td>
<td>0.0721</td>
</tr>
<tr>
<td>11-Jul-10</td>
<td>23.3021</td>
<td>23.3653</td>
<td>0.0632</td>
</tr>
</tbody>
</table>

Average Difference Between Min and Max i-buttons: 0.0586
Appendices

Appendix G – Building Energy Model Details

IES Ltd Helix Building, Kelvin Campus West of Scotland Science Park Glasgow G20 0SP

Project contact details

Project 3x3Office_4trN

Location & Site Data

<table>
<thead>
<tr>
<th>Location</th>
<th>Manchester Airport</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>Latitude</td>
<td>53.35 N</td>
</tr>
<tr>
<td>Longitude</td>
<td>2.28 W</td>
</tr>
<tr>
<td>Altitude</td>
<td>69.0m</td>
</tr>
<tr>
<td>Time zone</td>
<td>0.0 hours</td>
</tr>
<tr>
<td>Hours ahead of GMT</td>
<td></td>
</tr>
<tr>
<td>Daylight Saving Time</td>
<td></td>
</tr>
<tr>
<td>Time adjustment</td>
<td>1.0 hours</td>
</tr>
<tr>
<td>From</td>
<td>April</td>
</tr>
<tr>
<td>Through</td>
<td>October</td>
</tr>
<tr>
<td>Adjustment for other months</td>
<td>0.0 hours</td>
</tr>
<tr>
<td>Site Data</td>
<td></td>
</tr>
<tr>
<td>Ground reflectance</td>
<td>0.2</td>
</tr>
<tr>
<td>Terrain type</td>
<td>Suburbs</td>
</tr>
<tr>
<td>Wind exposure</td>
<td>(CIBSE Heating Loads)</td>
</tr>
</tbody>
</table>

Weather Simulation Data

ApacheSim File UK_Manchester_UH16_green_wind.epw

<table>
<thead>
<tr>
<th>Design Weather Data</th>
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</thead>
<tbody>
<tr>
<td>Source of Design Weather</td>
</tr>
<tr>
<td>ASHRAE weather location</td>
</tr>
<tr>
<td>Monthly percentile for Heating Loads design weather</td>
</tr>
<tr>
<td>Monthly percentile for Cooling Loads design weather</td>
</tr>
<tr>
<td>Heating Loads Weather Data</td>
</tr>
<tr>
<td>Outdoor Winter Design Temperature</td>
</tr>
<tr>
<td>Cooling Loads Weather Data</td>
</tr>
<tr>
<td>Max. Outside Dry-Bulb</td>
</tr>
<tr>
<td>Max. Outside Wet-Bulb</td>
</tr>
</tbody>
</table>
### Weather model data

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Humidity</th>
<th>Solar Radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry bulb T</td>
<td>Wet bulb T</td>
<td>Linke Turbidity</td>
</tr>
<tr>
<td>Min</td>
<td>Max at Max dry bulb</td>
<td>Factor</td>
</tr>
<tr>
<td>(°C)</td>
<td>(°C)</td>
<td></td>
</tr>
<tr>
<td>Jan</td>
<td>7.70</td>
<td>10.40</td>
</tr>
<tr>
<td>Feb</td>
<td>7.90</td>
<td>10.60</td>
</tr>
<tr>
<td>Mar</td>
<td>9.50</td>
<td>10.40</td>
</tr>
<tr>
<td>Apr</td>
<td>12.90</td>
<td>13.30</td>
</tr>
<tr>
<td>May</td>
<td>15.70</td>
<td>15.60</td>
</tr>
<tr>
<td>Jun</td>
<td>19.20</td>
<td>18.20</td>
</tr>
<tr>
<td>Jul</td>
<td>20.70</td>
<td>18.40</td>
</tr>
<tr>
<td>Aug</td>
<td>21.10</td>
<td>18.40</td>
</tr>
<tr>
<td>Sep</td>
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<td>Dec</td>
<td>8.90</td>
<td>11.50</td>
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</table>

### Thermal Template: General Office

**Building Regulations**

- **Room Type**: Heated or occupied room
- **External Ventilation**: 0 air changes per hour

**NCM Building Type**

**NCM Activity**

**Room Conditions**

- **Heating**
  - **Profile**: Plant type 1
  - **Setpoint**: Constant 19 °C
  - **Hot Water consumption**: 0.00 l/(h·pers)

- **Cooling**
  - **Profile**: Plant type 1
  - **Setpoint**: Constant 23 °C

**Model Settings**

- **Solar Reflected Fraction**: NaN
- **Furniture Mass Factor**: 1.00

**Systems**

- **HVAC System**: Main system
- **Auxiliary vent. system**: Main system
- **DHW system**: Main system

