‘LITERATURE REVIEW:
Impacts of Climate Change on Urban Environments’
~ Draft Copy ~

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Notes:

This report is the draft ***Literature Review*** carried out by the Centre for Urban & Regional Ecology, University of Manchester, as part of the ASCCUE project.

While every effort has been made to ensure accuracy, no responsibility can be accepted for errors or omissions.

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1. Introduction

The potential international and global impacts of climate change have been, and continue to be, explored (IPCC, 2001). Although some of these studies may be relevant, this review is mainly concerned with urban environments in the UK. The review forms part of the 'Adaptation Strategies for Climate Change in the Urban Environment (ASCCUE)' project, which is one of six components of the EPSRC/UKCIP funded 'Building Knowledge for a Changing Climate' initiative (EPSRC & UKCIP, 2003). ASCCUE focuses on the vulnerability of towns and cities to climate change and the development of adaptation strategies in the urban environment to cope with these changes. It will study two conurbations of contrasting size, vulnerability, and climate regime: Greater Manchester (a large conurbation in the North West) and Lewes (a low-lying town in a tidal river valley in the South East). It aims to assess the impacts of climate change at the town or city level; develop and test methodologies for the vulnerability assessment of three exposure units (building integrity, human comfort and urban greenspace); identify potential socio-economic impacts; and provide an evaluation of adaptation options. This literature review will inform these stages within the project.

The UK Climate Impacts Programme (UKCIP) was set up in 1997 to coordinate research into impacts of, and adaptation strategies to, climate change. It has developed climate change scenarios for the UK (UKCIP98, followed by the later, improved UKCIP02 scenarios), which present information on the possible changes in climate over the 21st century (section 2) (UKCIP, 2003). UKCIP has been a catalyst to regional studies of the potential impacts of climate change in the UK (UKCIP, 2003). The distribution of the potential impacts of climate change will vary depending on the physical, biological and socio-economic features of the environment. For example, a coastal urban environment will be impacted in differing ways to an upland rural environment. The climate change impacts assessment of London was the first UK study with a specifically urban focus (LCCP, 2002). Urban environments will experience many of the same impacts of climate change as other environments but perhaps in more unusual and costly ways as they interact with other effects of urbanisation. For example, riverine flooding may be combined with flooding from overwhelmed storm drains and sewers (IPCC, 2001). These impacts will also affect more people since a large proportion of the population live in urban environments. In the UK, 90% of the population lives in conurbations covering 10% of its land area (URGENT, 2003).

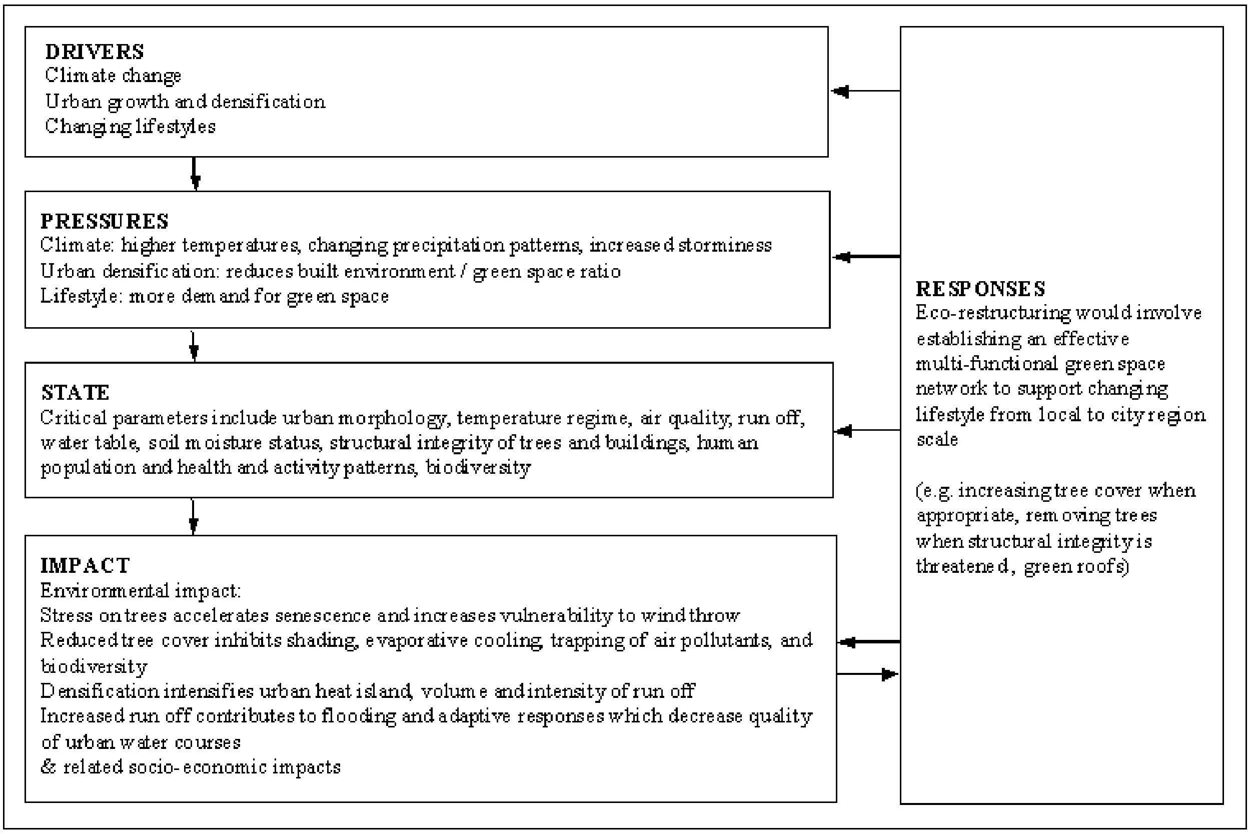
1.1 Structure of the Report

The report will be structured to follow the Driver-Pressure-State-Impact-Response (DPSIR) framework for reporting on environmental issues (fig. 1), employed by the European Environment Agency (EEA, 2003). This structure helps to highlight the dynamic nature of the urban system and the complex interactions and feedback loops that exist within it. The report focuses on the first four stages of the framework, from the drivers of change to the related impacts on the urban environment. It will not be overly concerned with possible responses to climate change impacts, which will be a topic of further research within the ASCCUE project itself.

The report initially considers three key drivers of change in the urban system (section 2): climate change, change of urban form and changing lifestyles. It is recognised that these drivers do not act in isolation, but rather that they act in conjunction with, and impact upon, each other. Additionally they will act in conjunction with other environmental, socio-economic and political drivers. Following this, the key pressures on the urban system are identified (section 3). In the case of climate change, the pressures relate to the projected UKCIP02 scenarios. Particular attention will be given to the scenarios for the north west and south east of England, where

Greater Manchester and Lewes are, respectively. Again, these pressures do not occur in isolation from each other.

Fig. 1. An example of the DPSIR framework for reporting on environmental issues (EEA, 2003) applied to climate change in the urban environment



The report then discusses the current state of the urban environment (section 4), in relation to climate, air quality, hydrology, green space, human well-being and building integrity. The latter three are considered to be the key components of the urban environment for the ASCCUE project, with human well-being substituted as a broader component which includes human comfort. It is helpful, for the sake of this report, to consider the state of urban climate, air quality, and hydrology separately. Climate change, urban form and lifestyle changes will impact upon each of these, and they, in turn, will impact upon the three components of the urban environment. Thus, climate change will be seen to act both directly and indirectly.

The next section of the report covers the potential impacts of the pressures, given the state, on the urban environment (section 5), as identified in the literature. This includes impacts on air quality, hydrology, green space, human well-being, and building integrity, as well as their related socio-economic impacts. Green space includes impacts of climate change on vegetation, soil, and biodiversity. Human well-being includes health and comfort. Building integrity includes the impacts upon building structure, fabric, design and construction, as well as upon infrastructure. Whilst the socio-economic impacts relate to tourism, crime and society, industry and business, and insurance. Finally, the conclusion (section 6) attempts to further draw out the complex interactions between the different components of the urban environment, mentioned in the report where appropriate. For example, an impact on green space quality may affect both human comfort and building integrity.

2. Drivers of climate change in the urban environment

The UKCIP02 climate change scenarios were developed by considering the rate of global greenhouse gas emissions and other pollutants, as well as the response of the climate to these emissions (Hulme *et al*., 2002). Carbon dioxide is the main greenhouse gas that is influenced by human activities (Hulme *et al*., 2002). The rate of pollutant emissions is described using different socio-economic scenarios, dependent on assumptions about how the world's population, economy, energy-technology and lifestyles evolve. The response of the climate system, is explored using global and regional climate models (Hulme *et al*., 2002).

Fig. 2. Global carbon dioxide emissions from 2000 to 2100 (for the four chosen IPCC (2000) emissions scenarios: A1FI, A2, B2 and B1 (see table 1)) in gigatonnes of carbon per year, where 1 Gt = 1 billion tonnes, and 1 tC = 3.67 t CO_2). Observed data to 2000 (Hulme *et al.*, 2002).

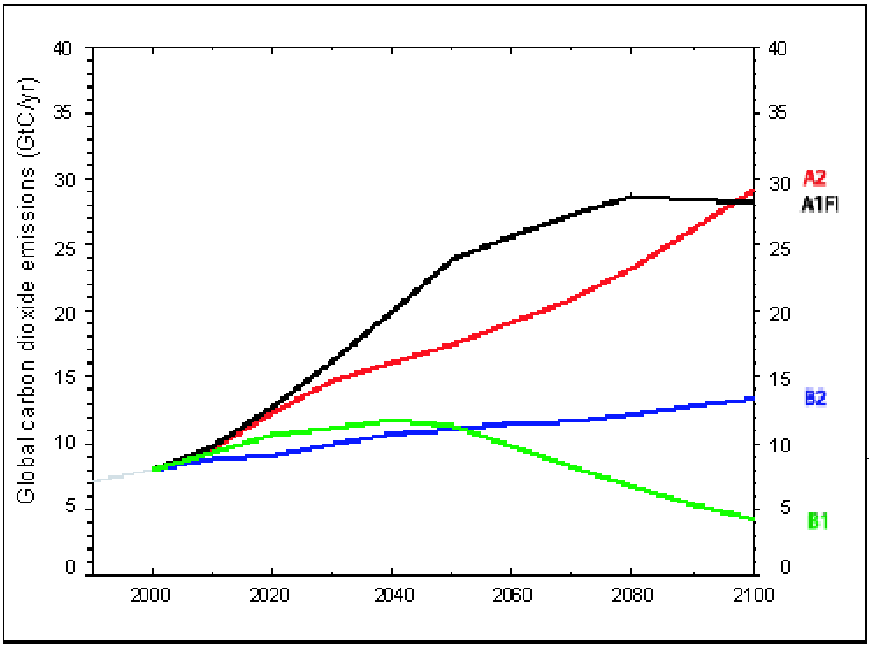
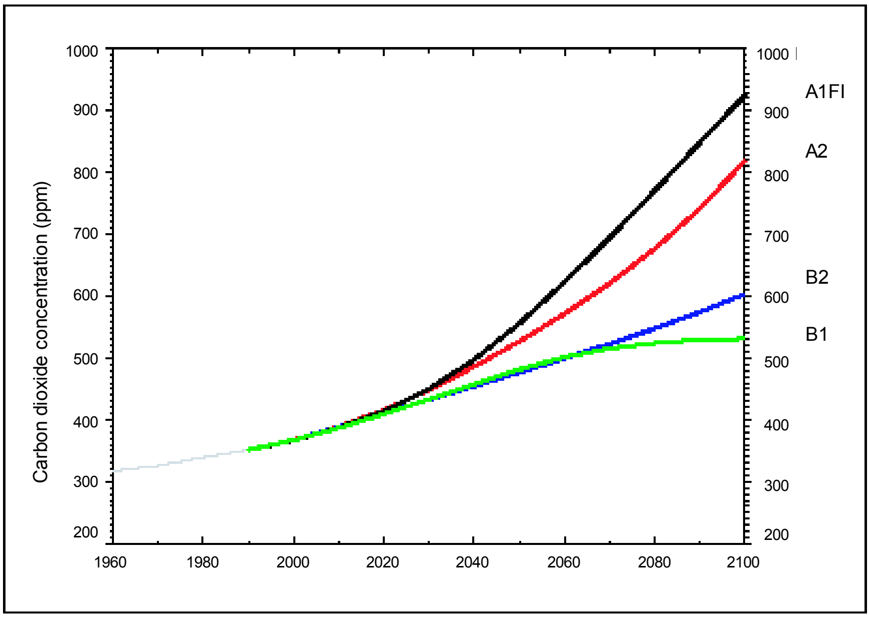


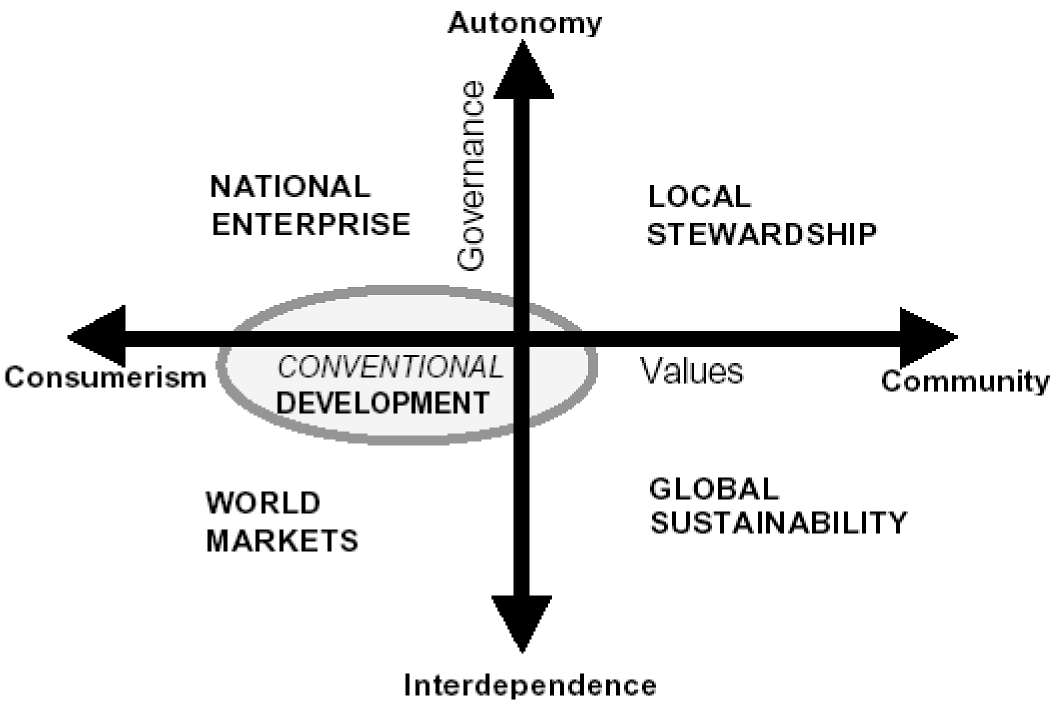
Fig. 3. Global carbon dioxide concentrations (ppm) from 1960 to 2100 for each of the selected IPCC (2000) emissions scenarios. Uncertainties associated with these concentrations are not shown (Hulme *et al.*, 2002)



The IPCC Special Report on Emissions Scenarios (SRES) (2000) developed alternative scenarios of global emissions based upon differing sets of assumptions (storylines) about the key drivers of emissions (fig. 2). CO_2 emissions in 2100 vary from below present day levels (storyline B1) to emissions four times the present day levels (storylines A2 and A1FI). The IPCC SRES (2000) also estimate how each scenario will change the atmospheric concentrations of greenhouse gases (fig. 3). CO_2 concentrations by 2100 range from about 540 ppm (B1 scenario) to 920 ppm (A1FI) compared to present day levels of under 400 ppm and pre-industrial concentrations of about 280 ppm.

UKCIP selected four of the IPCC SRES storylines (shown in figs. 2 and 3) in order to develop its socio-economic scenarios (UKCIP, 2001). The future socio-economic 'possibility space' is divided into quadrants defined by a 'values' and a 'governance' axis (fig. 4), taken to be the fundamental and independent determinants of future change (UKCIP, 2001). The 'values' axis captures alternative developments in social and economic values, with 'consumerism' at one end of the spectrum (where values are dominated by a drive to private consumption and personal freedom) and 'community' at the other (where values are shaped for the common good). The 'governance' axis shows alternative structures of political and economic power and decision-making. 'Interdependence' is at one end of the scale (where the power to govern is distributed upwards, downwards and outwards away from the national state level) whilst 'autonomy' is at the other end (where power is retained at national and regional level) (UKCIP, 2001).

Fig. 4. Four socio-economic scenarios for the UK (UKCIP, 2001)



The UKCIP02 climate change scenarios were then developed from these differing socio-economic scenarios, and represent four alternative climate possibilities referred to as Low, Medium-Low, Medium-High, and High Emissions. UKCIP does not assign probabilities as to which of these scenarios is most likely and acknowledges that other future climates are possible (Hulme *et al*., 2002). Table 1 shows the relationship between the IPCC SRES global storylines, the UKCIP socio-economic scenarios for the UK, and the UKCIP02 climate change scenario for the UK. It is apparent that the severity of the impacts of climate change will be dependant upon the socio-economic and lifestyle choices that we make as a society and the effects that these have on reducing our greenhouse gas emissions, and hence the degree of climate change. In the urban environment, development will be a key driver of any change. Land use change and development of the built environment is a key driver of change irrespective of climate change. The two combined will exacerbate pressures. For example, flooding events may be worse if there is a larger population living on flood plains as a result of planning decisions (Hulme *et al*., 2002).

Table 1. The relationship between UKCIP socio-economic scenarios (UKCIP, 2001), UKCIP02 climate change scenarios, IPCC (2000) emissions scenarios storylines (after Hulme *et al*., 2002) and the urban development scenario (OST, forthcoming)

UKCIP Socio-Economic scenario	**UKCIP02 Climate Change scenario**	**Brief IPCC SRES Storyline**	**Urban development scenario**
Global sustainability	Low	(B1) Clean and efficient technologies; reduction in material use; global solutions to economic, social and environmental sustainability; improved equity; population peaks mid-century	Strong regulation to contain urban sprawl and favour the compact city instead, with brownfield sites re-used
Local stewardship	Medium-Low	(B2) Local solutions to sustainability; continuously increasing population at a lower rate than in A2; less rapid technological change than in B1 and A1	Smallest level of land change and additional land use, lack of strategic planning
National enterprise	Medium-High	(A2) Self-reliance; preservation of local identities; continuously increasing population; economic growth on regional scales	Limited regulations will allow urbanisation without much constraint, with building in greenfield areas and flood plains (even more than today)
World markets	High	(A1FI) Very rapid economic growth; population peaks mid-century; social, cultural and economic convergence among regions; market mechanisms dominate; reliance on fossil fuels	Extensive rapid development of the urban area, with an emphasis on profit and lower environmental protection and social inclusion

3. Pressures

The urban environment will be subject to pressures resulting from climatic changes, changes of urban form (densification and sprawl) and lifestyle changes. These will act both independently and in conjunction with each other to produce impacts. For example, a sequence of hot and dry summers and unusually dry winters creates difficulties for the water supply industry (The Guardian, 26 November 2003). The pressure will not only result from ‘a change’ *per se*, but will depend upon factors such as the speed and predictability of that change. Thus, the IPCC (2001), with reference to climatic changes, describe key ‘determinants’ of impacts, which include: the magnitude of change; rate of change; transient scenarios; climate variability and extreme events; thresholds; surprises; and nonlinear, complex and discontinuous responses.

Magnitude of Change

The magnitude of change is the size of the change. It could, for example, be a mean temperature increase of 2ºC or 4ºC. The change in mean temperature is a significant variable, which serves as a modulus of change against which to compare climate sensitivities and impacts. Early studies of the impacts of climate change have concentrated on those resulting from changes in mean temperature, however other climatic measures of change are becoming important variables for analysis (IPCC, 2001). Similarly, the magnitude of urban densification and growth would be crucial in assessing its impact on the urban system.

Rate of Change

The speed of change is very important. For example, a 2ºC temperature rise over a decade would have a more profound impact than the same temperature rise over a century. Rates of change that exceed the ability of ecosystems to adapt or migrate could be especially damaging. A rapid rate of change is more likely to generate unexpected behaviour in non-linear systems (IPCC, 2001). Such ‘surprises’ inhibit effective adaptation (IPCC, 2001).

Transient Scenarios

Many early studies were based on equilibrium climate change scenarios, where, for example, the impacts of a fixed increase in CO_2 concentrations were modelled, not taking into account the dynamic nature of the system (IPCC, 2001). The climatic model was allowed to reach a steady state after the CO_2 increase had been applied. However, in the real world, CO_2 emissions (and hence concentrations) vary over time (figs. 2 and 3). Hence, the response of the climate system and the impacts of any change will also vary over time. Transient, or time-dependent, scenarios take into account the fact that both the forcings of global change (e.g. greenhouse gas emissions), as well as the responses of the climate systems, are time-evolving (IPCC, 2001). This means that climatic changes are likely to be different during the transient phase than in equilibrium (IPCC, 2001). Transient studies of climate change impacts suggest that many systems will be affected (adversely or beneficially) in the next two to three decades. However, further into the 21st century, the magnitude of adverse impacts increases whilst beneficial impacts decrease, as radiative forcing on the climate builds (IPCC, 2001).

Climate Variability and Extreme Events

Climate change is likely to bring changes in climate variability and extreme events, such as more frequent heatwaves, less frequent cold spells, and a greater intensity of heavy rainfall events (IPCC, 2001). Such changes are likely to be at least as important as changes in mean conditions in determining climate change impacts and vulnerability (IPCC, 2001). Extreme events are especially significant in the urban environment where concentrated human populations and high property values mean that the potential for loss is very significant. Decision makers will have to apply a risk management framework to plan for the possibility of low-probability but high-consequence events (IPCC, 2001).

Thresholds

It is possible that there are key threshold levels below which there are only minor impacts, and above which impacts become more severe. An example is hospital admissions for heat conditions above a threshold temperature (IPCC, 2001). Between August 4th and 13th 2003, a period for which the Met Office reported temperatures above 30°C at a number of its weather stations, the Office for National Statistics reported that London, the east of England and the south east (which saw the highest temperatures) had 1314 more deaths than the five-year average for that time of year. The total number of deaths in this area for the time represented 40% of the national total (Carvel, 2003).

Surprises

Under a changed climate surprises may occur and, by definition, it is difficult to give examples of such surprises. These can make even the most careful prediction of impacts severely inaccurate. Increasing the rate of forcing of the climatic system may increase the likelihood of surprises but the specific event in question is unexpected (IPCC, 2001).

Non-linear, Complex and Discontinuous Responses

Strongly non-linear, complex and discontinuous responses are called singularities. There is high confidence that under climate change such singularities will occur, but a low confidence is usually attached to any specific example of a possible abrupt event. Strongly non-linear responses are characterised by thresholds. Complex responses involve the interactions of many elements so results are not easily predicted, for example, disease outbreaks and changes in fire and disturbance regimes in vegetation systems. Large scale discontinuous responses could have large potential impacts (IPCC, 2001).

3.1 Climate Change Scenarios

The UKCIP02 climate change scenarios demonstrate the pressures placed on the urban system as a result of climate change. The UK can expect increased temperatures, changing precipitation patterns, with an increase in the frequency of more extreme events, along with the possibility of more wind storms (Hulme *et al*., 2002). This section considers these possibilities in turn. Under climate change, the weather in the UK will still vary substantially from year-to-year and from decade-to-decade, due to natural reasons. By the 2080s, however, it is likely that changes in the average climate will greatly exceed this natural variability (Hulme *et al*., 2002).

3.1.1 Temperature

3.1.1.1 National Scenarios

The UK climate will become increasingly warmer during the 21st century. By the 2080s, the average UK annual temperature may rise by 2ºC under the UKCIP02 Low Emissions scenario and by 3.5ºC under the High Emissions scenario. A greater warming may be experienced in summer and autumn than in winter and spring. The temperature of UK waters will also increase, but not as rapidly as over land (Hulme *et al*., 2002).

High summer temperatures will become more frequent whilst very cold winters become increasingly rare. Heatwaves, or extended periods of higher than normal temperatures, will become more common. For example, a very hot August, such as in 1995 when central England temperatures averaged 3.4ºC above normal may occur once in every five years by the 2050s and three years in five by the 2080s under Medium-High Emissions (Hulme *et al*., 2002).

By the 2050s, typical spring temperatures may occur one to three weeks earlier than at present and winter temperatures may be delayed by one to three weeks. This would lengthen the thermal growing season for plants and change the heating and cooling seasons of buildings (Hulme *et al*., 2002).

3.1.1.2 North West Scenarios

Higher temperatures (fig. 5), as well as changes in the occurrence of extreme events, will also be experienced in the north west over the next century. By the 2020s there is little change (0-1°C) in annual average daily temperature under both the UKCIP02 Low and High Emissions scenarios. By the 2050s the temperature could increase by 1-2°C (Low Emissions) and by up to 3°C (High Emissions) (fig. 5). An average annual temperature rise of 1ºC is equivalent to annual temperature change experienced in central England during the 20th century (CURE & Tyndall Centre, 2003). At this stage Manchester may have summer peak temperatures of 31ºC, similar to present day cities in Holland and Belgium (CURE & Tyndall Centre, 2003). By the 2080s, annual average daily temperatures rise by up to 3°C in the southern parts of the region (Low Emissions) and by 3-4°C over the whole region (High Emissions) (fig. 5). Maximum temperatures in autumn by the 2080s under High Emissions could increase by 4-5ºC and Manchester may experience summer maximum temperatures of 34ºC, similar to present-day Berlin, Frankfurt and Rome (CURE & Tyndall Centre, 2003).

3.1.1.3 South East Scenarios

There will be greater warming in the south east than the north west (figs. 5 and 6) (Hulme *et al*., 2002). By the 2080s, the annual average daily temperature in the south east may increase by 3ºC (Low Emissions) and 5ºC (High Emissions) (fig. 6). Even by the 2020s, parts of the south east may be 2ºC warmer under both Low and High Emissions scenarios (fig. 6).

Fig. 5. North West change in annual average daily temperature under UKCIP02 scenarios (UKCIP, 2003; N.B. these figures, downloaded from the UKCIP website, are slightly different to those in Hulme *et al.* (2002) due to a data smoothing process)

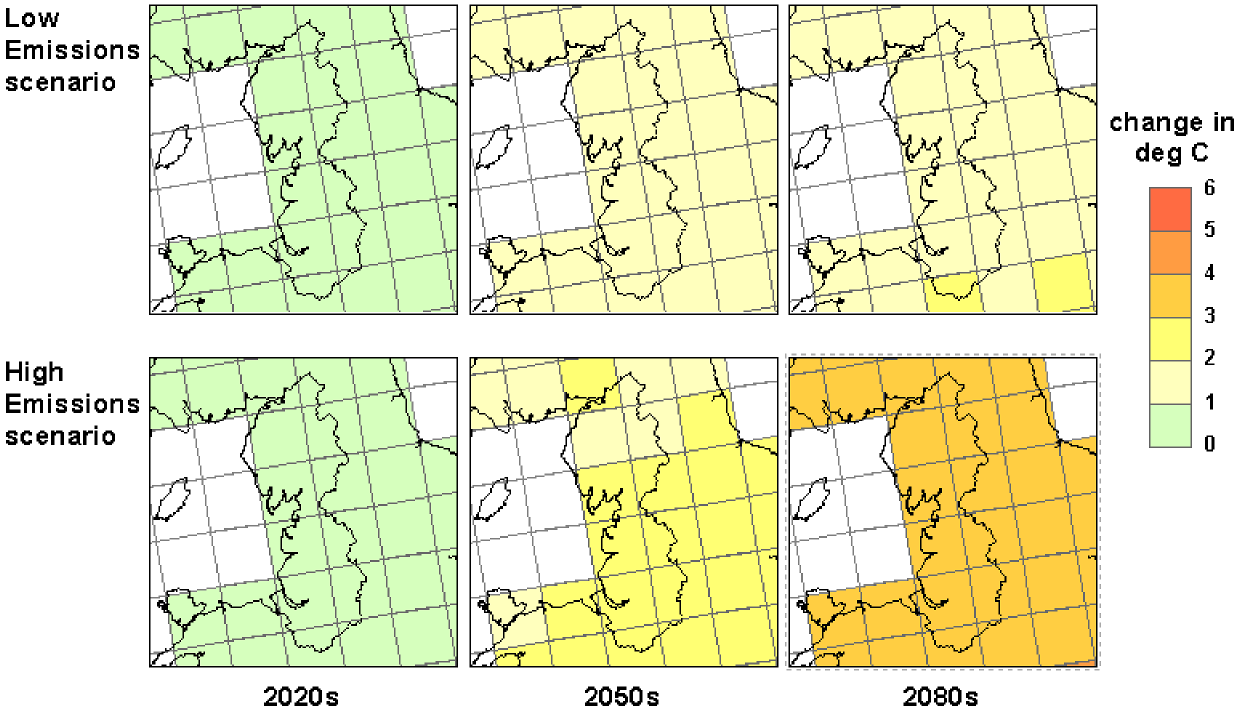
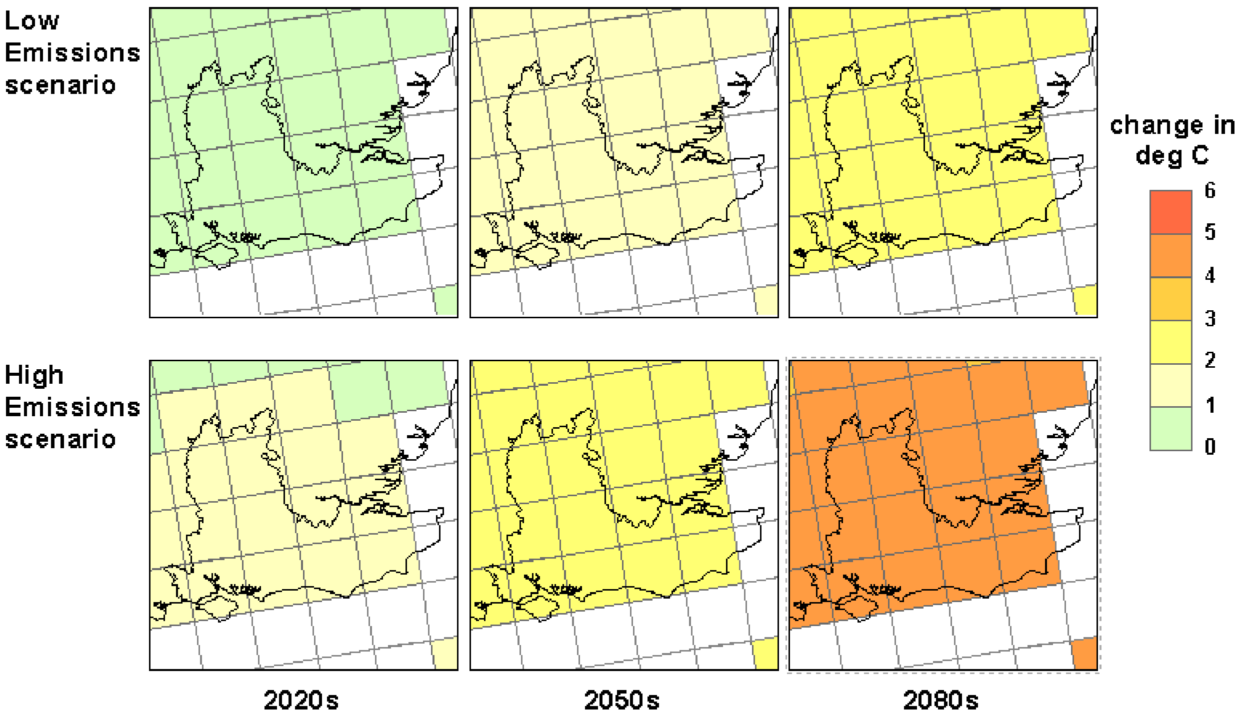


Fig. 6. South East change in annual average daily temperature under UKCIP02 scenarios (UKCIP, 2003; N.B. these figures, downloaded from the UKCIP website, are slightly different to those in Hulme *et al.* (2002) due to a data smoothing process)



3.1.2 Precipitation

3.1.2.1 National Scenarios

Annual average precipitation across the UK may decrease slightly by the 2080s (by 0-15% depending on the scenario), although it is likely that there will be large regional and seasonal differences. Winters will become wetter and summers may become drier throughout the UK, especially under the High emissions scenario (Hulme *et al*., 2002). Average winter snowfall may decrease by 30-70% (Low Emissions) and by 50-100% (High Emissions) throughout the UK by the 2080s (Hulme *et al*., 2002). Annual soil moisture contents may decrease by up to 10% (Low Emissions) and up to 20% (High Emissions) by the 2080s (Hulme *et al*., 2002). Winter soil moisture may increase slightly, but summer contents may reduce by up to 30% (Low Emissions) and 50% (High Emissions) by the 2080s (Hulme *et al*., 2002).

Additionally, there will be changes in the occurrence of extreme events. By the 2080s, winter daily precipitation intensities experienced once in every two years on average may become between 5% (Low Emissions) and 20% (High Emissions) heavier (Hulme *et al*., 2002). Very dry summers (such as that experienced in 1995) may occur one in every two years by the 2080s (Hulme *et al*., 2002). Under Medium-High Emissions, very wet winters (such as that in 1994/1995) may occur on average once a decade (Hulme *et al*., 2002).

The combination of hot temperatures and dry conditions in summer will become more common. Under all UKCIP02 scenarios, by the 2080s, virtually every summer in England and Wales will be warmer and drier than the summer of 2001 (Hulme *et al*., 2002).

3.1.2.2 North West Scenarios

In the north west, the change in summer precipitation is more marked than that in winter precipitation (figs. 7 and 8) over the next century. By the 2020s, under both Low and High Emissions scenarios, summer precipitation decreases by up to 15% (fig. 7) whilst winter precipitation increases by up to 15% (fig. 8). By the 2080s, however, summer precipitation decreases by 15-30% (Low Emissions) and by 30-60% (High Emissions) (fig. 7). Winter precipitation by this time increases by up to 15% (Low Emissions) and by 15-30% (High Emissions) (fig. 8).

3.1.2.3 South East Scenarios

The south and east of the UK will experience the largest relative changes in precipitation (Hulme *et al*., 2002). (figs. 9 and 10). By the 2080s, summer precipitation may decrease by 15-30% (Low Emissions) and by 45-60% (High Emissions) over most of the region (fig. 9). On the other hand, winter precipitation at this time may increase by up to 15% (Low Emissions) and by 15-30% (High Emissions) (fig. 10), which is the same as in the north west for these scenarios (fig. 8).

Fig. 7. North West percentage change in summer precipitation under UKCIP02 scenarios (UKCIP, 2003; N.B. these figures, downloaded from the UKCIP website, are slightly different to those in Hulme *et al.* (2002) due to a data smoothing process)

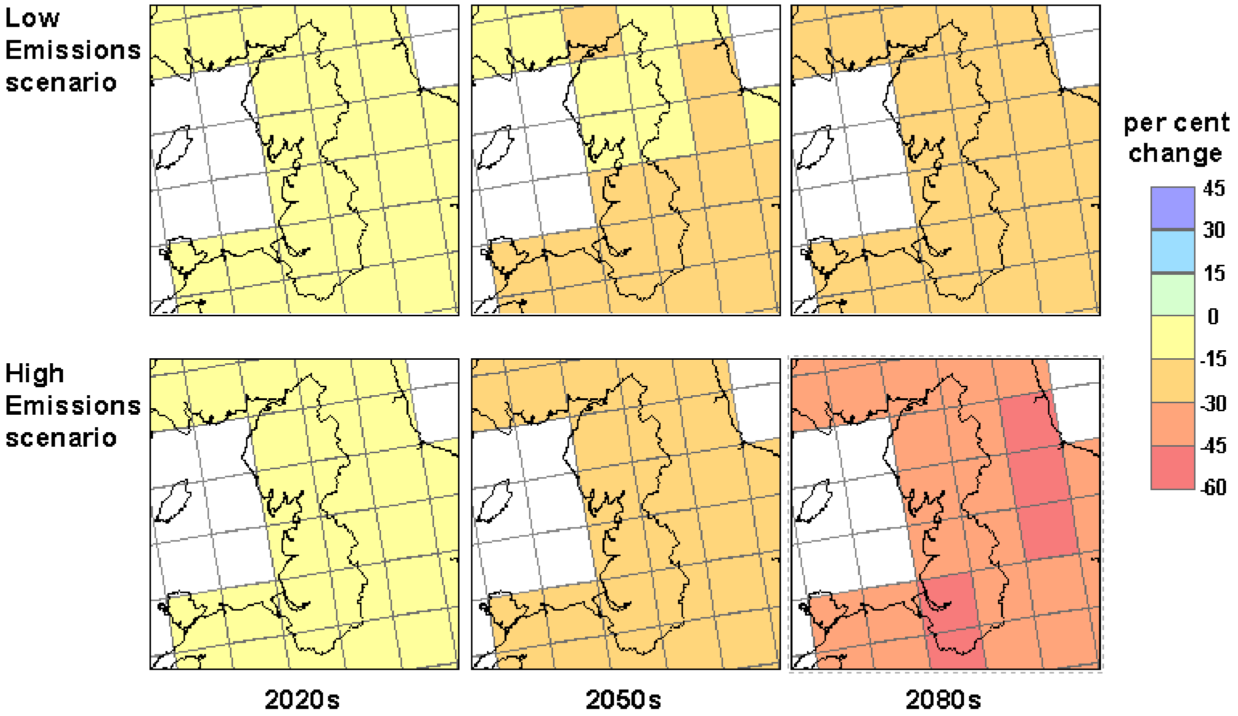


Fig. 8. North West percentage change in winter precipitation under UKCIP02 scenarios (UKCIP, 2003; N.B. these figures, downloaded from the UKCIP website, are slightly different to those in Hulme *et al.* (2002) due to a data smoothing process)

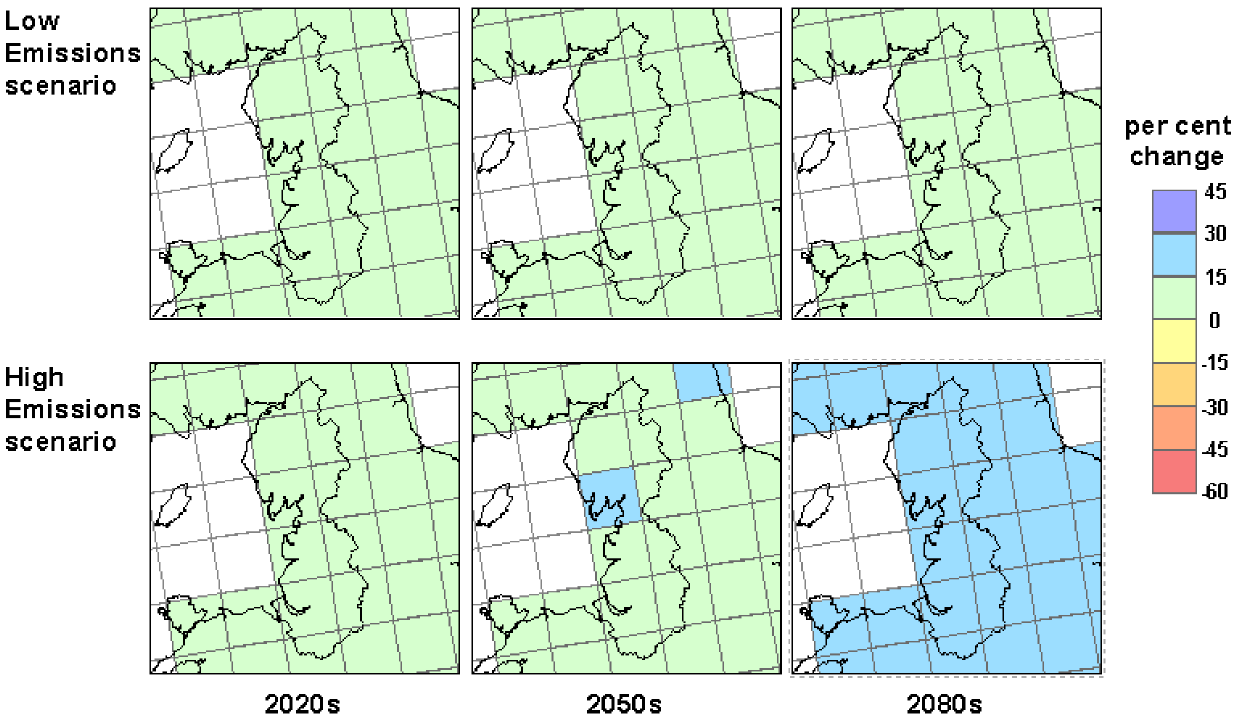


Fig. 9. South East percentage change in summer precipitation under UKCIP02 scenarios (UKCIP, 2003; N.B. these figures, downloaded from the UKCIP website, are slightly different to those in Hulme *et al.* (2002) due to a data smoothing process)

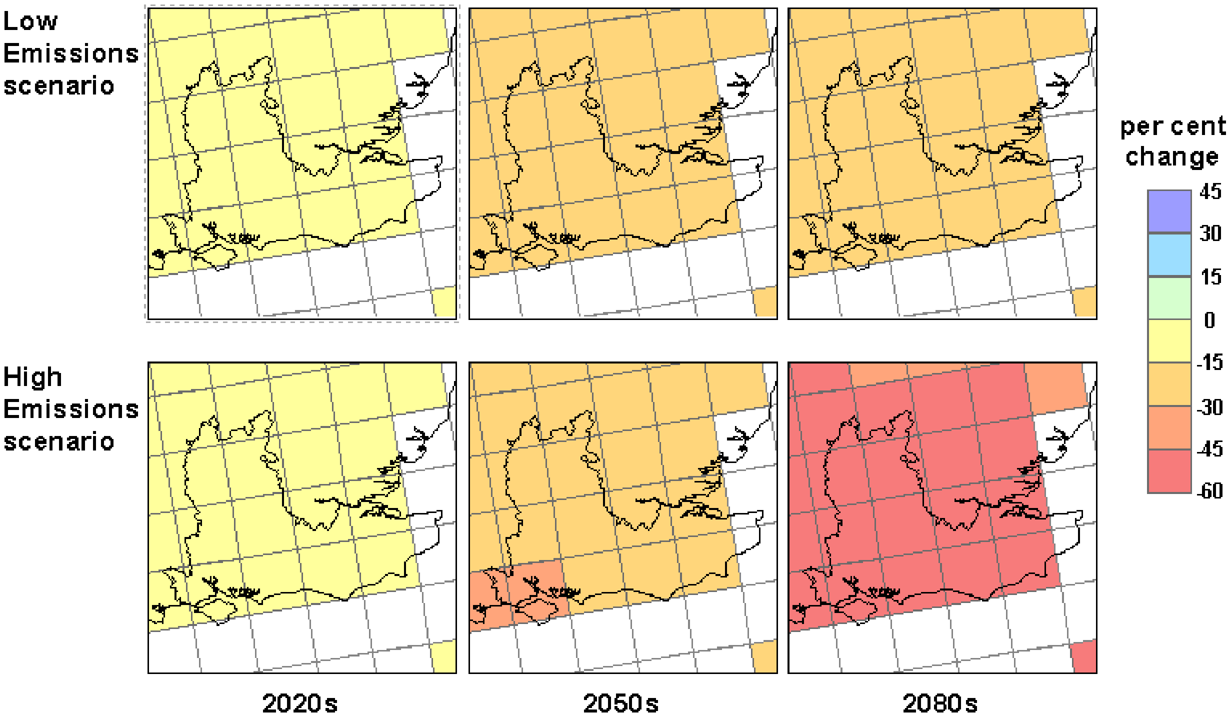
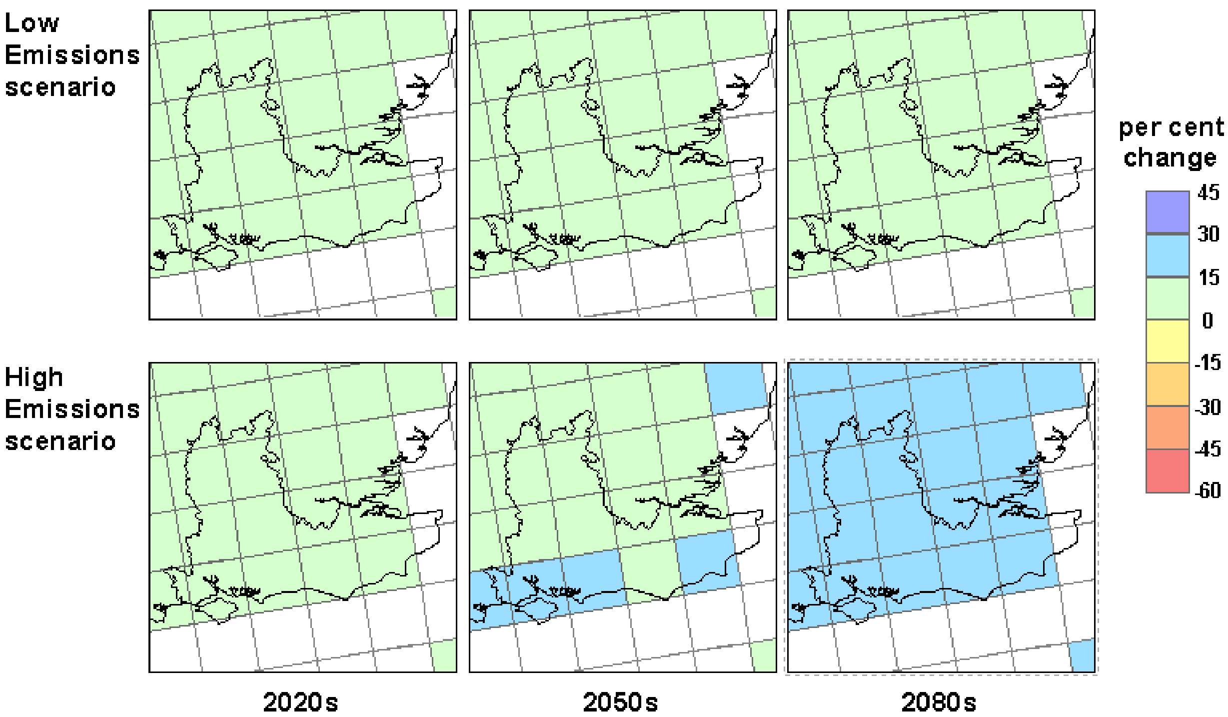