- **Heating**
  - **Radiant Fraction**: 0.20
  - **Capacity**: unlimited

- **Cooling**
  - **Radiant Fraction**: 0.00
  - **Capacity**: unlimited

- **Humidity Control**
  - **Min. % Saturation**: 0 %
  - **Max. % Saturation**: 100 %

- **System outside air supply**
  - **Min. Flow Rate**: 0.80 l/(s·m²)
  - **Add. Free Cooling Capacity**: 0.00 AC/h

**Internal Gains**

- **Computers : General Office**
  - **Max Sensible Gain**: 12.00 W/m²
  - **Max Power Consumption**: 12.00 W/m²

- **Fluorescent Lighting : General Office**
  - **Max Sensible Gain**: 12.00 W/m²

- **People : General Office**
  - **Variation Profile**: on continuously
### Max Sensible Gain
90.00 W/P

### Max Latent Gain
60.00 W/P

### Occupant Density
14.00 m²/person

### Variation Profile
Occupancy type 1

### Air Exchanges

<table>
<thead>
<tr>
<th>Type</th>
<th>Variation Profile</th>
<th>Adjacent Condition</th>
<th>Max A/C Rate</th>
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<tbody>
<tr>
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<td>External Air</td>
<td>0.25 AC/h</td>
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**Rooms using this template**

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Constructions associated with this model

<table>
<thead>
<tr>
<th>ID</th>
<th>Description</th>
<th>U-value CIBSE (W/m²·K)</th>
<th>Total shading coefficient (glazed only)</th>
<th>No. of rooms</th>
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<tbody>
<tr>
<td>Roof</td>
<td>FROOF2 [flat roof (2002 regs)]</td>
<td>0.249</td>
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<tr>
<td>Ceiling</td>
<td>CCR101 [Carpeted 100mm reinforced-concrete ceiling]</td>
<td>2.117</td>
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<tr>
<td>External Wall</td>
<td>STD_WAL2 [standard wall construction (2002 regs)]</td>
<td>0.349</td>
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<td>Internal Partition</td>
<td>IWP1B [13mm pl1</td>
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<td>Ground Floor</td>
<td>STD_FLO2 [standard floor construction (2002 regs)]</td>
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<td>Door</td>
<td>DOOR [wooden door]</td>
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<td>GDPK6 [low-e double glazing (6mm+6mm) (2002 regs)]</td>
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<tr>
<td>Internal Glazing</td>
<td>GSP4I [4mm Pilkington single glazing]</td>
<td>4.080</td>
<td>1.056</td>
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Electric Lighting Templates

- Template: default
  - Luminance Level: 500 cd/m²
  - Luminaire: DULCET: CROMPTON DULCET WITH OPAL DIFFUSER (source: unknown file)
  - Limiting Glare Index: 19
  - Lamp: 1203: 1200mm Polylux T8 lamp
  - Working Surface Height: 0.850 m
  - Lamp Colour: WW: 3450.0 lm, lmf=3
  - Mounting Height: 2.7 m
  - Luminaire Maintenance Factor (LMF): 0.90
  - Room Surface Maintenance Factor (RSMF): 0.90
  - Lamp-Lumen Maintenance Factor (LLMF): 5000.00
  - Replacement period: 5000.00
  - Lamp Survival Factor (LSF): 1.00

Rooms using this template

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<thead>
<tr>
<th>Room ID</th>
<th>Room Name</th>
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<tbody>
<tr>
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<td>ROOM_G_F_1</td>
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<td>[ROOM0001]</td>
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### Template: General Office

<table>
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<th>Parameter</th>
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<tr>
<td>Luminance Level</td>
<td>500 cd/m²</td>
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<tr>
<td>Luminaire</td>
<td>DULCET: CROMPTON DULCET WITH OPAL DIFFUSER (source: unknown file)</td>
</tr>
<tr>
<td>Limiting Glare Index</td>
<td>19</td>
</tr>
<tr>
<td>Lamp</td>
<td>1203: 1200mm Polylux T8 lamp</td>
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<tr>
<td>Working Surface Height</td>
<td>0.750 m</td>
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<td>Lamp Colour</td>
<td>WW: 3450.0 lm, lm=3</td>
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<td>Mounting Height</td>
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<td>Luminaire Maintenance Factor (LMF)</td>
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<td>Room Surface Maintenance Factor (RSMF)</td>
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<tr>
<td>Replacement period</td>
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<td>Lamp Survival Factor (LSF)</td>
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</table>

| Rooms using this template     |                                            |
| Room ID                       | Room Name                                  |
| [ROOF0000]                    | ROOF                                       |
# Room Attributes Templates

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<tbody>
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<td>Lettable Area</td>
<td>80.0%</td>
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Rooms using this template

<table>
<thead>
<tr>
<th>Room ID</th>
<th>Room Name</th>
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References


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