Fig. 10. South East percentage change in winter precipitation under UKCIP02 scenarios (UKCIP, 2003; N.B. these figures, downloaded from the UKCIP website, are slightly different to those in Hulme *et al.* (2002) due to a data smoothing process)



3.1.3 Wind Storms

Climate models, including those used to generate the UKCIP02 scenarios, do not yield consistent or robust estimates of wind speed changes (Hulme *et al*., 2002). The most significant change in the UKCIP02 scenarios is that in winter, when the most severe winds occur, more depressions will cross the UK which will lead to stronger winds in southern and central Britain, yet these will be no stronger than present winds in Scotland and Northern Ireland. Since the north west is currently windier than the south east in winter, this change implies a weakening in the differences in average wind speed across the country. Average winter wind speed along the south coast could increase by 4% (Low Emissions) to 10% (High Emissions) by the 2080s, with less increases in summer (Hulme *et al*., 2002). It must be stressed, however, that these results are very uncertain and caution must be taken when using them (Hulme *et al*., 2002).

3.1.4 Other Changes

In addition to changing temperatures, precipitation patterns and wind storms, other changes will be experienced. As the climate warms, the oceans expand in volume, causing a rise in the average sea level. The melting of glaciers and ice sheets also contributes to sea level rise (Hulme *et al*., 2002). The relative sea level will continue to rise around most of the UK coastline. However, the rate of increase will depend upon the natural vertical land movement in each region (much of southern Britain is sinking at between 1 and 1.5 mm per year, and northern Britain rising at between 0.5 and 1 mm per year relative to the sea) as well as the UKCIP02 Emissions scenario (table 2) (Hulme *et al*., 2002). Actual sea-level is therefore expected to rise more in the south east than in the north west.

Table 2. Historic rates of vertical land movement and the estimated net change in sea level by the 2080s using the low estimate of the UKCIP02 Low Emissions scenario (9 cm global sea-level rise) and the high estimate of the High Emissions scenario (69 cm rise) (after Hulme *et al*., 2002)

Region	Vertical land change (mm/yr)	Sea-level change 2080s (cm) relative to 1961-1990	
		Low Emissions	High Emissions
SE England	-0.9	19	79
NW England	+0.2	7	67

In addition, extreme sea levels (as experienced during coastal storms) will be experienced more frequently. The largest rise in extreme sea level may be experienced around south east England, since it experiences both large changes in winds and storms and the greatest fall in the height of the land (Hulme *et al*., 2002). Whilst changes in mean sea level can be predicted with a high degree of confidence (subject to uncertainty about the climate change scenarios) there is less confidence about the increased frequency of tidal surges (Hulme *et al*., 2002).

It is expected that the Gulf Stream will continue to be influential on the UK climate. Although its strength may weaken by up to 25% by 2100, it is believed that this is unlikely to lead to a cooling of the UK climate in the next 100 years since the warming by greenhouse gases will offset any cooling (this cooling has been factored into the UKCIP02 climate changes). However, the factors controlling this ocean circulation are not sufficiently understood to be completely confident of this prediction, especially in the long-term (Hulme *et al*., 2002).

As the climate warms, specific humidity increases in all seasons and scenarios. However, the relative humidity decreases for all seasons and scenarios (except in some areas of northern Scotland). In summer, these changes are largest. In the north west, by the 2080s, relative humidity in summer may fall by 3-6% (Low Emissions) and 6-8% (High Emissions), whilst in the south east it may fall be 6-6% (Low Emissions) and 12-20% (High Emissions) (Hulme *et al.*, 2002).

By the 2080s, summer cloud cover decreases over most of the country, especially in the south where it may be reduced by 10% (Low Emissions) and more than 20% (High Emissions). Winter cloud cover increases slightly, but by no more than 2 or 3%. By the 2080s, annual cloud cover decreases over the whole country by 0-6% (Low Emissions) and 0-8% (High Emissions) (Hulme *et al.*, 2002). As a consequence, the climate becomes increasingly sunny, especially in summer, when solar radiation increases by 10-30 Wm^{-2} over southern parts of the country (Hulme *et al.*, 2002).

The main climatic pressures for urban environments, identified in the UKCIP02 climate change scenarios for the UK, are increased temperatures, precipitation changes, and the possibility of wind storms.

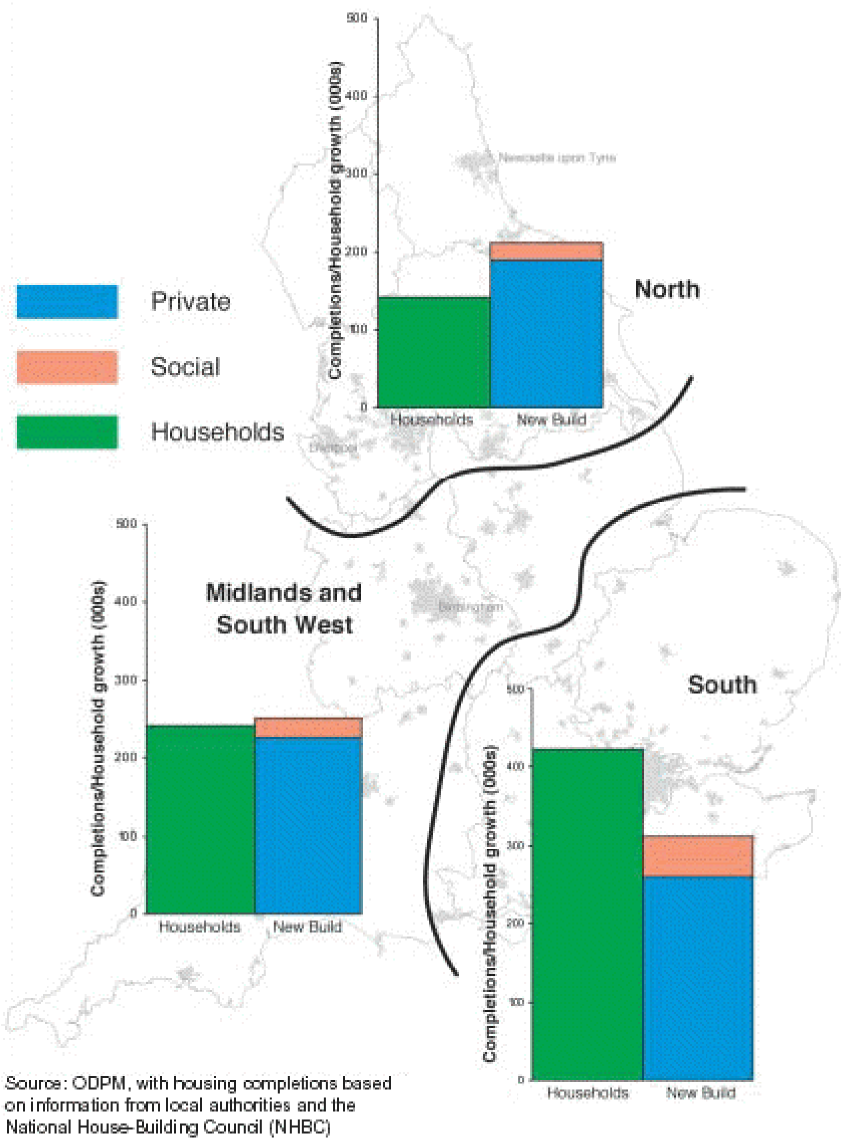
3.2 Change of urban form through growth and densification

Urban areas have grown, and continue to grow, strongly throughout Europe. A recently published report by the European Environment Agency compared the development of 25 urban areas between 1950 and 1990 (Moland Project; EEA, 2002). It interpreted aerial photography and satellite imagery and used a methodology that allowed comparisons to be made between urban areas. The proportionate cover of urban area increased between 26% (Sunderland, UK) and 270% (Algarve, Portugal), whilst agricultural land and areas defined as ‘natural’ declined by between 7% (Dresden, Germany) and 41% (Iraklion, Greece). The overall amount of urban green space generally increased in the study areas, but the rate of increase did not keep up with the pace of urban expansion. Therefore, the proportionate cover of urban green space declined over the 40-year period.

The main processes driving this urban growth are the sprawl of low density residential areas at the urban fringe and urban development along transport corridors and around airports. The latter has been shown to have a strong impact on the countryside surrounding towns (e.g. Antrop, 2000) and it is feared that this will have negative consequences for wildlife and environmental quality (e.g. Kaufman & Marsh, 1997; Alberti, 2001). In England, most new housing developments are in the south east of the country, followed by the Midlands and the south west and then the north (fig. 11) (ODPM, 2003).

In order to counter the trends of urban sprawl, which increases travel demand and encroaches on neighbouring countryside, a target has been set within the UK to build 60% of all new homes on brownfield sites (ODPM, 2002). Planning policy also requires that approval should only be given where new residential developments achieve a minimum density of 30 dwellings per hectare (ODPM, 2002). While these policies may have beneficial environmental effects at the city regional level, they will reduce the built environment to green space ratio in the urban area, which places pressure on the urban ecosystem, impacting on surface temperatures, stormwater runoff, carbon storage, and biodiversity (Whitford *et al.*, 2001; Pauleit & Duhme, 2000). Similarly, new developments on flood plains increase pressures on the urban system, with less potential water storage space in the event of a flood. In the past 20 years, 350,000 residential properties have been built on flood plains, with 20,000 of these built between 1997 and 2000 (Austin *et al.*, 2000).

Fig. 11. Housebuilding and new household numbers during 1997 to 2001: private and social (ODPM, 2003)



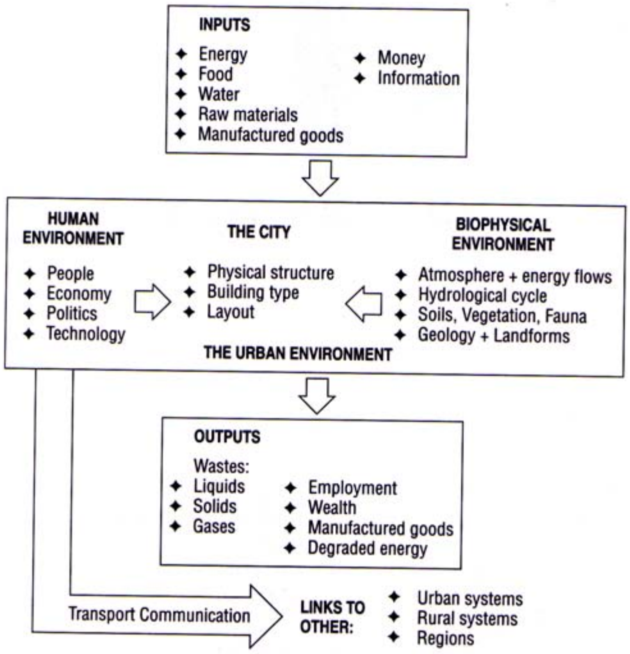
3.3 Lifestyle

It has been demonstrated that lifestyle changes drive the climate change scenarios through the differing greenhouse gas emissions depending on socio-economic choices (section 2). These, in turn, place climatic pressures upon the urban system (section 3.1). Similarly, urban growth and densification is partly dependent upon lifestyle choices (section 3.2). Climatic changes themselves may facilitate, inhibit or accentuate lifestyle choices. For example, warmer temperatures and less rainfall could result in a greater demand for green spaces within urban areas, as it may encourage people lead a more outdoors and active lifestyle. This would place greater pressure on urban green spaces to be multi-functional, serving recreational and environmental purposes. For most people, lifestyle changes are the result of a mixture of social, economic and cultural factors, rather than directly related to environmental concerns. This may change in the future as a result of value shifts or because of adverse environmental impacts (LCCP, 2002).

4. State of the Urban Environment

The process of urbanisation has strong impacts on the elements of the atmosphere, the geosphere, the hydrosphere and the biosphere (fig. 12) (Bridgman *et al*., 1995).

Fig. 12. The urban system, illustrating the interactions between the city, the human environment, and the biophysical environment (Bridgman *et al*., 1995)



4.1 Urban climate

The physical structure of the city, its artificial energy and pollution emissions, and the reaction of climatic elements with urban surfaces interact to create an urban climate (table 3) (Bridgman *et al*., 1995).

Table 3. General alterations in climate created by cities (from Bridgman *et al*., 1995; after Landsberg, 1981)

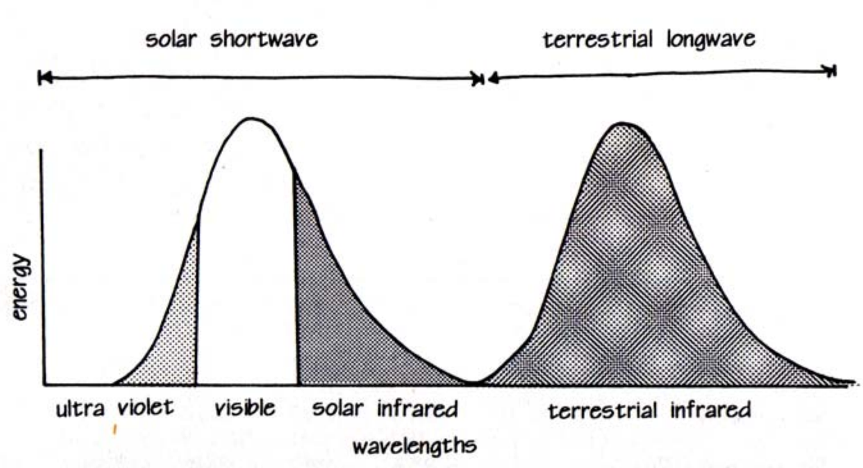
Climatic Element		Comparison with rural areas
Temperature	Annual mean	0.5-3.0°C higher
	Winter minimum	2.5-4.0°C higher
	Summer maximum	1.0-3.0°C higher
Relative humidity	Annual mean	6% lower
	Winter	2% lower
	Summer	8% lower
Cloudiness	Clouds	5-10% more
	Fog, winter	100% more
	Fog, summer	30% more
Solar radiation	Total, horizontal surface	0-12% less
	Ultraviolet, winter	30% less
	Ultraviolet, summer	5% less
	Sunshine duration	5-15% less
Windspeed	Mean	20-30% lower
	Extreme gusts	10-20% lower
	Calms	5-20% more
Precipitation	Amounts	5-10% more
	Days with <5 mm	10% more
	Thunderstorms	10-15% more
	Snowfall, inner city	5-10% less
	Snowfall, lee of city	10% more

4.1.1 Radiation and energy

The major radiation parameters, which affect climate at any location, are (Bridgman *et al*., 1995):

- the incoming shortwave (solar) radiation (fig.13), partitioned into direct and diffuse (scattered) components;
- the fraction of shortwave energy reflected back to the atmosphere (referred to as the albedo and expressed as a percentage);
- the longwave radiation (fig. 13) released from the surface to the atmosphere, dependent on the temperature of the surface;
- the longwave radiation released from the atmosphere toward the surface, dependent on the temperature of the atmosphere;
- the net radiation, which is the deficit between the incoming and outgoing components.

Fig. 13. The solar (shortwave) radiation received by the earth and the terrestrial (longwave) radiation emitted by the earth (Brown & Gillespie, 1995)

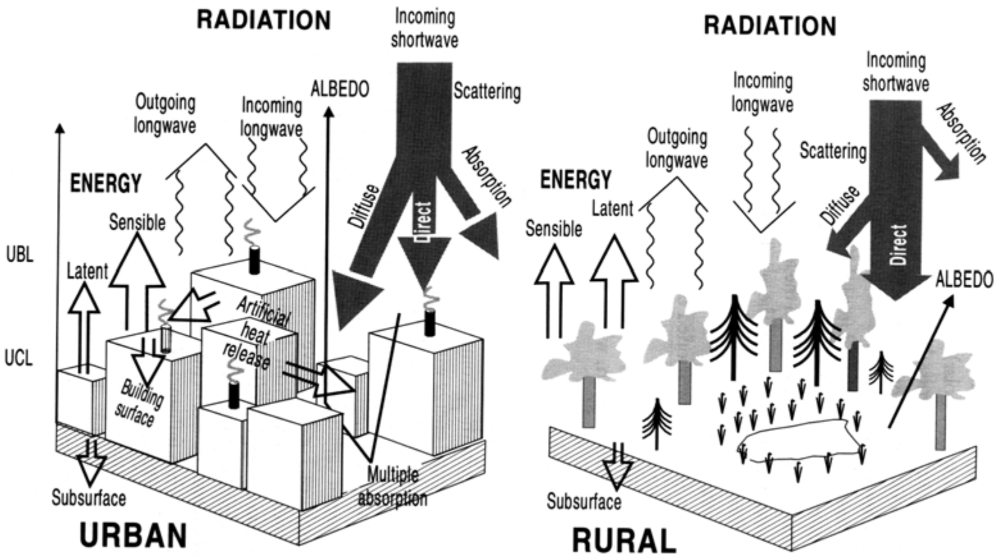


Net radiation is partitioned between the components of the heat budget. The relationship of these components with advection must also be considered (Bridgman *et al*., 1995):

- sensible heat, represented by the change in temperature;
- latent heat of evaporation, where energy is stored in the form of water vapour;
- heat flux to the subsurface;
- artificial heat released from anthropogenic sources, and relevant to the city only.

These fluxes interact in different ways in the urban environment compared to a rural setting (fig. 14) (Bridgman *et al*., 1995).

Fig. 14. Schematic depiction of radiation and energy fluxes over a rural and an urban area on a clear day. The width of the arrows approximates the size of the flux. The urban canopy layer (UCL) is the urban atmosphere from the ground to just above rooftop layer, whilst the urban boundary layer (UBL) is from the top of the UCL to an altitude when urban influences are no longer felt in the atmosphere (Bridgman *et al.*, 1995)



4.1.2 Urban Heat Island (UHI)

Urban environments can be several degrees warmer than surrounding rural areas, a phenomenon known as the urban heat island (Graves *et al*., 2001; Wilby, 2003). Within the urban area temperatures tend to decrease as the radial distance from the city centre increases, with the most marked effect during the night when rural areas cool more in relation to urban areas (fig. 16) (Graves *et al*., 2001).

The UHI is the result of: a lower rate of radiant cooling during the night in urban areas which leads to an overall net radiation gain relative to a rural area; the storage of solar energy by building materials (especially those with a dark surface), which is then released at night; anthropogenic heat sources (e.g. transportation, heating, air conditioning, cooking and industrial processes); the decrease in evaporation from soil and vegetation; the decrease in convective heat loss from buildings to the air due to a decrease in wind speeds (Graves *et al*., 2001). There is a relationship between the size (and population) of a city and the heat island intensity (fig. 15).

Fig. 15. Trend line of maximum peak difference in urban and rural temperatures with population, for American and European cities (Graves *et al.*, 2001; after Oke, 1982)

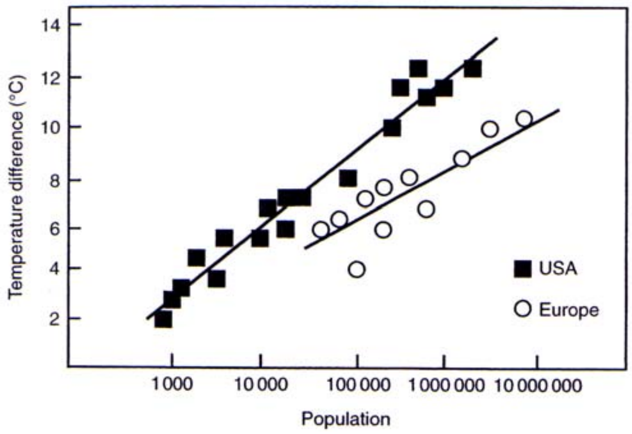
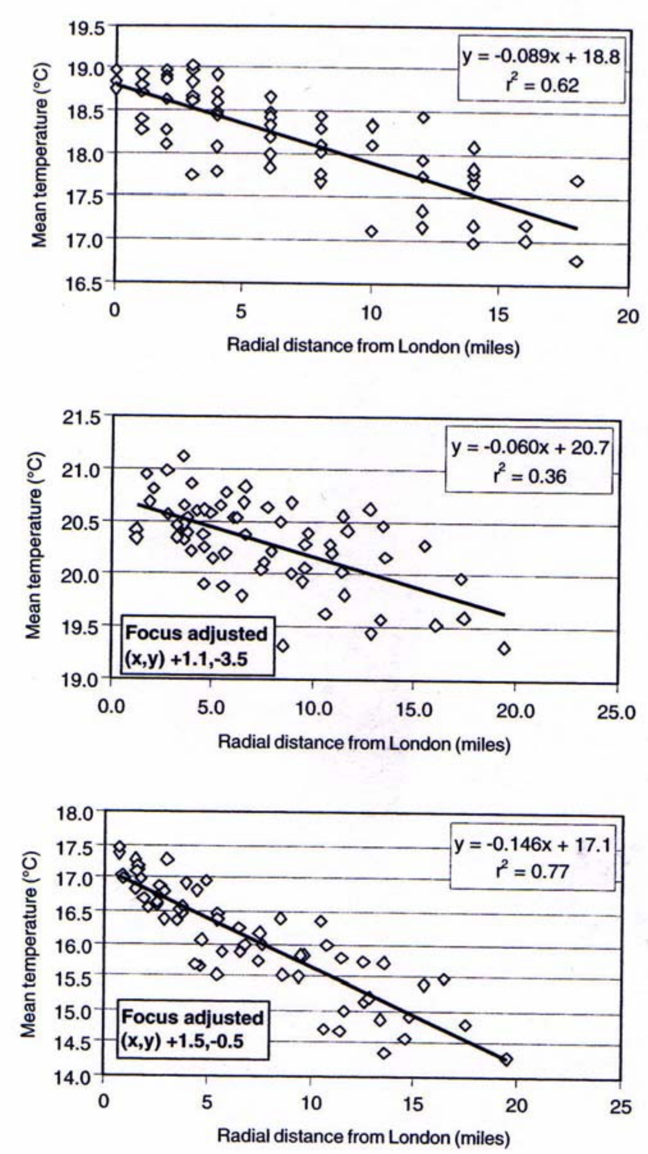


Fig. 16. The change in temperature with distance from London in August (a) mean; (b) daytime mean; (c) night-time mean (Graves *et al.*, 2001)



The UHI effect may be both accentuated by climate change and exacerbate the impacts of heatwaves (IPCC, 2001). Higher temperatures experienced under climate change, combined with the UHI effect, have impacts for air and water quality that will, in turn, impact upon green space, human comfort and building integrity.

The design of a building or group of buildings and the surroundings can help reduce, or even eliminate, the UHI effect via choices of colours (surfaces with a high albedo will reflect more solar radiation), building material, glazing distribution and shading, vegetation (using trees and green areas, vines and wall plants), energy use for heating and cooling (including natural ventilation, night cooling and mixed mode) and water features, density of built up area, height of buildings, orientation of streets with respect to wind directions (to encourage wind flow and ventilation) and reducing casual gains (avoiding unnecessary cooling caused by inefficient equipment and lighting) (Graves *et al.*, 2001).

The distribution of air temperatures in urban areas does not follow a simple zoning from higher temperatures in the inner city to lower temperatures at the urban fringe but is more complex as thermal imagery clearly shows (e.g. Eliasson, 2000; Nachbarschaftsverband Stuttgart, 1992; Pauleit & Duhme, 1995; Quattrochi & Ridd, 1998; Wilson *et al.*, 2003). In cities, there is not one single heat island, but a number of them interspersed with areas where air temperatures can be as low as in the surrounding countryside. The temperature distribution is associated with the pattern of urban land use and morphology, with densely built up areas such as inner city business districts being considerably warmer whereas large urban parks are relatively cool areas (e.g. Henry & Dicks, 1987; Pauleit & Duhme, 1995; Nichol, 1996; Wilson *et al*., 2003). Climate studies in open spaces of the city of Munich showed a linear increase of temperatures by 0.7ºC when the cover of asphalt increased by 10% of the overall area (Matzarakis, 2001).

Micro-climate can also be important at the meso-scale. Lewes was selected as a case study location for this project primarily because of its acute vulnerability to riverine flooding, especially under tidal surge conditions. It's microclimate is equally distinctive given its location in a steep sided river valley, less than 10 km from the sea. For human comfort work there may be a case for considering a non-'representative' location in the south-east, perhaps Oxford.

Greater Manchester was chosen as a 'representative' case for a large conurbation towards the north-west end of the UK climate axis. It is sufficiently large to permit full expression of the UHI effect, with a population of about 2.5 million (fig. 15) (National Statistics, 2001). Temperature readings from the 1940s and 1950s (Crowe, 1962) were suggestive of a temperature gradient demonstrating an UHI, with consistently lower temperatures at Ringway (at the southern edge of the conurbation) in comparison with Whitworth Park (less than 1 km from the city centre) both for winter minima and summer maxima.

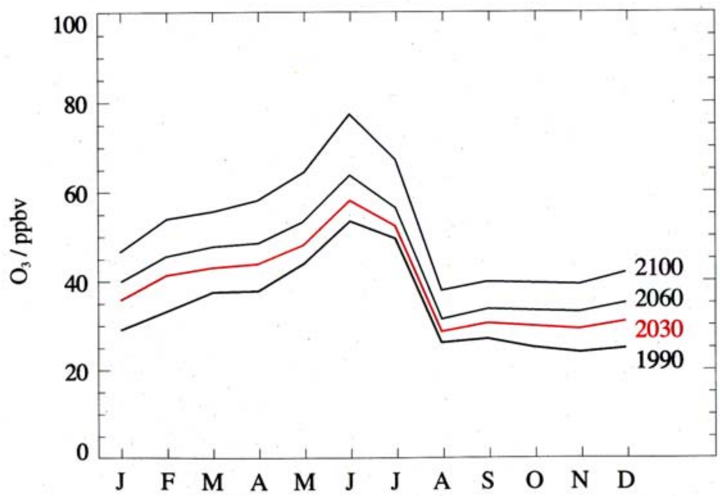
4.2 Air quality

4.2.1 Ozone

The mechanisms involved in the creation, transport and decay of ozone (O_3) in the lower atmosphere are extremely complicated (O'Hare & Wilby, 1995). Two factors determine the ozone balance in an area: the atmospheric chemistry and meteorological conditions.

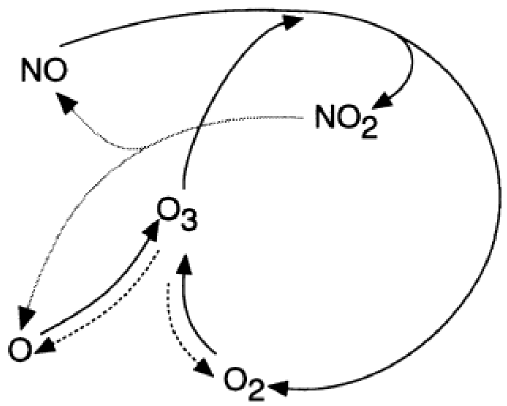
Ozone occurs naturally in the troposphere as the result of atmospheric processes involving sunlight and anthropogenic and natural emissions of methane (CH_4) and nitrogen oxides (NO_X) (Anderson *et al*., 2002). Such background levels vary regionally and seasonally, and have doubled since measurements began last century and are projected to continue rising over the next century (fig. 17) (Anderson *et al*., 2002).

Fig. 17. Seasonal cycles in ozone for Central England in 1990, 2030, 2060 and 2100 (using the IPCC SRES (2000) A2 storyline which corresponds with the UKCIP02 Medium-High Emissions scenario (see table 1) (Anderson *et al*., 2002)



The ozone occurring over and above these background levels is a secondary pollutant, created by the reaction of UV light with nitrogen dioxide (NO_2) and volatile organic compounds (VOCs), both of which are primary anthropogenic emissions (fig. 18) (Anderson *et al*., 2002). Ozone is removed from surface air particularly in the dark, by physical (e.g. dry deposition onto vegetation, soil and buildings) and chemical processes (fig. 18) (O'Hare & Wilby, 1995).

Fig. 18. Basic mechanisms of ozone production and destruction involving precursor nitrogen oxides (O'Hare & Wilby, 1995)



In urban areas, *in situ* summer photochemical production and prolonged destruction by nitrous oxide dominates the ozone budget (O'Hare & Wilby, 1995). Ozone tends to be lower in urban areas because concentrations combine with nitric oxide (NO) from combustion sources to form NO_2 (Anderson *et al*., 2002). Future ozone concentrations will be determined by weather factors and the availability of precursor pollutants (Anderson *et al*., 2002). There has been a reduction in emissions of particles, NO_X, VOCs and SO_2 (sulphur dioxide) due to the continuing tightening of both fuel and vehicle emissions legislation (Anderson *et al*., 2002). As NO_X emissions in cities decline it is likely that urban concentrations will rise and become more similar to rural levels (Anderson *et al*., 2002).

4.2.2 Summer episodes

High surface concentrations of ozone are normally associated with warm summer anticyclonic days with high levels of sunshine, light windspeeds, and precursor pollutants confined by a subsidence inversion (O'Hare & Wilby, 1995). Temperatures tend to have to exceed 25ºC and winds are light and from the east (Anderson *et al*., 2002).

Since ozone production is driven by solar radiation, concentrations rise during the day (O'Hare & Wilby, 1995). Seasonally warm cities with calm air and sunny weather and high traffic densities are prone to the net formation of ozone and other photochemical oxidants (IPCC, 2001; Sillman & Samson, 1995). At high temperatures volatile organic compound (VOC) emissions (e.g. evaporative emissions from motor vehicles (Grambsch, 2002)) sources increase (Samson *et al.*, 1989; Sillman & Samson, 1995).

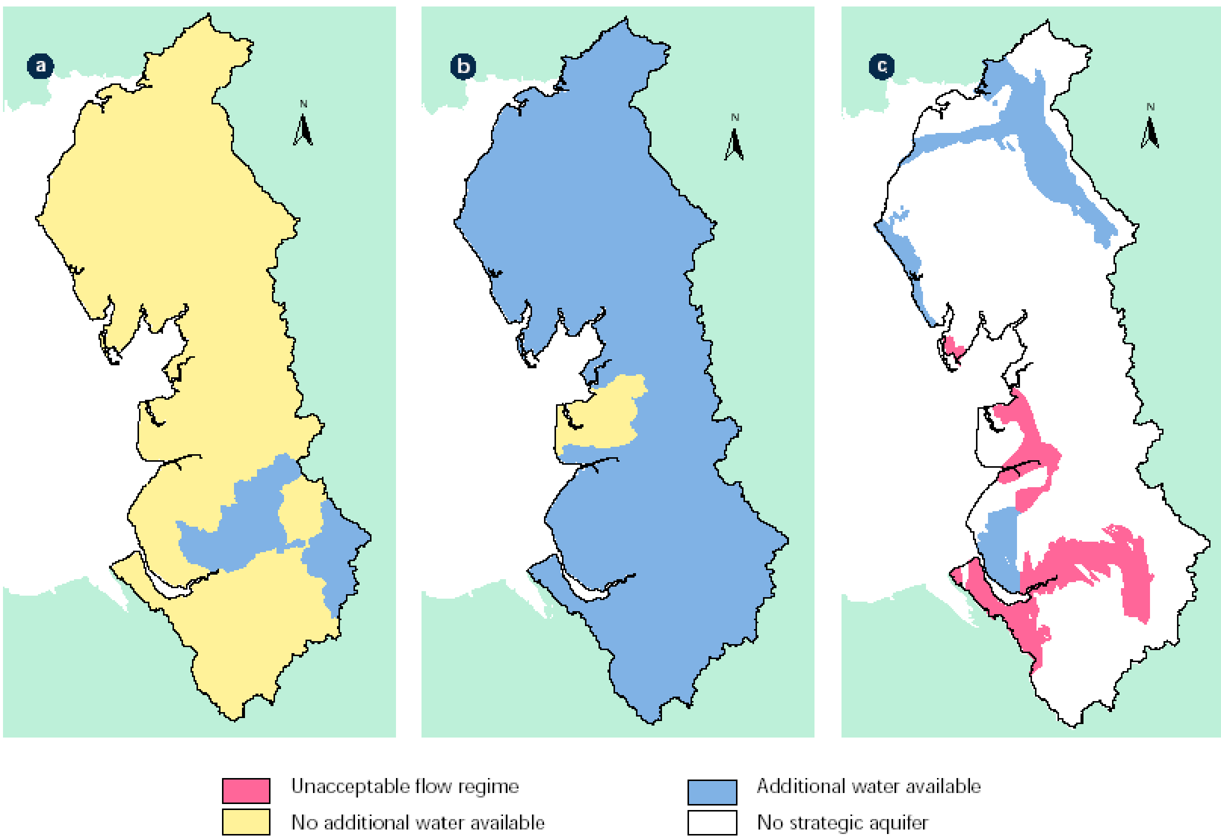
4.2.3 Winter episodes

In urban areas, motor vehicles are now the main source of primary air pollutants, including NO_X, carbonaceous particles, carbon monoxide and various organic compounds. Cold still winter weather tends to prevent the dispersion of such local emissions and is associated with winter air pollution episodes. Such episodes (for example, in 1991 in London) are characterised by high concentrations of NO_2, CO and VOCs (Anderson *et al*., 2002).

4.3 Hydrology

In the north west, 85% of water comes from reservoirs and river sources, with the remaining 15% from groundwater and sandstone aquifers (Environment Agency, 2001a). However, many dams are reaching the end of their safe working lives (CURE & Tyndall Centre, 2003). There is little scope for additional summer abstraction from rivers but the possibility of more winter abstraction (fig. 19(a) & (b)). Figure 19(c) highlights aquifers where there is an unacceptable balance between recharge and abstraction, particularly in the south of the region where the large conurbations are located. This has been a problem historically in Manchester and in some places has led to increasing salinity in the groundwater (Environment Agency, 2001a).

Fig. 19. Water resource availability in the north west: (a) summer surface water; (b) winter surface water; (c) groundwater resource (Environment Agency, 2001a)



Aquifer vulnerability maps provide basic information on the sensitivity of an aquifer to pollution, but take little account of the role of superficial deposits in determining recharge and runoff potential. Such drift characterisation is essential for a meaningful appraisal of aquifer sensitivity (Hough *et al*., 2003). Domain maps constructed from 3D geological models provide a qualitative guide to aquifer sensitivity. Such a map for Manchester and Salford shows the main area of potential recharge occurring along the Irwell and beneath Trafford Park Industrial Estate, where sandstone is near the surface. There is potential for a pollution incident to contaminate the groundwater in these areas. In areas with clay layers substantial infiltration is unlikely. Knowledge of surface sealing will help to delineate the recharge areas more accurately and is an aim of the BGS project (Hough *et al*., 2003).

In the south of England groundwater is the most important source of water. Aquifers underly much of the region, acting as natural reservoirs by storing rainfall and then slowly releasing it. The main water-bearing rock is chalk, supplying around 70% of the water used in the region and helping rivers to continue flowing in dry periods. Dry winters can limit groundwater recharge and the filling of reservoirs (Environment Agency, 2001b). Both surface and groundwater abstraction in the region currently exceed availability in a dry summer/year (figs. 20 and 21), and there is a predicted future deficit of water resources for Lewes regardless of climate change (fig. 22) (Environment Agency, 2001b).

Fig. 20. Surface water availability in the South of England – based on licensed abstraction during a dry summer (Environment Agency, 2001b)

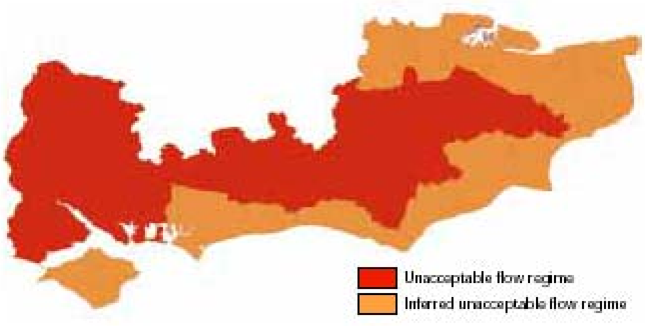


Fig. 21. Groundwater availability in the South of England – based on licensed abstraction during a dry year (Environment Agency, 2001b)

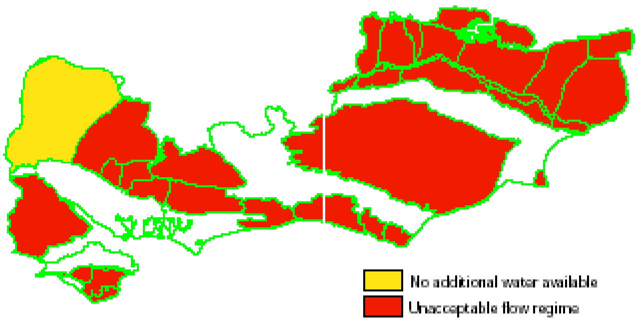
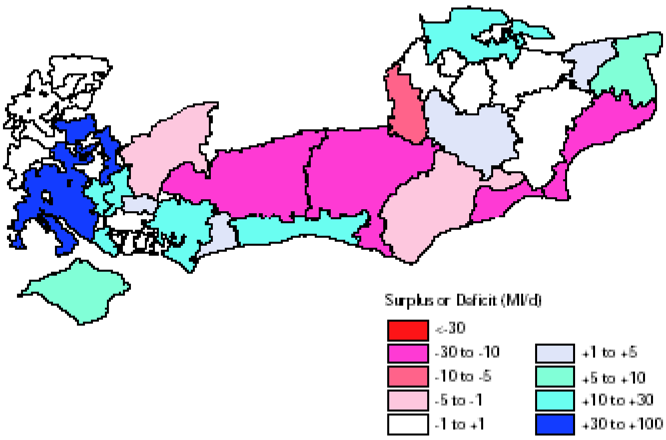


Fig. 22. Forecast, dry year, annual average, supply-demand balance 2009/10 (Environment Agency, 2001b)



Assessing the flood risk in an urban environment is difficult because of the extent of the drainage system, effects of blocked culverts and the surfacing of river channels (natural/artificial), and hydraulic capacity of sewers, all of which are of consequence to the rate and volume of runoff following excessive rainfall or snowmelt (DETR, 2000a; LCCP, 2002). This will be information that will need to be gathered for both Manchester and Lewes for use in the ASCCUE project.

4.4 Green space

The process of urbanisation replaces vegetated areas with the built environment. The urban green spaces remaining between the buildings can vary greatly in size, from large public parks to small private back gardens. Although urban areas are perceived as built areas, the overall cover of vegetated areas can exceed that of buildings and asphalt. However, within urban areas, the amount of green space greatly differs between densely built up inner urban areas and commercial and industrial areas where the vegetation cover can be below 5% of the total surface cover, and low density residential areas with a high vegetated surface cover (e.g. McPherson, 1998; Pauleit & Duhme, 2000; Akbari *et al*., 2003). Green spaces also vary greatly in composition (types and quantities of different vegetation) and function. Often such green spaces are multi-functional, serving biophysical as well as social, psychological and economic roles within the urban environment (Givoni, 1991).

The biophysical functions served by urban green spaces include benefiting microclimate, air quality, hydrology, carbon storage and sequestration, and biodiversity (Whitford *et al*., 2001). It has been suggested that the percentage of green spaces, and particularly of trees, is the greatest influence on the ecological performance of urban areas (Whitford *et al*., 2001). Green spaces benefit microclimate through shading and evapotranspiration, which in turn help to create a comfortable external environment for humans as well as potentially reducing energy usage in buildings. Vegetation filters pollutants from the air, and trees store and sequester carbon as they grow. However, whilst larch and maple remove pollutants such as ozone, nitrogen dioxide and particles from the atmosphere, others such as oaks and willows emit VOCs that combine with other gases to form ozone, hence potentially worsening local air quality (CEH, undated). Trees are also a source of pollen, which may cause allergies (CURE & Tyndall Centre, 2003). Green spaces allow for storm water runoff as the surfaces are generally permeable, as well as providing floodwater storage. They also provide habitats for plants and animals in the urban environment, and can serve as wildlife corridors to maintain local habitats and allow species to move to new climate spaces (Whitford *et al*., 2001).

4.5 Human well-being

Human well-being includes health, comfort, and quality of life. Urban areas typically comprise people of differing socio-economic status, age and health. Health is strongly related to socio-economic circumstances such as housing, employment, education and lifestyle (LHC, 2002). Urban air pollution represents a health risk, even under current climatic conditions (Anderson *et al.*, 1996; COMEAP, 1998). Human comfort is related to climatic conditions which generally include rainfall, sunshine, temperature, humidity and wind (Giles & Perry, 1998).

Thermal comfort has been the subject of scientific study since the start of the twentieth century, when improvements of building techniques and the introduction of central heating and air conditioning systems led to the consideration of improving comfort conditions in indoor environments (Edholm, 1978). When considering thermal comfort studies worldwide it is important to understand the perspective of the study. Whilst in hot climates consideration will be given to the cooling of indoor environments by the use of air conditioning systems, in colder climates the emphasis will be placed on how to heat environments in order to provide comfort (Parsons, 2003). In the United States, the American Society of Heating and Ventilating Engineers (ASHVE), later the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), was one of the main financiers of research into understanding and improving thermal indoor conditions (Edholm, 1978). A series of studies were undertaken which resulted in the development of comfort indices and mathematical models to predict thermal comfort and discomfort.

Probably some of the most influential pieces of thermal comfort research were the publication of the book *Thermal Comfort* by Fanger (1970), which introduced the concepts of the 'Predicted Mean Vote' (PMV) and 'Predicted Percentage Dissatisfied' (PPD), and Gagge's research into determining improved rational indices of thermal comfort and the concept of the 'Standard Effective Temperature' (SET) (Parsons, 2003). Fanger's model forms the basis for ISO Standard 7730, which includes a computer programme for calculating PMV and Gagge's that for ASHRAE Standard 55 (Nicol, 1993). Whereas ISO 7730 views thermal comfort as a specific combination of thermal conditions that will ensure the sensation of comfort, ASHRAE 55 tries to define a zone of comfort (Ramos & Steemers, 2003).

Although these models represent a widely adopted international standard for thermal comfort calculations, a number of problems have been identified with these purely analytical approaches, when compared to the results of empirical studies. A number of field studies showed differences between the average values of the calculated PMV and the actual sensation votes (comfort votes) provided by field study participants (e.g. Humphreys & Nicol, 2002; Nicol, 1993; Nikolopoulou *et al*., 2001) and thereby indicated an overestimation of discomfort by the PMV. The reason for this discrepancy could be the use of erroneous predicted clothing insulation and metabolic rate values and other estimated variables. The problem may also simply lie in the fact that predicted mean vote predictions, which are derived from steady-state models (usually climate chamber experiments) and artificial environments, cannot be directly applied to the real world (Nicol, 1993). Nicol (1993) emphasises that analytical models alone are not capable of taking into account the social and psychological factors that affect fieldwork. People react and adapt to their environments, for example, by using environmental controls, by changing their level of activity and clothing, and further, by having preset expectations of climate and weather conditions. Additional problems arise when analytical models, which have been designed predominantly for indoor conditions, are to be applied to outdoor environments.

Due to the greater complexity of the outdoor environment, in terms of variability, as well as a greater range of activities people are engaged in, there have been fewer attempts to understand outdoor comfort conditions (Nikolopoulou *et al*., 2001). However, in the light of changing climates and predictions for warmer and more extreme weather conditions, there has been a growing interest in the way that people behave in and use outdoor spaces, particularly with respect to urban microclimatic conditions, in order to predict future change and potential means for adaptation.

Urban environments have been of particular interest to climate change and thermal comfort research due to their distinct processes of heat exchange and the resulting phenomenon of the urban heat island (UHI) (section 4.1.2). With regard to thermal comfort, the variability of urban conditions may complicate research as a wide number of geomorphologic as well as urban morphologic characteristics define microclimatic conditions within cities. These may be dependent on elements including spatial conformation, roughness, porosity, construction density, building height and dimensions, land use, orientation of the sun and wind, soil permeability, thermodynamic properties of construction materials and green cover (Santos & Boas, 2000). The potentials of using specific building and pavement materials for mitigating the UHI effect have been discussed in more detail elsewhere (e.g. Tan & Fwa, 1992; Shimoda, 2003; Akasaka *et al*., 2002; Rosenfeld *et al*., 1995; Bretz *et al*., 1998; Ashie *et al*., 1999).

The problems associated with the applicability and transferability of indoor thermal comfort standards to outdoor conditions have been widely debated in recent studies on outdoor thermal comfort. In addition to the problem of complex urban morphology, there is a greater degree of freedom in which people can adapt to outdoor environments and which cannot accurately be predicted by models that have been based on climate chamber conditions (Ramos & Steemers, 2003). Thus, there may be an even wider range of tolerance for outdoor climates and thereby an even greater discrepancy between predicted and actual votes (Ramos & Steemers, 2003). More researchers in the field of outdoor thermal comfort are beginning to acknowledge that thermal sensations outdoors are perceived differently from those indoors and that those indoor thermal comfort standards are not applicable to the outdoor settings (Höppe, 2002). Höppe (2002) isolates the absence of internationally accepted non-steady state indices as a key problem and highlights the importance of distinguishing between thermal comfort requirements, depending on the type of application (e.g. common weather reports, urban regional planning, climate therapy, health watch/warning systems or individual spare time activities).

In order to address the gap in dynamic outdoor comfort indices, a special Commission of the International Society of Biometeorology has been created, which aims at developing a new Universal Thermal Climate Index (UTCI). A workshop on the UTCI was held in Freiburg, Germany in June 2001 (International Society of Biometeorology, 2003). However, it has also been questioned whether a universal comfort index is suitable, as research findings suggest that predictors for comfort conditions vary from climate to climate and that a climate-group orientated approach would be more appropriate in predicting outdoor comfort conditions (Ramos & Steemers, 2003). Moreover, research indicates that a purely physiological approach is inadequate for characterising outdoor thermal comfort conditions and that psychological adaptation may be more important (Nikolopoulou *et al*., 2001). Specifically, Nikolopoulou *et al*. (2001) identified six basic human parameters that influence the psychological adaptation: naturalness, expectations, experience (short and long term), time of exposure, perceived control and environmental stimulation.

Research on outdoor thermal comfort is in its early stages and many different routes and aspects of thermal comfort are open for exploration. In Europe, much of the research has been carried out as part of the EU-funded RUROS project (Rediscovering the Urban Realm and Open Spaces), which in turn is part of the Key Action 4 "City of Tomorrow and Cultural Heritage" from the programme "Energy, Environment and Sustainable Development" within the European Fifth Framework Programme for the Environment (CRES, undated). The focus of outdoor thermal comfort to date has predominantly been on the study of public open spaces, in which people choose to stay. Little work has been done on subjects whose use of outdoor spaces is less due to personal choice, such as builders, market traders, etc. This matter provides a potentially new and interesting aspect of considering thermal comfort in outdoor urban spaces.

4.6 Building integrity

A large proportion of the urban environment is built. The structural integrity of buildings will depend, amongst other factors, on the ground it has been built on. Clay soils in particular, are subject to shrink and swell depending on their moisture content. This process could lead to subsidence of buildings. Thus, for the ASCCUE project it is important to determine where clay soils are located in Manchester and Lewes. The British Geological Survey is currently integrating its data holdings across 75 km^2 of central Manchester and Salford (Hough *et al*., 2003).

Geologically, the Manchester and Salford region straddles the southern part of the Carboniferous South Lancashire Coalfield and the northern part of the Permo-Triassic Cheshire Basin (Hough *et al*., 2003). To the south and west the Carboniferous Coal Measures are overlain by Permo-Triassic rocks of the Sherwood Sandstone Group, which is the second most important aquifer in the UK. Quaternary superficial deposits laid down during the Devensian glaciation cover most of the area, reaching thicknesses of over 40 m. These deposits include glacial till (pebbly and sandy clay), glaciolacustrine deposits (laminated clays and sands) and glaciofluvial outwash (sands and gravels). Post-glacial deposits include alluvium, river terrace gravels, and peat. There are extensive areas of made ground. Many rivers in south Lancashire have been culverted and their valleys infilled, as at Crofts Bank and along much of the course of the lower Medlock and its tributaries (Hough *et al*., 2003).

The plasticity of soils is commonly measured during routine ground investigations and is an important engineering characteristic of fine-grained soils (Hough *et al*., 2003). It gives an empirical understanding of the susceptibility of the soil to deformation and shrink-swell. In normal ground conditions, low plasticity values indicate a lower shrink-swell potential than higher values. The alluvial silts and clays of the River Irwell floodplain display low- to medium-plasticity, except for a couple of samples with a high organic (peat) content which have high-plasticity, whilst glaciolacustrine clays that subcrop to the south of the Irwell cover similar fields but generally have a higher plasticity. Thus, the alluvial sits and clays have a lower shrink-swell potential than the glaciolacustrine deposits (Hough *et al*., 2003).

5. Impacts

5.1 Air Quality

Climate change may change air quality in several ways (Patz *et al.*, 2000): affecting weather systems and thereby local pollution production, transport and dispersion (O'Hare & Wilby, 1994); affecting both anthropogenic and natural emissions; and changing the distribution and types of airborne allergens.

Increased windy weather and strong westerly airflows could cause fewer air pollution incidents by dispersing pollutants such as NOx, PM_{10}, and VOCs (e.g. Bower *et al.*, 1994). In winter, it is the simultaneous occurrence of a low windspeeds and freezing conditions that is associated with poor air quality (Anderson *et al*., 2002). From 2050 to the end of the century the number of days with these conditions decreases (table 4), and winters become generally warmer and windier (Anderson *et al*., 2002). It is possible, therefore, that there will be a reduction in stagnant winter weather episodes (Anderson *et al*., 2002). This, combined with a reduction in emissions (section 4.2.1), would mean a significant decrease in mean and episodic winter ambient concentrations of particles, NO_2 and SO_2 (especially the latter) (Anderson *et al*., 2002).

Table 4. The number of days, in central England, with at least one hour in which the windspeed is less than 2ms^{-1} and the minimum temperature is in the range shown for each decade up to 2100, using daily meteorological parameters produced by the Hadley Centre Climate Model (HadCM3) coupled with an ocean-atmosphere global climate model, driven by the IPCC IS92a (business as usual) scenario (Anderson *et al.*, 2002), which roughly corresponds with the UKCIP02 Medium-High Emissions scenario (IPCC, 2000).

Decade	No. of days between -15ºC and -10ºC	No. of days between -10ºC and -5ºC	No. of days between -5ºC and 0ºC
1990-1999	0	1	32
2000-2009	0	2	17
2010-2019	0	1	38
2020-2029	1	3	43
2030-2039	1	3	11
2040-2049	0	2	30
2050-2059	0	1	20
2060-2069	0	1	30
2070-2079	0	0	26
2080-2089	0	1	24
2090-2099	0	0	17

By contrast, it is likely that there will be an increase in episodes of hot, sunny summer days, an increase in background ozone concentrations (as part of a north west Europe phenomenon), as well as a reduction in the emissions of ozone precursors such as NO_2 and a reduction in concentrations of particles. The overall effect of these changes could be a small net increase in ozone episodes (Anderson *et al*., 2002). Summer episodes are characterised by high ozone concentrations and often, also of particle concentrations (Anderson *et al*., 2002). The number of days with low windspeeds and high temperatures, favourable conditions for high surface ozone concentrations, is likely to occur with increasing frequency during the present century (table 5) (Anderson *et al*., 2002).

Atmospheric and air-shed modelling has suggested that temperature increases of 4ºC, combined with more stable air episodes, could lead to 1-20% increases in peak ozone concentrations in US urban areas (Morris *et al*., 1989; Penner *et al*., 1989) and more violations of clean air standards

(Morris *et al.*, 1995). In London, it has been estimated that a 1ºC summer air temperature rise (also a proxy for the amount of catalysing sunshine) could see a 14% increase in surface ozone concentrations (Lee, 1993).

Table 5. The number of days, in central England, with at least one hour in which the windspeed is less than 2ms^{-1} and the maximum temperature is in the range shown for each decade up to 2100, using daily meteorological parameters produced by the Hadley Centre Climate Model (HadCM3) coupled with an ocean-atmosphere global climate model, driven by the IPCC IS92a (business as usual) scenario (Anderson *et al.*, 2002), which roughly corresponds with the UKCIP02 Medium-High Emissions scenario (IPCC, 2000).

Decade	No. of days in the range from 25 - 30ºC	No. of days in the range from 30 - 35ºC	No. of days in the range from 35 - 40ºC
1990-1999	1	0	0
2000-2009	1	0	0
2010-2019	3	0	0
2020-2029	3	0	0
2030-2039	5	0	0
2040-2049	8	1	0
2050-2059	9	2	0
2060-2069	8	2	0
2070-2079	6	1	1
2080-2089	14	2	0
2090-2099	15	5	2

Through studying the change in the frequency of high pressure systems over Eastern England, it was estimated that: under the Medium-High Emissions scenario there would be an average increase in pollution episodes of over 4 days per summer by the 2080s compared with the 1961 to 1990 mean; whilst under Medium-Low Emissions the increase would be a little over 2 days. The inter-annual variability would be high (LCCP, 2002). A shift to airflows from the south east and east favours incursions of (polluted) air from Europe (O'Hare & Wilby, 1995).

The literature focuses mainly on the impacts of changes in temperature and wind on air quality (e.g. Anderson *et al*., 2002). There is no (or in any case, very little) literature relating to air quality and precipitation. It is possible (although a hypothesis of the authors of this review) that changing precipitation patterns could impact on air quality. For example, increased rainfall in winter may lead to improved air quality as a result of an increased washout of particles. Similarly, decreased summer rainfall may lead to a decreased washout of particles.

5.2 Hydrology

The effects of increased temperatures and changing precipitation patterns and the occurrence of extreme events will impact upon urban hydrology. Higher air temperatures will increase lake and river water temperatures (Webb, 1996; Pilgrim *et al.*, 1998), leading to an absence of shorter periods of ice cover (Magnuson *et al.*, 2000). Organic nitrogen decomposition is enhanced by warmer, drier climates causing potential contamination for rivers and groundwater (Murdoch *et al.*, 2000). The higher water temperatures combined with higher nutrient concentrations encourage increased primary production (including algal blooms), eutrophication and deoxygenisation of the water (Hassan *et al.*, 1998; LCCP, 2002). Similarly, low mixing rates, less cloud cover and higher summer temperatures cause stratification and algal growth, leading to increased raw water treatment costs (Hassan *et al.*, 1998). Nutrient losses to aquifers is also increased through cracks in clay as a result of shrinkage, which create a more direct hydrological link between the surface and the groundwater (Rounsevell *et al.*, 1999).

Precipitation changes will impact upon soil moisture, surface runoff, river flows, and flooding. Other impacts include changes in the availability of physical habitat (Keleher & Rahel, 1996) and changes in biogeochemical cycles including the mobilisation of heavy metals and pesticides (Schindler, 1997).

UKCIP02 scenarios suggest that both the annual and summer average soil moisture will decrease, most obviously in the south east (Hulme *et al.*, 2002). A preliminary assessment of potential water resource impacts for two tributaries of the River Thames was made for the London Climate Change Partnership study (LCCP, 2002). Soil moisture deficits were modelled for rivers Kennet and Loddon (tributaries to the Thames). Both catchments show 1-9% decreases in annual precipitation and 6-10% decreases in actual evapotranspiration (AET) (despite higher temperatures) by the 2080s (due to drier summer soils reducing the potential for AET; Marsh, 2001). Thus, there is an increase in the annual maximum soil moisture deficit (SMD, which is the quantity of water from rainfall or irrigation needed to return a soil to field capacity or the maximum water holding capacity when free drainage can occur; Kettlewell *et al*., 2003), especially in the latter half of the century. Since the soil is drier at the end of the water year, it takes more precipitation before it will become saturated and groundwater recharge or surface runoff can occur. Thus, the recharge season is shortened, by up to eight days by the 2050s and 14 by the 2080s, compared to the average season of 60 days between 1961 and 1990. The River Loddon displays a 4-6% reduction in recharge by 2050s and 3-10% by 2080s. The River Kennet has a 7% increase in recharge by the 2080s under the Medium-Low Emissions scenario yet a 10% reduction in recharge under Medium-High Emissions. Since runoff approximates recharge in the long-term (assuming no abstraction) the annual resource might change between +7% (Kennet, Medium-Low) and –10% (Kennet and Loddon, Medium-High) by the 2080s (LCCP, 2002).

Studies have suggested increases in UK winter runoff (especially in the north) and decreases in summer runoff (especially in the south) under climate change (Arnell, 1998; Arnell & Reynard, 1996; Pilling & Jones, 1999; Sefton & Boorman, 1997). However, individual catchments will vary significantly (Sefton & Boorman, 1997). Climate change scenarios constructed from the Hadley Centre’s high resolution general circulation model (UKHI) for 2050 found effective runoff increasing throughout most of Britain, whilst the transient global circulation model (UKTR) for 2065 found it decreasing over much of England and Wales (Pilling & Jones, 1999). Both scenarios, especially UKTR, showed an increasing gradient between the wetter north and drier south-east, which may accentuate imbalances in available water resources (Pilling & Jones, 1999).

Analysis of extreme events suggests that there will be an increase in the frequency of both high- and low-flow events (Pilling & Jones, 2002). Reduced summer flows could cause reduced nutrient dilution and hence increased concentrations of pollutants, especially when intense rainfall follows a period of drought (Wilby *et al.*, 1998). Research in Manchester has suggested that water quality is affected by wash-off pollutants accumulated on impermeable surfaces, such as roads, during extended dry periods (Robertson *et al*., 2003). A study collected surface pollution samples on an urban road surface in Melbourne, Australia, over a thirty-six day period. It indicated that pollutants accumulated quickly on the surface following a rain event, but slowed down after several days as redistribution occurred. Over the days the pollutant becomes finer as it is disintegrated by, for example, traffic. The subsequent pollutant washoff is dependent on rainfall and runoff characteristics, but common storms seemed to only remove a small proportion of the pollutant load whereas a high intensity rainfall event may remove more of the pollutant load (Vaze & Chiew, 2002).

Under summer dry periods, especially in consecutive years, reservoir levels could reduce substantially. Thus, plans will be required for greater winter storage of water, water rationing, or alternative sources (CURE & Tyndall Centre, 2003). The impacts of climate change may raise awareness of the environmental costs of water consumption and hence the need to use water wisely.

In the Thames region, a slight increase in winter rainfalls exceeding 12.5 mm/d by the 2080s and a strong decline in summer rainfall suggests that the frequency of pollution events from flushing of combined sewer outflows (CSOs) would decline. The polluting potential of CSOs may still be higher because of less diluted sewage (as a result of less summer infiltration to sewers) and lower flows in the receiving water course (LCCP, 2002).

Climate change impacts outside of the urban environment will affect a city's water supply. Catchment-scale studies in the Thames region indicate that river flows are controlled by local variations in geology (Davis, 2001; Wilby, 1994), landuse change, surface and groundwater abstraction (Wilby *et al.*, 1998). Catchments with large groundwater bodies will be less sensitive to climate change (Pilgrim *et al.*, 1998). The UKCIP98 scenarios, demonstrate winter recharge enhancing summer baseflows in a chalk catchment, whereas in clay and urban catchments there is less opportunity for groundwater recharge so baseflows decline (Davis, 2001). UKCIP98 scenarios predict an overall increase in water resources of between 2.5 to 6% in the Thames region by the 2020s (when the temperature will have risen by less than 1.4ºC), yet no studies evaluate beyond this or the effects of successive dry years. The hotter and drier UKCIP02 scenarios may be less favourable (LCCP, 2002).

High flow events could lead to increased flooding. Under the UKCIP98 Medium-High Emissions scenario, British reservoirs could see a total surcharge (rise in water level above normal retention level during a storm) increase of about 5% by the 2050s. Concrete and masonry dams may be less vulnerable than embankment dams, however, more than half of Britain's reservoirs are over 100 years old and made of earth embankments (LCCP, 2002). Dams could be physically damaged as a result of foundations subsidence, landslip into reservoirs, or overtopping in heavy rain. Heavy rainfall and flooding may also cause the silting up of reservoirs, pumping stations and boreholes (CURE & Tyndall Centre, 2003).

Flooding is likely to be the most serious direct impact of climate change in the north west (CURE & Tyndall Centre, 2003). Climate change will probably reduce the level of protection offered by flood defences (LCCP, 2002). Factors of concern for flooding include: sea level rise (combined with severe storms and wave heights); more frequent, severe, or prolonged rainfall events; the large size of urban catchments; an increasingly built-up environment which increases surface water runoff, in particular, the rate of development on floodplains; the age, condition and lack of capacity of existing urban drainage infrastructure; and the impact of rising groundwater in conjunction with surface flooding (CII, 2001).

Riverine flooding is location specific and modelling of river catchment, including size, shape, soil type, geology and land uses can address how particular rivers respond to changing rainfall patterns (CURE & Tyndall Centre, 2003). However, as a result of the difficulties of modelling high intensity precipitation (or snowmelt) at catchment levels and land cover controls on runoff, it is at present rather uncertain how, how much, and at which spatial scale climate change is likely to affect the generation of storm runoff and the consequent flood discharges of rivers (Bronstert *et al*., 2002).

Simplistic impact assessments infer riverine flooding from predicted changes to extreme rainfall events (LCCP, 2002). For example, the regional climate model HadRM2 (predecessor of the model used in UKCIP02) predicted increases in the magnitude of 30-day and 60-day duration events (witnessed in October/November 2000 floods) in catchment areas influencing Lewes, Shrewsbury and York (CEH & Meteorological Office, 2001). Other approaches have been to examine changes in effective rainfall (as a proxy for discharge) from global climate models for large river basins (e.g. Milly *et al.*, 2002), and to downscale meteorological variables to an experimental watershed for hydrological modelling (Pilling & Jones, 2002).

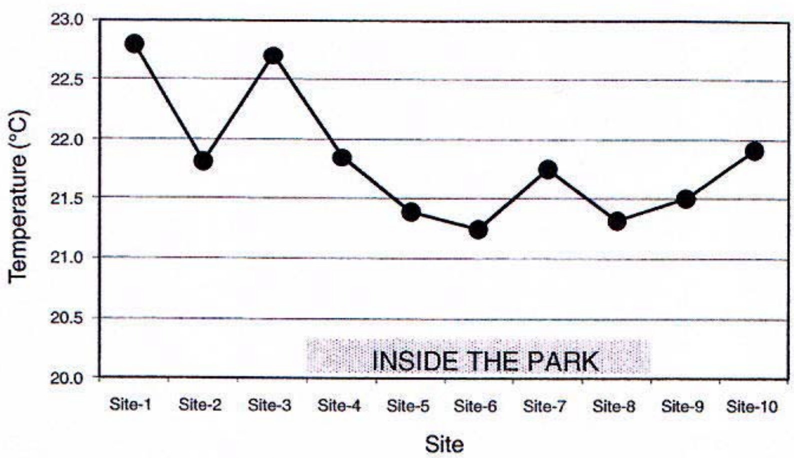
Coastal cities will also be affected by interactions between sea level rise, runoff from the land and extreme coastal storm surge events (Holt, 1999; Lowe *et al.*, 2001; Von Storch & Reichardt, 1997). The potential implications of sea-level rise for the UK have been reviewed by de la Vega-Leinert and Nicholls (2002). It is estimated that by 2100 the Thames Barrier will have to close 200 times a year to protect London from tidal flooding (Environment Agency, 2001c). There has been no thorough assessment of the risks of sea-level rise and extreme rainfall affecting river levels over long time periods, such as beyond 2100 (LCCP, 2002). Extreme storm surges may be more important from an impacts point of view than the slower changes in mean sea level (Lowe *et al*., 2001).

5.3 Green space

Little attention has been given to the study of climate change impacts on urban ecology. However, it has been assumed for this report that the results from studies on rural environments may, to some degree, be applicable to urban greenspaces. This section considers the general impacts of climate change on green spaces, followed by the impacts on individual plants and species that may characterise the green spaces.

Climate change puts increased pressure on both the structure and function of urban green spaces. Warmer temperatures may increase the demand for urban green spaces as people enjoy a more outdoors lifestyle and green areas offer oases from the higher temperatures. Urban parks have been shown to be cooler than surrounding areas. A study measuring air temperature at ten sites on a transect across a London park (Primrose Hill) found temperatures to be on average 0.6ºC cooler in the park than on neighbouring streets over a 12 hour period (fig. 23). The main shopping street, which offered no shading, was up to 3ºC warmer than the centre of the park (Graves *et al.*, 2001).

Fig. 23. Mean temperature over twelve hours at sites inside and outside of the park (Graves *et al.*, 2001)

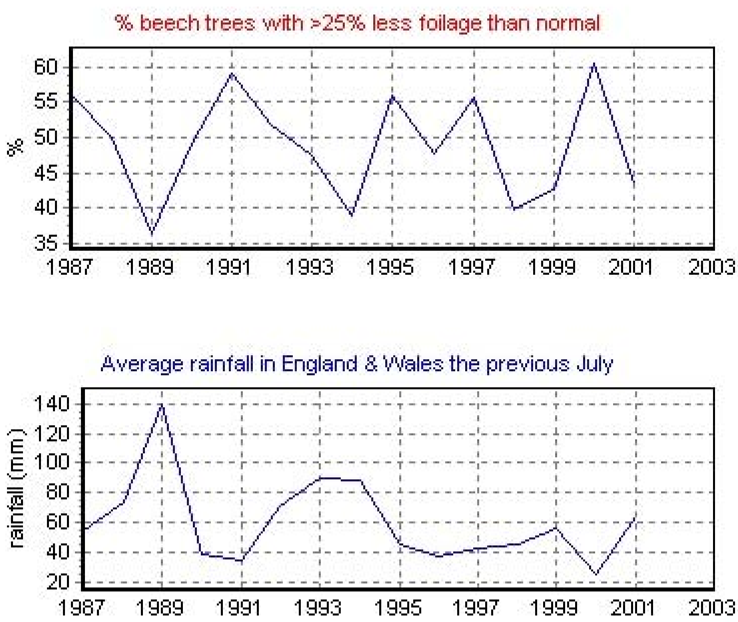


Increased temperatures, together with less rainfall, could increase the water demand for irrigating green spaces (Herrington, 1996). Grass productivity is reduced in hotter, drier summers (Sparks & Potts, 1999), thus more water would be required for lawn irrigation. This demand would have to compete with other demands such as more water for manufacturing and hygiene purposes.

Poorer air quality, associated with higher temperatures under climatic change (section 5.1) will impact on the vitality of urban trees and green spaces. Tropospheric ozone damages vegetation (Ashmore *et al*., 1985; Rose, 1990) and crops (Skarby & Selden, 1984; Krupa & Manning, 1988). Surface ozone has had negative effects on the structure and productivity of forest ecosystems in industrialised countries (Krupa & Manning, 1988), and together with acid rain, it may be a contributory factor in the destruction of upland forests in North America and Europe (Ashmore *et al*., 1985; Rose, 1990). Studies showing the effect of ozone on plants (and health) are complicated since it is rare to be solely exposed to ozone and not other pollutants, pathogens and pests (Krupa & Manning, 1988). Long exposures (24 or 36 hours) at lower concentrations (60 ppb) may be as injurious as short exposures (one hour) to high concentrations (over 100 ppb), and injury does not always manifest itself in physical symptoms (O'Hare & Wilby, 1995). Plants may have reduced growth and productivity, and certain crop plants can be damaged at low concentrations such as 40-60 ppb over several hours (Skarby & Sellden, 1984).

Garden plants are susceptible to damage from summer drought and winter water logging (Burroughs, 2002). Tree health is a function of air pollution concentrations (Ashmore *et al.*, 1985) and water stress (Bisgrove & Hadley, 2002). The crown density of beech reduces with droughts in southern Britain (fig. 24) (Cannell & Sparks, 1999). However, drought stress in summer can offer natural woodlands protection from ozone damage by enforcing stomatal narrowing or closure (Zierl, 2002). Drier summers may make natural woodlands more susceptible to insect pests, disease and windthrow during the stormier winters (Bisgrove & Hadley, 2002)

Fig. 24. Percentage of beech trees surveyed in the UK whose crowns were more than 25% less foliated than they should have been (note that large values indicate many poorly-foliated trees), shown in relation to average rainfall in England and Wales the previous July (Cannell & Sparks, 1999)



With an increased frequency in extreme precipitation events, green areas could serve an important role in floodwater storage. This could impact either negatively or positively on biodiversity, and access to parks may be restricted to protect habitats and species. The multiple land use and loss of access will impact on existing users, with knock-on effects for human health.

It has been suggested that wetter soils in winter combined with a higher frequency of storms may lead to higher levels of tree fall (Bisgrove & Hadley, 2002). Richmond Park, London, lost 10% of its trees in the storms of 1987 and 1990. Storm damage in 1987 was much higher in over-aged trees and in single-species plantations (Bisgrove & Hadley, 2002). Additionally, during droughts and in areas subject to subsidence, trees are the biggest cause of soil drying and subsidence, resulting in foundation movement and damage (Biddle, 2001).

Soil erosion is influenced by the amount and intensity of rainfall, as well as wind speed and direction (Lee *et al.*, 1999). More intense winter rainfall could increase soil erosion especially when there is no vegetation cover. This may wash away soil minerals as well as sediment, impacting on biodiversity, polluting watercourses, and decreasing the productivity of the land (Bisgrove & Hadley, 2002; Lee *et al.*, 1999).

Climate change may interact with other pressures facing ecosystems. For example, climate change may favour an invasive species over a native species (Dukes & Mooney, 1999). It could also affect the ecological niches of species both directly (thermal tolerance) and indirectly (soil nutrient cycling) (Schimel *et al.*, 1991). Despite the heavy management of gardens and parks, climate still drives the potential ranges of species, phenology, physiology and behaviour (Bisgrove & Hadley, 2002). Garden plants are susceptible to temperature related events, such as damage from extreme winter and late spring frosts (Burroughs, 2002) as well as weather related pests and disease (Hardwick, 2002).

Temperature and carbon dioxide interact. Higher temperatures and higher carbon dioxide levels combine to stimulate more rapid growth and development but the end result is not always a higher yield. Increased speed of development may mean that the plant is unable to use the full length of the growing season before it dies (Bisgrove & Hadley, 2002).

Higher temperatures will favour certain plants and animals that are better adapted to cope with them. Climate change combined with the UHI may help exotic plant species that have been introduced inadvertently or ‘escaped’ from gardens to be naturalised (e.g. Oxford Ragwort, Rhododendron, Himalayan Balsam and Japanese Knotweed) (Bisgrove & Hadley, 2002). These introduced species may compete with native species. However, it may be questioned whether this argument is relevant to urban areas as these are already characterised by a high percentage of introduced species because of urban climates, soils, high levels of disturbance and import of species.

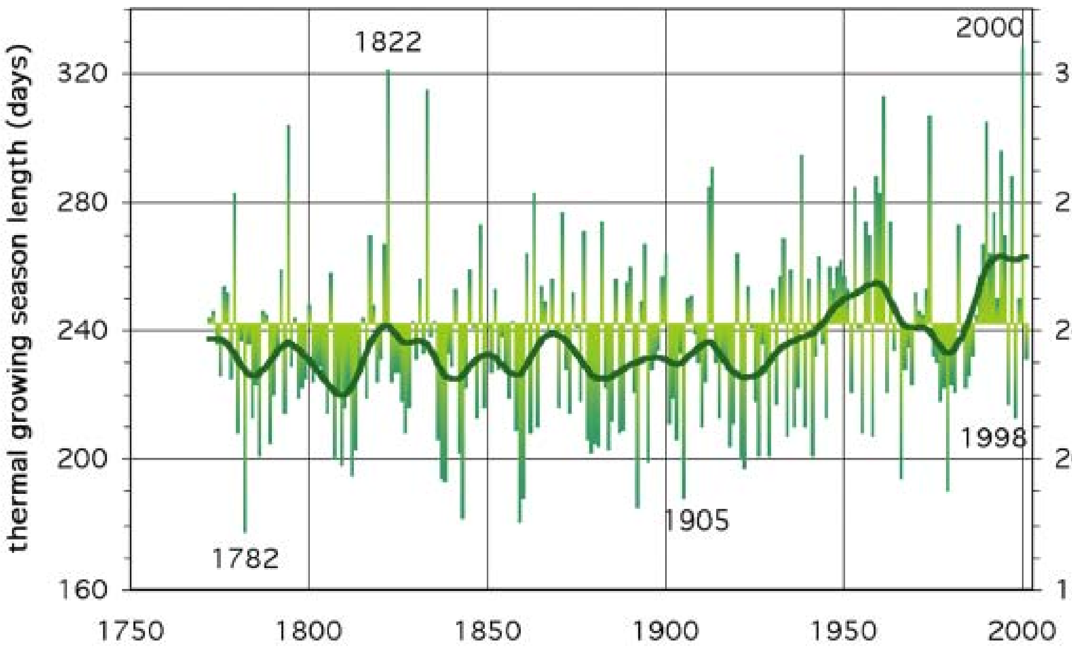
Similarly, the types of trees that can grow successfully will probably change (table 6). Beech trees are failing to thrive as they once did (although this could be due to damage by grey squirrels) (Bisgrove & Hadley, 2002). The London plane tree (*Platanus acerifolia*) is better adapted to climate change, being a hybrid of the oriental and western plane that grows in hotter climates such as the Mediterranean. Sweet chestnuts also grow well in hot and dry climates, and support a wider range of species than the plane (LCCP, 2002). In a changing climate the multifunctional role of trees is likely to become increasingly important for negating erosion and flooding; shelterbelt function; reducing UHI effect; and providing shade and water storage functions (CURE & Tyndall Centre, 2003). However, there may also be disadvantages as woodlands have a higher water demand than other land uses (CURE & Tyndall Centre, 2003) and therefore groundwater replenishment is reduced.

Table. 6. Quality timber that should benefit from extra warmth in Britain and trees that are resistant to storm damage (White, 1994)

Benefit from extra warmth		Resistant to storm damage	
Acer saccharinum	Silver maple	*Acer pseudoplatanus*	Sycamore
Carya cordiformis	Bitter nut	*x Cupressocyparis leylandii*	Leyland cypress
Cladrastis lutea	Yellow wood	Magnolia (tree species)	Magnolia
Corylus columa	Turkish hazel	*Ilex aquifolium*	Holly
Cupressus glabra	Smooth Arizona cypress	*Metasequoia glyptostroboides*	Dawn redwood
Cupressus sempervirens	Italian Cypress	*Robinia pseudoaccacia*	Black locust
Eucalyptus delegatensis	Woolybutt	*Sequoiadendron giganteum*	Wellingtonia
Fagus grandifolia	American beech	*Taxus baccata*	Yew
Juglans nigra	Black walnut		
Ligustrum lucidum	Tree privet		
Liriodendron tulipifera	Tulip tree		
Paulownia tomentosa	Foxglove tree		
Platanus acerifolia	London Plane		
Prunus serotina	Black cherry		
Pyrus pyraster	Wild pear		

Temperature changes and longer frost-free seasons are extending the UK growing season (fig. 25). Spring is arriving between two to six days earlier and autumn two days later each decade. The growing season has extended by 24 days over the last 30 years. It extended by an average of 0.7 days per year from 1920 to 1960 and by 1.7 days per year from 1980 to 2000 (Bisgrove & Hadley, 2002). Each degree of annual warming lengthens the growing season by about three weeks in southern areas and one and a half weeks in northern areas (Hulme *et al*., 2002).

Fig. 25. The length of the thermal growing season in central England. The bars emphasise deviations from the 1961-1990 average (242 days). The smoothed curve emphasises variations on time scales of at least 30 years (Hulme *et al.*, 2002).

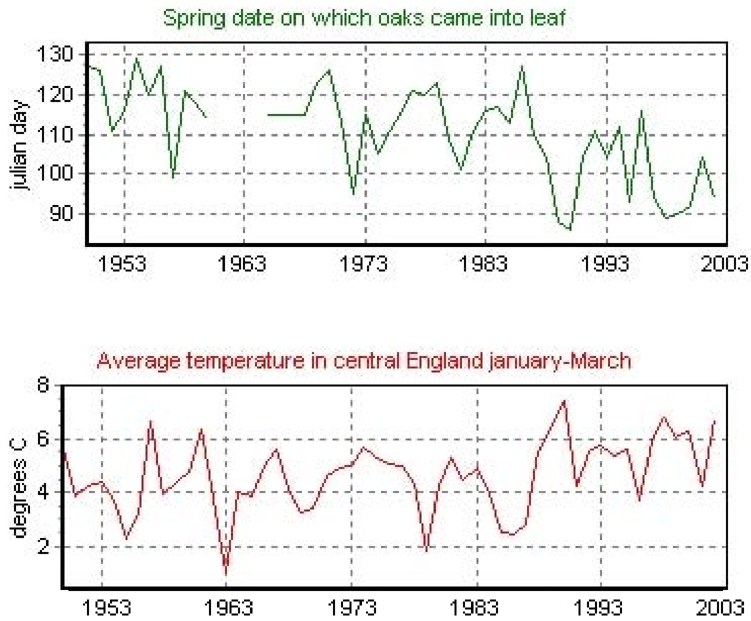


A longer growing season will affect the rate of development, or phenology, of plants. The UHI has been shown to affect plant phenology (Roetzer *et al*., 2000; White *et al*., 2002). We may see earlier bud burst and flowering; appearance of leaves; and plant maturity. As well as delayed leaf fall and flowering into winter time, 'unseasonal' spring bulb flowering, and the near continuous growth of lawns (Bisgrove & Hadley, 2002). The early flowering of certain plant species has already been noted. A study of 25 native British garden species found that following a 1ºC increase in temperature, 24 of the species displayed a significant advancement in flowering time (table 7). Similarly, each 1ºC increase in early spring temperature sees oak leafing about six days earlier at Ashtead, Surrey (fig. 26) (Sparks, 1999). The prolonged growing season will increase the attractiveness of green spaces for recreational use but it may also increase maintenance costs (e.g. grass cutting).

Table 7. Results from stepwise regression of flowering time on Central England monthly temperatures (from the preceding October through to the month of mean flowering of that species) (after Sparks *et al*., 2000). The value in the second column gives the pooled effect of a 1ºC rise across all months on the date of flowering (expressed in days). A negative sign indicates an advancement in flowering time, a positive sign indicates a delay in flowering time. Six species for which 58 years of data exist are given first followed by species with 20 years of data.

Species	**Net effect (days)**
Greater bindweed (*Calystegia silvatica*)	-9.9
Bird cherry (*Prunus padus*)	-9.1
Almond (*Prunus dulcis*)	-8.9
Purple lilac (*Syringa vulgaris*)	-8.8
Hawthorn (*Crataegus monogyna*)	-8.6
Dog rose (*Rosa canina*)	-8.2
Laburnum (*Laburnum anagyroides*)	-7.9
Horse chestnut (*Aesculus hippocastanum*) – flowering	-7.7
Ivy (*Hedera helix*)	-7.3
Lesser celandine (*Ranunculus ficaria*)	-6.7
Elder (*Sambucus nigra*)	-6.5
Madonna lily (*Lilium candidum*)	-6.4
Yellow crocus (*Crocus aureus*)	-5.8
Ox-eye daisy (*Leucanthemum vulgaris*)	-4.9
Redcurrant (*Ribes rubrum*)	-4.9
Horse chestnut (*Aesculus hippocastanum*) – leafing	-4.9
Winter aconite (*Eranthis hyemalis*)	-4.7
Coltsfoot (*Tusilago farfara*)	-4.2
Hazel (*Corylus avellana*)	-4.1
Garlic mustard (*Alliaria petiolata*)	-4.1
Wood anemone (*Anemone nemorosa*)	-3.6
Snowdrop (*Galanthus nivalis*)	-3.4
Harebell (*Campanula rotundifolia*)	-2.6
Christmas rose (*Helleborus niger*)	-1.9
Autumn crocus (*Colchium speciosum*)	+3.8

Fig. 26. Spring date on which oaks were observed to be coming into leaf in Ashtead, Surrey, shown in relation to the average temperature in Central England in January to March (Sparks, 1999)

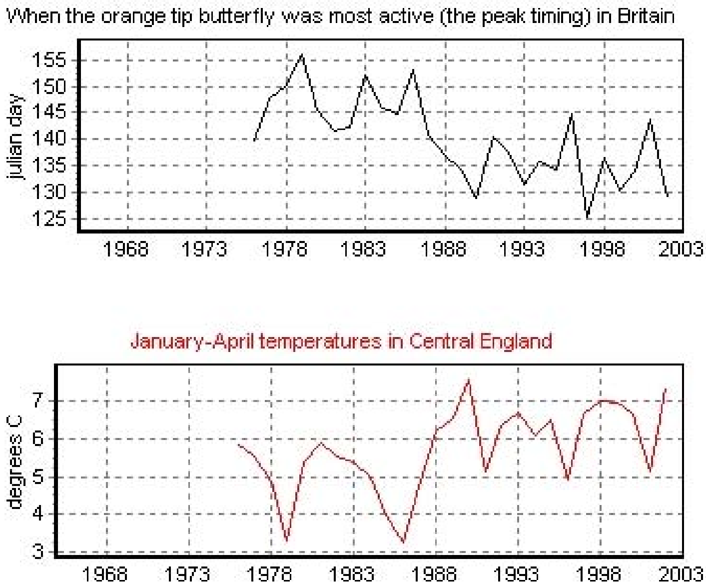


In addition to changes in plant phenology, the health of plants is affected by earlier springs, longer frost-free seasons, and reduced snowfall (Sparks & Smithers, 2002). The natural regeneration of trees may be affected if a lack of winter chilling impacts on seed fertility (Forestry Commission, 2000). Exposure to a period of low 'chilling' temperatures is required before a plant can resume active growth in spring. This is often measured as the accumulation of temperature below a particular threshold temperature. If chilling is inadequate the development and/or the latter expansion of leaf and flower buds may be impaired (Bisgrove & Hadley, 2002).

Insect distributions and the timing of their activities are highly weather dependent (Burt, 2002). This is relevant not only for biodiversity in itself but because insect species include agricultural, horticultural and forestry pests as well as carrying human and animal diseases (Sparks & Woiwod, 1999). Growth and production may increase for species presently in thermal environments cooler than their optimum yet decrease for those at or above their optimum (Magnuson *et al*., 1997). The range of some pests and diseases will be increased under climate change, whilst some will be decreased. The warmer climate will see native pests and insects moving northwards, and an increased risk of pests from continental Europe (Bisgrove & Hadley, 2002). Ranges of many species in North America and Europe have shifted poleward (such as the marbled white and gatekeeper butterflies and some rare dragonflies) in response to key physiological controls such as warmer temperature, moisture and length of growing season (Parmesan *et al.*, 1999; 2000; Thomas & Lennon, 1999). British insect records since the 1960s suggest the association of a 1ºC temperature rise with a 16-day advancement in the appearance of the peach-potato aphid (*Myzus persicae*); a 6-day advance in peak flight time of the orange tipped butterfly (*Anthocharis cardamines*) (fig. 27); and a 7-day advancement in the average time of activity of the common footman moth (*Eilema lurideola*) (Sparks & Woiwod, 1999).

Bird populations are also sensitive to environmental change and their position near the top of the food chain allows for an indication of overall ecosystem functioning. Increasing grey heron numbers in London have been attributed to better water quality (allowing for fish to survive) and less severe winters (Marchant *et al.*, 1990). Small birds, such as the wren, are prone to high mortality during prolonged spells of cold, wet or snowy weather. They are an excellent index of very cold winters, with their populations on farm and woodland since 1962 being strongly related to mean winter temperatures in central England. Their numbers have been high since the 1990s (Crick, 1999). Models suggest that, in the south east, under UKCIP98 High Emissions scenario, the willow tit, nuthatch and nightingale witness a reduction in climate space as a result of warmer drier conditions affecting woodlands and insects. On the other hand, the potential distribution of the reed warbler, yellow wagtail and turtle dove may increase nationally (Berry *et al.*, 2001). Annual variations in first laying dates are strongly correlated with spring temperature variations (Crick *et al.*, 1997). However, the mismatched timing of egg laying in relation to food supplies could lead to declines in populations (Visser *et al.*, 1998). Changes noted to migratory patterns and arrival dates will depend upon the specific triggers for migration. For example, a 1ºC increase in spring temperature is associated with the swallow arriving in the UK 2-3 days earlier (Sparks & Loxton, 1999).

Fig. 27. When the orange tip butterfly was most active (the peak timing) in Britain in relation to mean January-April temperatures in Central England (Sparks & Woiwod, 1999)



5.4 Human Well-Being

5.4.1 Comfort

Temperature changes influence people's comfort (Eliasson, 2000; Svensson & Eliasson, 2002). Human thermal comfort can be measured by indices and thermophysiological models (Jendritzky & Nübler, 1981; Gómez *et al.*, 2001; Zacharias *et al.*, 2001). It is more difficult to apply such models in the outdoor environment because of the complexity of the radiative conditions there in comparison to indoors (Jendritzky & Nübler, 1981). Human comfort can be measured as physiological equivalent temperature (PET), an index derived from the human energy balance which expresses thermal stress on people (Svensson & Eliasson, 2002). It requires information about wind speed, temperature, moisture, and global radiation and a clothing index and activity value and estimates the thermal stress for differing groups of people (e.g. an 'average European male', 35 years old, 1.7 m tall and weight 75 kg). 'Comfortable conditions' (when the body does not experience any thermal stress) are represented by 18-23ºC on the PET scale (Matzarakis *et al.*, 1999). PET values have been shown to be higher within densely built-up urban environments, and values on a clear and calm occasion were higher than those on a cloudy and windy occasion (Svensson & Eliasson, 2002). This demonstrates how wind affects how people experience temperature (Svensson & Eliasson, 2002).

5.4.2 Health

The impact of climate change on health is complex and involves interactions between the physical attributes of the settlement and precursors for the direct effects of heat stress and disease (IPCC, 2001). Health is affected by heat, air and water quality, flooding and wind storms.

Exposure to both hot and cold temperatures can result in death, especially for the most sensitive members of the population (Kunst *et al.*, 1993; Laschewski & Jendritzky, 2002), such as the elderly, poor, those in ill health and the very young (IPCC, 2001). Whilst England and Wales had a mortality increase of 8.9% during a summer heatwave in 1995, Greater London (where the temperatures were higher and with lesser falls at night) witnessed an increase in mortality of 16.1%. It is suggested that some of the excess mortality may be attributable to the concurrent increases in air pollution (Rooney *et al.*, 1998). Research suggests that the most important factor in urban heat deaths may be variability in summer nighttime minimum temperatures (above 32ºC) combined with a lack of acclimatisation, high humidity and poorly ventilated and insulated housing (Chestnut *et al.*, 1998). Climate change is expected to raise nighttime minimum temperatures more than daytime maximums (IPCC, 2001). There is also less cooling at night in urban areas due to the urban heat island (UHI) effect (section 4.1.2). High temperatures and ozone concentrations have been linked to deaths during a summer heatwave in Belgium in 1994 (Sartor *et al.*, 1995). Whilst higher temperatures are expected to increase the risk of dying from heatstroke or cardiovascular diseases (Kilbourne, 1990; Pan *et al.*, 1995) exposure to ozone may increase the risk of dying from respiratory diseases (Sartor *et al.*, 1995).

In the UK, heat-related deaths begin to occur when mean daily temperature rises above the minimum mortality band of 15.6-18.6°C (Donaldson *et al*., 2002). Currently, an estimated 800 'heat-related' deaths occur per year in the UK. It is estimated that these deaths are accompanied by about 80,000 days additional NHS hospitalisation (Donaldson *et al*., 2002). The impact of climate change on temperature related mortality can be estimated from current trends, assuming that this relationship is causal and does not change in the future. Under Medium-High Emissions there could be 2800 heat-related deaths by the 2050s (an increase of 250% from current levels) and 280,000 days per year of heat-related NHS hospitalisation (Donaldson *et al*., 2002). However, these results may be overestimations as they do not take into account effects of physiological acclimatisation and adaptive changes in lifestyle (Donaldson *et al*., 2002). These increases would be more than matched by a fall in cold-related deaths (to 60,000 compared with 80,000 currently) and hospitalisation (to 6,100,000 days per year compared with 8,200,000 presently) due to progressively milder winters (Donaldson *et al*., 2002).

Studies have demonstrated that acclimatisation is important. Populations are most vulnerable to hotter or colder spells in relation to what they are used to. For example, a similar cold spell causes more suffering in Athens than in Stockholm, whilst a heatwave affects those in Stockholm more than those in Athens (Martens, 1996; Gawith *et al.*, 1999).

Warmer winters would shorten the heating season, thus demanding less energy for heating buildings. This would have a positive effect on winter comfort, especially for those in fuel poverty (Langford & Bentham, 1995). However, increased summer temperatures and poorer air quality could make natural ventilation options less attractive and could therefore lead to an increased use of air conditioning (AC) for cooling buildings, which may exceed the energy saved through less winter warming (LCCP, 2002). It is estimated that the use of AC in Los Angeles saved 800 lives during the 1963 September heatwave (Oechsli & Buechley, 1970; Goldsmith, 1986; Marmor, 1978; Rogot *et al.*, 1992). However, more research is needed into the risks of AC spreading infectious disease. The outbreak of Legionnaire's disease in Barrow-in-Furness in

August 2002 was attributed to a faulty or poorly maintained AC unit (BBC News, 2002). Also, it has been suggested that the contrast between the cool air-conditioned interior and warm exterior will impact on the body's physiology, making people more susceptible to illness (LCCP, 2002). An increased use of AC requires a greater energy consumption, and hence more urban waste heat, further exacerbating the UHI effect (LCCP, 2002).

Using a derived relationship between cooling energy and average summer temperature, the 'standard air conditioned office building' in London, with no attempts made to reduce the cooling demand such as solar shading, could see increases in cooling energy demand of 12-15% by the 2050s and 18-26% by the 2080s under Medium-Low and Medium-High Emissions scenarios (LCCP, 2002). It has been estimated that in the north west these figures would be slightly less: 12-14% by the 2050s and 17-24% by the 2080s (CURE & Tyndall Centre, 2003). Increased AC demand in peak hours requires a disproportionately high increase in generation capacity, putting further strain on transmission and distribution networks and perhaps causing 'black-outs'. Also, the increased average temperatures will restrict the load that can be carried by the networks due to the increased risk of overheating (LCCP, 2002). Loss of electrical power has serious social, political, economic and health impacts – for example the more vulnerable are less able to deal with the heat stress, increased crime in some neighbourhoods during power cuts (LCCP, 2002).

According to building simulations for the 2050s, under the UKCIP98 Medium-High Emissions scenario, working conditions in a small non air-conditioned commercial property in London could be outside of established 'comfort levels' for 23% of working hours. With the best use of natural ventilation and green design it could still be uncomfortable for 8% of working hours (Connor, 2002). This will have knock-on effects for flexible working hours and rush hour congestion (LCCP, 2002). However, in a similar property in Manchester, working conditions would be outside of established 'comfort levels' for 9% of working time, and natural ventilation and green design could reduce this to 1.5% of working hours (Connor, 2002). Generally private dwellings are not air-conditioned but the market is rapidly growing in the South East and London, where the summers are hotter and wealth greater. There is at least one new luxury housing development in Manchester that includes air conditioning (CURE & Tyndall Centre, 2003). There are also an increasing number of private cars with AC (CURE & Tyndall Centre, 2003). Poorer households may suffer more from warmer summers as they feel less able to open doors and windows as this makes them more vulnerable to crime and noise pollution and they are unable to afford AC installation (LCCP, 2002).

Rather than always opting for the higher energy air conditioning alternative, which causes more greenhouse gas emissions (LCCP, 2002), innovative sustainable ways to cool buildings could be developed, as well as using best practice design. These include: high thermal mass; solar shading; green roofs; natural (e.g. windows open) or mechanical (e.g. fans) night-time ventilation; as well as mixed-mode cooling, where natural ventilation is used in all but the hottest periods (LCCP, 2002). There is the opportunity to design and refurbish buildings such as mills and commercial buildings, as well as Victorian housing (such as that found in Manchester) so that AC is avoided and lighting loads are kept to a minimum (CURE & Tyndall Centre, 2003).

Hotter weather has other negative implications for health such as: an increased risk of skin cancer due to the increase in outdoor activities (especially in children who are the most vulnerable) which could result in 5000 extra cases per year by the 2050s; 2000 more cases of eye cataracts per year by the 2050s (Bentham, 2002a); an increasing incidence of food poisoning (largely as a result of warmer conditions allowing bacteria to grow) (Bentham, 2002b); and possible enhanced pollen production which would increase the risk of aggravating allergies. Meteorological factors strongly influence the timing and duration of the pollen season (Emberlin, 1997) as well as the total pollen count (Takahashi *et al.*, 1996), thus the seasonality of pollen-related disorders such as hay fever may be affected by climate change (Emberlin, 1994). High pollen levels in combination with thunderstorms have been linked to acute asthma epidemics (Newson *et al.*, 1998). Positive health impacts include a tendency for people to eat more healthily in hotter, drier climates, including fresh fruit and vegetables (Palutikof *et al.*, 1997). However, there are widespread variations in access to fresh food in cities as a result of both economic and physical limitations (NPI, 2000). Those on low incomes, the elderly and the disabled may live in areas with limited local shops and transport networks, where the price of healthy foods in local shops may be more expensive than in supermarkets which can sell basic foodstuffs for below cost price and have price wars with smaller retailers (NPI, 2000).

The effects on humidity and health are not very certain (LCCP, 2002) and there are few studies. External relative humidity falls in winter under all scenarios but absolute humidity rises since warmer air can hold more water. Internal relative humidity in heated buildings could rise since it is determined by absolute humidity. This, combined with higher internal temperatures, could increase asthma (LCCP, 2002). A study, however, has suggested that humid weather may be protective against the effects of heat, since inhaling dry hot air is harmful to the respiratory organs (Kunst *et al.*, 1993). Another study of the influence of meteorological parameters on asthma attacks in children found that in both winter and summer, asthma attacks are more frequent in situations with lower relative humidity, higher air pressure, and a positive air pressure tendency (Zaninovic & Raos, 2001). It is also possible that there will be less internal condensation and mould growth because of warmer internal faces on external walls and windows (likely to be a stronger effect than the rise in absolute humidity), which will have small beneficial effects on health (LCCP, 2002), however, other factors such as driving rain penetration and changing ventilation rates will also impact upon internal dampness (see section 5.5; Graves & Phillipson, 2000).

Ventilation allows required environmental conditions to be maintained by removing indoor pollutants and excess heat (Graves & Phillipson, 2000). Poor ventilation can lead to condensation and mould problems, as well as increased concentrations of pollutants. Ventilation is influenced by climatic factors such as: the temperature difference between internal and external environments, wind speed, and external humidity conditions which influence the ability of the ventilation system to remove water vapour (considered to be a key pollutant) from indoors. Solely taking into account temperature changes, under the UKCIP98 Medium-High scenario, the ventilation rates in a modern three-bedroomed house could fall by 5.4% by the 2050s and 7.4% by the 2080s. This, combined with increases in external vapour pressure, leads to a significant reduction in the capacity for water vapour removal. By the 2080s, there is a risk of moisture accumulation in autumn in dwellings in London. Where condensation is persistent or frequently recurring there will be mould growth, which is linked with respiratory health problems (Graves & Phillipson, 2000). Modelling of non-domestic buildings found water vapour increase to generally not be a problem (Graves & Phillipson, 2000).

Climate change could have a beneficial impact on our physical exposure to air pollution. A more outdoor lifestyle could mean less exposure to internal damp, whilst the potential increase in activity resulting from the outdoor lifestyle could reduce respiratory illness. Greater opening of doors and windows would increase air circulation. On the other hand, increased incidences of asthma could result from dust mites living for longer in drier air (LCCP, 2002). More time spent outdoors could mean a greater exposure to air pollution, yet this is not necessarily the case since an average air change in a room of one hour means that the indoor environment is chemically similar to the outdoors with added internal sources. However, on major roads at low levels (including in cars and buses) there would be greater exposure to pollutants (LHC, 2002).

In 1991, London experienced a winter pollution episode in which concentrations of NO_2 and particles increased five-fold over the seasonal mean over four days (Bower *et al.*, 1994). After allowing for the effects of the cold weather, mortality and hospital admissions increased by 10%. It is difficult to untangle whether the effects were due to particles or associated gases (Anderson *et al*., 1995). It is likely that there will be a considerable reduction (estimated as a 50% decrease) in the adverse health effects associated with winter concentrations of particles, NO_2 and SO_2 (table 8) mainly as a result of reduced mean levels rather than fewer episodes (section 4.2) (Anderson *et al*., 2002).

Table 8. Summary of predicted climate change associated pollution effects on health (Anderson *et al*., 2002)

Pollutant	Year 2020	Year 2050	Year 2080
Particles	Large decrease	Large decrease	Large decrease
Ozone (no threshold)	Large increase (by about 10%)	Large increase (by about 10%)	Large increase (by about 10%)
Ozone (threshold)	Small increase	Small increase	Small increase
Nitrogen dioxide	Small decrease	Small decrease	Small decrease
Sulphur dioxide	Large decrease	Large decrease	Large decrease

It has been estimated that 7060 additional or brought forward deaths in urban areas of the UK in 1995 were attributable to PM_{10} (Anderson *et al*., 2002). PM_{10} emissions are expected to decline over the next 10 to 20 years (section 4.2). By 2005 the number of deaths brought forward is expected to decline to 6170 per year. It is likely that climate change will lead to a better dispersal of PM_{10} emissions and the health impacts of annual mean concentrations will continue to decline over the next century (Anderson *et al*., 2002).

Tropospheric ozone damages human health (WHO, 1987; Lippmann, 1989; National Research Council, 1991). This may manifest itself through reduced physical performance or lower resistance to infections (O'Hare & Wilby, 1995). Exposures of more than 100 ppb over several hours are believed to cause or exacerbate asthmatic and bronchial problems, eye, nose and throat irritation, chest discomfort, coughs and headaches (Lippmann, 1989; HMSO, 1991). In the UK, during the summer heatwave of 1994, the biggest documented outbreak of asthma anywhere in the world was recorded (O'Hare & Wilby, 1995). At concentrations close to background ozone levels, there is a detectable but reversible effect on the lungs (Anderson *et al*., 2002). Short-term associations have been observed between ozone and daily mortality, hospital utilisation, respiratory symptoms and lung function (Anderson *et al*., 2002). Evidence from high exposure environments suggests a link with increased incidences of chronic lung disease. There is evidence to suggest that asthma sufferers may be more sensitive to the effects of ozone (Anderson *et al*., 2002).

We may experience an increase in adverse health effects as a result of summertime ozone concentrations. Summer pollution episodes are associated with increased mortality and morbidity. The largest UK episode was in 1976, when high hourly concentrations occurred daily for a fortnight, increasing mortality by 9.7% in England and Wales, and 15.4% in London. Whilst it is difficult to identify the contribution of ozone to these effects, it has been estimated that, in London, it was responsible for nearly half of the increase (6.7%) (Macfarlane *et al*., 1997). There was a 34% increase in respiratory hospital admissions in the Oxford region, which was similarly affected by heat and high ozone levels (Anderson *et al*., 2002).

The increase will only be slight if a threshold (50 ppb) of effect is assumed (table 8). Threshold studies focus on pollution episodes. In the summer of 1995 an estimated 720 deaths were brought forward due to ozone episodes. This could reduce to 235 deaths per year by 2010 due to precursor emission reductions leading to reduced peak ozone concentrations (section 4.2). However, if no threshold is assumed the increase in mean ozone concentrations will be more significant, with an increase (over a 1996 baseline) in premature deaths predicted at 10%, 20%

and 40% for the years 2020, 2050, and 2080 respectively. Mean ozone concentration is expected to be the most important issue for the impact of climate change on air pollution with its associated health effects (table 8) (Anderson *et al*., 2002). The fall in concentrations of particles and NO_2 may counter these effects to some extent (Anderson *et al*., 2002). A threshold approach is probably not appropriate at a population level since individuals probably vary in their threshold and are exposed to a larger range of concentrations than are indicated by fixed site background monitoring stations (Anderson *et al*., 2002). However, there is discussion about whether there is a threshold, since some studies have noticed one and background ozone levels are close to those which have been found in experimental studies to have toxic effects (Anderson *et al*., 2002).

Warm weather is expected to increase the incidence of vector-borne diseases (Subak, 1999): directly, through its effects on insect development, and indirectly through its effects on host plants and animals (Rogers *et al*., 2002). Cities provide standing water, rubbish dumps and sheltered areas, which are suitable habitats for disease vectors and organisms (IPCC, 2001). Lyme disease is spread entirely by ticks. Reported cases in the UK have doubled since 1990 and increased tenfold since 1986 (Subak, 1999). Under warm and dry climates it is expected that we would see more cases of Lyme disease, through increased recreational exposure, as well as increased tick numbers and activity (Subak, 1999). However, according to the Department of Health review, predictions of significant increases in tick-borne diseases (Lyme disease and encephalitis) are not well founded, since the effects of warm, dry weather on tick biology are not well understood and it is therefore difficult to predict changes in abundance (Rogers *et al.*, 2002).

By the 2050s, indigenous strains of malaria are likely to re-establish themselves in the UK but will not pose a major health threat. Outbreaks of the more serious strain *Plasmodium vivax* are possible, especially in low-lying salt marshes. The even more serious strain *Plasmodium falciparum* is unlikely to become established in the UK, but tourists abroad may be vulnerable (Marchant *et al.*, 1998; Rogers *et al.*, 2002).

A reduced water supply and possible increased costs may have public health and hygiene implications. Dry conditions reduce the supply and quality of water (section 3.2). However, the Department of Health dismisses the risk of severe health problems due to decreased water quality because of stringent controls in the UK (Stanwell-Smith, 2002). The implications of water pollution are more serious for developing countries without adequate water treatment (UNCHS, 1999).

Flooding may also affect human health and comfort. The health impacts of flooding follow several phases (Baxter *et al*., 2002a). Firstly, there is potential death by drowning and exposure, followed by an immediate post impact stage where deaths may occur within vulnerable groups unable to obtain first aid treatment. During the recovery phase there is subsequent morbidity and mortality in the flooded groups in the months after the flood, as well as mental health problems such as post-traumatic stress disorder, anxiety and depression. Research following the major flooding in April 1998 in Northampton found very high levels of post-traumatic stress as a consequence of the flooding (Shackley *et al.*, 2001). Hundreds of people in affected areas suffered from symptoms, and it was judged that some may never work again. Doctors reported several hundred additional patients from the affected areas. Some children were traumatised by the flooding and become frightened when it rains, which may in turn impact upon their educational performance. The risk of infections arising from floods in the UK appears to be quite low, however, it is possible that toxic substances could enter flood waters and add to any health impacts (Baxter *et al*., 2002a). Shackley *et al.* (2001) suggest that more research is needed to understand the medium- and long-term health and social impacts of flooding on individuals and communities.

The predicted increase in the frequency of severe gales is likely to be associated with significant damage to buildings and trees, and injuries from flying debris and falling trees, as well as by being physically blown over and traffic accidents, are likely to increase. Analysis of the worst-case scenario, a windstorm in the late afternoon in London and south east England, suggests that several hundred deaths might occur as well as several hundred hospital admissions and many minor injuries (Baxter *et al*., 2002b). A secondary impact on health may result from loss of electricity in such events (Baxter *et al*., 2002b).

Stern and Zehavi (1989) found the risk of road accidents increased in hot weather. This research was undertaken on a desert highway, where the most accidents were from cars running off the road or turning over (a result of heat stress on driver concentration), and obstacles such as parked cars and trees were not present. A survey found that 9% of drivers thought warm weather induced drowsiness when driving (Thornes, 1997; after Maycock, 1995).

Changes to the timing and type of illnesses experienced under climate change will result in changes to the pattern of demand placed on the health services. Severe and extreme weather events will place temporary demand on resources and emergency services. For example, there could be illnesses associated with flooding and lack of clean water, asthma epidemics due to poor air quality, and food poisoning outbreaks (LCCP, 2002).

5.5 Building Integrity

Timber may be more prone to insect attack as a result of warmer, damper winters with more rain. House longhorn beetle and termite damage could become a problem (there is evidence of their activity in south west England). Their range is currently limited by temperature, so warming could see their migration northwards. Such damage is not covered by insurance (Garvin *et al*., 1998; Radevsky *et al*., 2001). It has been suggested that declining ambient air quality could potentially damage building fabric (LCCP, 2002). It is likely that chloride attack of buildings will be reduced since its main source is de-icing agents which will be used less at higher temperatures (Garvin *et al*., 1998).

In higher temperatures cement sets more quickly which may decrease working time but high alumina cement will form a lower strength (Garvin *et al*., 1998). Similarly, concrete is weaker if it dries too quickly (Garvin *et al*., 1998). Poor quality concrete lacks durability due to corrosion, frost damage, sulphate attack and alkali-silica reaction. Future climate is likely to exacerbate concrete durability problems. Additionally, concrete can react with atmospheric CO_2, which causes cracking. This process will be accelerated with increased CO_2 concentrations (Garvin *et al*., 1998).

The vulnerability of a building to flooding is partly a function of its design and the materials used, as well as being crucially dependent on the height of the flood water in relation to the floor level of the house. Flood damage is worse if the water is fast flowing and if it is sea water (Baxter *et al*., 2002a). In modern housing, the use of chipboard floors, dry wall plasterboard, cavity insulation and lower thresholds for easier access, make the building more vulnerable to flood damage (ABI, 2002a). Suspended timber floors may trap water between the concrete underslab and floor timbers, which could lead to rot. Suspended concrete floors could also be affected, although frost damage and sulphate attack are more critical (Garvin *et al*., 1998). Vulnerability estimates have been made for the UK building stock (N'Jai *et al*., 1991).

According to the Association of British Insurers (ABI), their members incur an average cost of £1m every day from subsidence. This will be more important in warmer, drier summers with shrinking soils, especially clay soils, affecting building foundations (Doornkamp, 1993). It could threaten the stability of old buildings, which are less adaptable to climate change, as well as of tall buildings and tunnels drilled through the clay (ABI, 2002a). Clay areas are also to be found in Manchester (section 4.6), where there could be a similar problem, since soil moisture levels could fall by about 10–20% by the 2080s (Hulme *et al*., 2002). Permanent Scatter Synthetic Aperture Radar Interferometry (PS InSAR) is a new technique using satellite data, to measure sub millimetre movements in buildings, which could identify the worst areas for subsidence and give early warning of the failure of mass structures (LCCP, 2002).

In warmer and wetter conditions building foundations face a greater risk of attack from sulphates in soils as they become more mobile (Garvin *et al*., 1998). Higher ground temperatures make water-based contaminants more soluble and mobile, yet drier soils have the opposite effect. Where flooding or heavy rain occurs it may be more difficult to control contamination (Garvin *et al*., 1998).

More stormy weather poses a threat to the integrity of buildings, which may require more maintenance and repairs. Well-known effects of high winds include damage to roofs, cladding, overhead electric and telephone connections, and even whole buildings (if they are very lightweight and temporary) (CURE & Tyndall Centre, 2003). Assessments of the vulnerability of the UK building stock to windstorm damage have been undertaken (Spence *et al*., 1998; Walker, 2001). The frequency of damage varies according to building type, age and configuration (table 9). The vulnerability indices refer to damage repair costs, but can be used to help identify the buildings most likely to suffer some damage. Bungalows appear to be the most vulnerable, whilst high-rise flats are the least vulnerable. Generally, the older the building the more vulnerable it is to wind damage. The frequency of damage rises steeply with increasing wind speed according to a logarithmic relationship. Thus, with an increase in wind speed from 40 to 45 m/s it would be expected that the number of damage incidents would increase by a factor of five (Spence *et al*., 1998). In much of England, buildings are not currently designed to withstand the severity of storms experienced in other parts of Europe (LCCP, 2002). It may be useful to consider the designs of continental and Scottish buildings, which are built to withstand more severe storms.

Table 9. The UK building stock divided by building type and age, together with the proposed vulnerability to wind damage indices (shaded grey). Based on the relative areas and frequency of occurrence of key vulnerable elements (chimneys, tiled roofs, windows), their likelihood to damage based on data from the Building Research Establishment, and their condition based on the English House Condition Survey (after Spence *et al*., 1998)

	% of stock	Pre-1919	1919-1945	1945-1964	Post-1964
% of stock	-	26.4	19.7	21.5	32.4
Terraced houses	28.2	1.32	1.15	0.79	0.40
Semi-detached houses	26.7	1.54	1.32	0.93	0.49
Bungalow	23.5	2.00	1.72	1.21	0.65
Converted flats	6.9	1.01	1.13	0.83	0.47
Low-rise flats	12.7	0.81	0.70	0.48	0.25
High-rise flats	2.0	0.49	0.42	0.29	0.17

Changes to wind speed, direction and rainfall will determine changes to driving rain. It has been suggested that since wind speed and winter rainfall are expected to increase, and rainfall events become more intense, it is likely that the amount of driving rain will also increase and become more intense (Graves & Phillipson, 2000). Figure 28 shows the current wind driven rain map for the UK. Predicted increases in driving rain under climate change will alter the areas of the UK subject to the four exposure zones (fig. 28). Graves and Phillipson (2000) suggest using the pragmatic approach of increasing the exposure rating of all properties by one zone to account for climate change, however, although their work is based on the UKCIP98 Medium-High scenario, it is not clear what time period they are considering. Exposure to driving rain leads to more weathering and therefore higher maintenance requirements for buildings and could lead to increased water penetration (Garvin *et al*., 1998; Graves & Phillipson, 2000). This may cause dampness problems, which affect both the building and the occupants (Graves & Phillipson, 2000). Internal surfaces such as wallpaper and plaster may suffer from increased winter dampness (CURE & Tyndall Centre, 2003). Structures may need greater protection against rain penetration through render, cladding and water repellents. It may also be necessary to redesign windows in England, perhaps by adopting the Scottish approach where windows are set on the inner rather than outer leaf (Garvin *et al*., 1998). In high areas of driving rain, cavity wall insulation can act as a bridge for the moisture between the inner and outer layers of the building, thus leading to the penetration of rain through the structure. Where the insulation is wet, less energy from heating will be saved by it (Garvin *et al*., 1998).

Higher indoor temperatures could cause an increased release of solvents and other pollutants from building materials and furnishings into the air (Garvin *et al*., 1998). Similarly, higher temperatures in the walls and cavities of buildings could increase the release of formaldehyde into the internal building space (Garvin *et al*., 1998). Internal temperature control is important to maintaining delicate fabrics, furniture and furnishings in historic buildings (LCCP, 2002).

5.5.1 Building Design and Construction

Climatic changes and the increased likelihood of extreme events could lead to improved design for new developments (LCCP, 2002). There may be more days available for construction with fewer rainy days in summer, combined with more frost-free days in winter. However, site flooding in winter may increase the need to pump out ground water before construction can continue (Garvin *et al*., 1998). Higher winds may also affect the safety of cranes and scaffolding (Garvin *et al*., 1998). Whilst warmer temperatures and more sunlight could affect workers at building sites since there would be higher dust levels and VOC emissions (Garvin *et al*., 1998).

5.5.2 Infrastructure

Higher winter temperatures could result in fewer burst pipes as a result of freezing. However, wetter winters may cause clay expansion and hence more burst pipes. Summer leakage may increase due to drier soils and clay subsidence (Doornkamp, 1993). Variable temperatures could also put stress on pipes. Thames Water blamed a burst mains pipe on the fall in temperature following a summer heatwave, which caused the pipe to fracture (BBC News, 19 Aug 2003; 20 Aug 2003). Changing rainfall patterns could have detrimental effects on the foundations of electricity pylons, thus impacting negatively on the robustness and effectiveness of electricity networks (LCCP, 2002). Additionally, clay shrinkage may reduce the resistance of below ground communications infrastructure (e.g. cabling) (LCCP, 2002). Damaging ice forms when temperatures are close to freezing rather than at very low temperatures. Thus, places that were relatively ice-free could be vulnerable in the future. Overhead cables and supporting structures could be vulnerable to icing (CURE & Tyndall Centre, 2003).

Fig. 28. Current wind-driven rain map (Graves & Phillipson, 2000)

Increased flood risk is one of the main threats to utility infrastructure. Some energy infrastructure is located on coasts and next to rivers and estuaries since they require large volumes of water for cooling. Hence they are susceptible to flooding (CII, 2001). Flooding may also impact on existing floodplain landfill sites and lead to a decrease in potential landfill sites (LCCP, 2002). Current research is evaluating the performance of existing sewerage systems in relation to past and future patterns in rainfall event sequences and storm event profiles (UKWIR, 2002). It is also investigating the climate sensitive secondary factors in sewer performance arising from groundwater infiltration, soil moisture deficits, and changes in the water levels of receiving water courses. Higher groundwater means an increase of infiltration into sewers as well as an ingress of surface water into sewers. This leads to higher flows in sewers, associated pumping and treatment costs, and increased flooding (LCCP, 2002). Sustainable Drainage Systems (SUDS) are soft engineering solutions that attempt to alleviate flooding from moderate rainfall events. They may help prevent, and thereby reduce vulnerability to, flooding downstream of developments in which they are incorporated by reducing storm runoff volume through 'peak-lopping' and increasing the travel time of the flood peak to the water course (CIRIA, 2003).

Higher wind speeds and more frequent gust returns would increase stresses and fatiguing on power lines, pylons and other assets, including above ground communications infrastructure, such as radio masts. Increased lightning events may also disrupt power supply (Baxter *et al.*, 2002b).

Higher temperatures would lead to a faster rate of refuse decay. Thus, more frequent collections may be required to prevent odour problems (LCCP, 2002). Hosing down streets could be an option especially with higher dust levels from construction or blowing in from the land, however this places pressure on water resources, although there are potential opportunities to use recycled water (LCCP, 2002).

5.5.3 Transport

Climatic changes could severely disrupt transport systems, causing time loss and costs to repair damage. Direct sunshine together with summer heat can cause rails to buckle, leading to speed restrictions on the railways to mitigate risk. This problem is more likely to occur when there are rapid changes in temperature between night and day and extreme hot weather. However, in warmer winters point heaters (used to ensure points function in freezing conditions) are likely to be used less often, thereby incurring fewer technical difficulties and fewer delays (LCCP, 2002). Hot weather spells can cause road surfaces to buckle. For example, in the summer of 1995 the binder materials in asphalt roads melted and caused rutting. As a result of this the British Standard specification for road surface performance was amended (Palutikof *et al.*, 1997), but it is unknown how it will perform in a hotter climate. On the other hand, higher winter temperatures will mean less grit and salt will need to be applied to the roads to prevent ice forming (LCCP, 2002).

High intensity rainfall events could lead to increased road flooding (LCCP, 2002). Clay shrinkage impacts on structures such as bridges, tunnels, embankments and cuttings, on which the rail network is reliant. Higher winter rainfall intensities could lead to bank and slope instability causing landslips, as already noted in southern Scotland. Water (e.g. from flooding) on the rails acts as a conductor for electricity and mimics the presence of a train, thereby requiring checks by engineers to assess the situation resulting in delays. High levels of river water combined with debris scour away the foundations of bridges, reducing their stability (LCCP, 2002). A reduction in winter snowfall and frost frequency could mean reduced time disruption and associated aircraft and runway infrastructure costs, yet there may be more disruption from winter storm events (LCCP, 2002).

There may be a reduction in traffic accidents in poorer weather (Thornes, 1997; Edwards, 1999) as people take greater care to drive safely. However, an increase in the severity of wind storms carries with it a high chance of damaging infrastructure and thus causing delays (Baxter *et al*., 2002b). Lightning can damage rail infrastructure including signalling equipment and telecommunications, wind can affect overhead lines, and fallen trees and vegetation can block roads and railways (Baxter *et al*., 2002b). Flooding events and storms may lead to the closure of ports and reduced manoeuvrability of ships (CURE & Tyndall Centre, 2003). Passenger and freight movement on rivers and canals could also be jeopardised by low flows threatening navigability (LCCP, 2002).

Climate change could also impact on the preferred modes of transportation. For example, wetter winters may mean fewer people are willing to cycle, whereas warmer and drier summers may see more people travelling by bicycle and walking. This could benefit human health as well as helping to reduce greenhouse gas emissions, yet may result in more bicycle related accidents (LCCP, 2002). The hot summer of 1995 saw an increase in car (and train) use for leisure purposes and if public transport improvements do not keep track with climate change (e.g. through installing AC) we may see more people using private cars (LCCP, 2002).

5.6 Related socio-economic impacts

5.6.1 Tourism

Increased temperatures would probably result in more year round domestic tourism and possibly less international tourism, with Southern Europe and other destinations becoming less popular for summer holidays (Giles & Perry, 1998). An increase in domestic holidays would reduce international flights, and would have knock-on effects for transport infrastructure and water demand, possibly leading to congestion and pollution (LCCP, 2002). Heatwaves and air pollution may deter visitors from cities, however, it is expected that the temperature would not be too off-putting to tourism, since hot European cities still attract tourists today and London in 50 years time is unlikely to exceed the temperature of these cities. We may, however, see air conditioning in more hotels (LCCP, 2002). It has been suggested that Scottish tourism is unlikely to be affected by warmer temperatures, since good weather is not seen as a major determinant for visitors to Scotland (Scottish Executive, 2001).

Increased domestic tourism might mean that rivers, canals and other water bodies become attractive destinations. However, in dry summers there may be insufficient water to maintain inland canal navigation, which may also impact on the attractiveness of canal-side developments, and sports and recreational fishing could suffer. The increased likelihood of algal blooms carries with it potential aesthetic and health implications (LCCP, 2002). The increased domestic tourism could also put pressure on conservation sites, perhaps impacting on biodiversity, and leading to restricted access to sensitive sites and habitats (LCCP, 2002). There may be an increased demand for swimming pools and outdoor recreation centres, as well as for travel out of urban areas for short breaks, benefiting out-of-town excursion destinations (Giles & Perry, 1998). However, different populations have different abilities to adopt outdoor lifestyles due to income, location, dependents and cultural issues (LCCP, 2002).

5.6.2 Crime and Society

Controversial theories suggest that hot weather produces public disorder, yet these have generally been discredited as not taking into account underlying structural and economic reasons for discontent (Shackley & Wynne, 1994). It is more likely that hot weather encourages some types of anti-social behaviour in those who are already prone to such behaviour. Also adaptation to climate is likely to occur (LCCP, 2002). Hotter weather could see more outdoor drinking and associated violence, anti-social behaviour and drink-driving, although again adaptation to hotter weather may mean that sunny days are less of an excuse to go for a drink (LCCP, 2002). If the attractiveness of a city declined under climate change, economic conditions may deteriorate, leading to conditions where crime and disorder could grow (dependent on factors such as the distribution of wealth) (LCCP, 2002).

Better networked communities will be able to respond quicker to warnings of flooding, than those that are highly fragmented. Generally, more affluent communities will be able to respond more effectively than poorer communities (Shackley *et al.*, 2001). Case studies of community responses to flooding in North Wales (1990), Perth (1993) and Strathclyde (1994) show that whilst there is often community cohesiveness in the response to the initial emergency, in the longer term there can be differential impacts, with more vulnerable groups carrying the greater burden as they have limited access to resources enabling them to cope with both short and long term effects (Fordham & Ketteridge, 1995). There have been few studies on the possible impact of climate change on social conditions, such as the economic impacts on low-income households, inner city communities and changing employment patterns (Shackley *et al.*, 2001). The disruption caused by flooding might make some systems more susceptible to crime. For example, shop looting followed earthquakes in America (LCCP, 2002). The evacuation of people into temporary communal accommodation is stressful and may encourage crime and anti-social behaviour amongst residents (LCCP, 2002).

Climate change is unlikely to effect net migration into and out of UK cities. There may, however, be more seasonal flows of wealthier inhabitants (LCCP, 2002). Flows from non-EU countries may be the most sensitive to climate change in the areas where people are coming from if there is a large-scale, climate related disaster (LCCP, 2002). Observations of ethnic conflicts in the developing world suggest that environmental degradation, loss of access to resources and resulting migration may, in certain circumstances, lead to political or military conflict. However, it is difficult to discern the role of climate change in this process since there are many causes of inter and intra group conflicts (Wolf, 1998).

5.6.3 Industry and Business

Increased temperatures combined with the UHI effect could lead towards relocation from the city by parts of the public administration workforce as well as businesses (LCCP, 2002). This may be accompanied by a shift to other sectors, and an increase in tele-working, thus decreasing commuter journeys (LCCP, 2002).

Climate change offers potential to the renewable energy market. Less summer rainfall and cloud cover would allow the solar energy market to expand, whilst a slight increase in wind speed will increase the power output (LCCP, 2002). The power available in wind is proportional to the cube of the windspeed. So, if the windspeed doubles, the power available at the wind generator blades increases by a factor of eight, or a 1% increase in wind speed is equivalent to a 3% increase in available wind power (Argotrade, 2003). However, increased storm events and gusting will increase wind turbine fatiguing (LCCP, 2002). Wetter winters and drier summers will concentrate hydro-power production even more during the winter months than at present (LCCP, 2002). The exacerbated seasonal differences in energy consumption could see more seasonal demand for contract workers in the energy sector (LCCP, 2002).

The disruption to transport as a result of flooding and storm damage could be the biggest climate change cost for the manufacturing industry, causing delays to the arrival of raw materials which may be needed for a ‘just-in-time’ industrial process (for example, in the food industry) (LCCP, 2002). Additionally, changes in water resource availability and cost, such as seasonally variable water tariffs (reflecting the greater variability in water supply) may impact on certain industries that use large amounts of water in their manufacturing processes, for example, the drinks sector (especially brewers) and the automotive industry (LCCP, 2002). It is also likely that climate change would alter consumer behaviour in some ways. For example, if the weather is hotter there may be a greater demand for ice creams and sandals and less demand for thick socks. This would impact on the manufacturing industry, as different goods in different quantities would be demanded (LCCP, 2002).

If the supply of virgin raw materials from other parts of the world is affected as a result of climate change (transport disruption or cultivation changes as a result of changes in temperature or rainfall), their prices could rise. This might increase the demand for recycled materials in manufacturing and retailing (assuming these prices stayed constant), thus impacting on the recycling industry (LCCP, 2002). For example, a significant part of the market share of paper is manufactured from virgin pulp in South and East Asia. Estimates of cultivation change suggest a possible 1-5% increase in paper pulp price in the next fifteen years as a direct result of climate change (IPCC, 2001). This could have an effect on the UK recycling industry. There is a similar story for rubber, with virgin rubber currently supplied from Asia (LCCP, 2002).

Climate change may have other positive effects for environmental businesses. Firstly, increased awareness of human responsibilities may lead to producers and consumers taking more pro-active steps to limit their environmental impact – for example, by consuming less or recycling more (benefiting environmental businesses). If carbon consumption were constrained, there could be more energy focussed audit work for consultancies as well as a potential market in carbon trading. Secondly, an increased awareness could lead to increased regulation of environmentally detrimental activities, which would benefit environmental businesses. Examples include the development of new risk management tools and greenhouse gas mitigation regulation. This could simply shift employment from one sector (e.g. the regulated industry) to another (e.g. environmental consultancy), with no net gain. There is also the potential for creative industries to benefit through an increased demand for more innovative urban design (LCCP, 2002), which may help to make future buildings more resilient to climate change.

5.6.4 Insurance

In the UK, unlike in continental Europe, most natural perils are insured under individual policies. It is the only major country in the world where flood insurance is offered as a standard with buildings and contents insurance (Radevsky *et al.*, 2001). However, blanket coverage is no longer the case (CURE & Tyndall Centre, 2003). Climate change will increase the actuarial uncertainty in risk assessment and thus in the functioning of the insurance markets (IPCC, 2001). It will interfere with the operation of the insurance industry in three fields: underwriting, investment, and environmental policy (Dlugolecki, 2001). The global nature of the insurance market also means that climate change impacts elsewhere in the world may affect the UK insurance market if assets are insured here (LCCP, 2002).

Currently, underwriting losses are offset against investment income. However, if there is a severe climate event the insurance companies will have to pay out to policy holders and therefore will not have as much to invest (LCCP, 2002). Predicted higher rainfall is likely to result in more claims against the insurance industry as a result of flooding. In autumn 2000, floods caused an estimated £500 million insured loss in the UK (Austin *et al.*, 2000). Similarly, underwriting losses could result from subsidence, pipe damage, and wind storms (Austin *et al.*, 2000).

A greater exposure to flooding (such as more houses on floodplains and in risk areas) and the ownership of more possessions that could get damaged add to the cost of flood events (Pielke, 1999; 2000). In the UK, an estimated 1 million properties are built on inland floodplains (ABI, 2000), with the total insured value of properties at risk being £35 billion (Austin *et al.*, 2000). Annual average flood damage would account for £2.8 billion without flood defences, £640 million with flood defence at its current standard, and less than £200 million with the recommended standard set by MAFF (Austin *et al.*, 2000). These figures, however, do not take into account the impacts of climate change and sea level rise (Austin *et al.*, 2000). Damages caused by riverine and coastal flooding could increase by a factor of 2 or 3 over the next 50 years (DETR, 2000b), whilst economic losses could be a further £3 billion (Austin *et al.*, 2000).

A significant proportion of insurance claims are a result of flooding from overwhelmed drainage systems (ABI, 2002a). There is an increased likelihood of such flooding by the 2080s (LCCP, 2002). Even new drainage systems are only designed to cope with normal rainfall levels and will surcharge several times a year in the future (Futter & Lang, 2001). This threat can hopefully be reduced by the implementation of sustainable urban drainage systems (LCCP, 2002).

These increasing costs resulting from climate related events could have a deflating effect on investment in the economy and hence on economic growth. It could also lead to an internal retrenchment of insurance operations and less employment in the sector. With increasing climate events and less investment income to offset the underwriting losses, either premiums will increase or insurance cover will be reduced or withdrawn (LCCP, 2002). If insurance premiums increase as a result of flooding, it will increase the number of low-income households without insurance cover. Thus, in the event of a flood, social inequality would be increased (CURE & Tyndall Centre, 2003). Whilst if insurance cover were reduced or withdrawn it could have significant impacts on households and businesses with assets at risk from floods (CURE & Tyndall Centre, 2003).

A perceived flood risk may result in an area becoming less attractive to live, work, and buy property in, meaning that higher income businesses and households can move to other areas. This will affect land prices in other areas and force lower income households to inhabit areas at a greater risk from flooding (LCCP, 2002). Combined with this, mortgage and insurance difficulties may blight communities (LCCP, 2002). It is also unlikely that house conveyancy agencies would raise the issue of flood risk with a buyer. Thus, the buyer would need to investigate for themselves. This favours white collar professionals rather than the socially excluded. Agencies providing information on flood risk may also be subject to legal challenges since their uncertain information may affect house prices (LCCP, 2002).

A risk based pricing system is one alternative, however, problems occur when the risk is too high and the premiums become too expensive for policy holders, making properties uninsurable. Insurance companies may also face capacity problems in the future in areas of high density and high risk (Berz & Loster, 2001). Urgent government action is required by the insurance industry, in order to ensure that affordable flood insurance is available throughout the greater part of the UK (ABI, 2001), this would include three key areas: greater investment in flood defence; curtailment of development in flood risk areas; and faster and more consistent decisions on flood defences (ABI, 2001; 2002b) The ABI has also agreed five aims with the government (ABI, 2002b): full access to a competitive market for insurance for a vast majority of house owners and businesses; improved security for people in risk areas; new provision for those who want to sell a house in a flood risk area; better use of new solutions to make properties insurable (even in high risk areas); clear incentive for more investment by government in flood defence (ABI, 2002b). As well as working alongside the government, the insurance industry will need to undertake adaptive responses such as: catastrophe modelling; risk transfer; catastrophe bonds; weather derivatives; scientific research initiatives; seasonal forecasting and underwriting (Walker, 2001).

6. Discussion and Conclusions

6.1 General Discussion and Conclusions

The literature review identified the key drivers of climate change in the urban environment as greenhouse gas and pollutant emissions, lifestyle changes and urban development. Greenhouse gas emissions, and hence the degree (and severity of the impacts) of climate change, will be dependent on the socio-economic and lifestyle choices that we make as a society. Global carbon dioxide emissions in 2100, for example, vary from below present day levels (IPCC storyline B1; UKCIP02 Low Emissions scenario) to emissions four times the present day levels (IPCC storylines A2 and A1FI; UKCIP02 Medium-High and High Emissions) and concentrations range from about 540 ppm (B1; Low Emissions) to 920 ppm (A1FI; High Emissions) compared to present day levels of under 400 ppm and pre-industrial concentrations of about 280 ppm (IPCC, 2000; Hulme *et al*., 2002). Thus, it is apparent that the drivers of climate change do not act in isolation, but rather that they act in conjunction with, and impact upon, each other. Additionally they will act in conjunction with other environmental, socio-economic and political drivers.

The main pressures on the urban environment result from these key drivers. Again, these will act both independently and in conjunction with each other to produce impacts. Pressures not only result from 'a change' *per se*, but depend upon other factors such as: the magnitude of change; rate of change; transient scenarios; climate variability and extreme events; thresholds; surprises; and nonlinear, complex and discontinuous responses (IPCC, 2001). The UKCIP02 climate change scenarios demonstrate the pressures placed on the urban system as a result of climate change. The UK can expect increased temperatures, changing precipitation patterns including less summer rain and more winter rain (with the change in summer precipitation more marked), an increase in the frequency of more extreme events, the possibility of more wind storms, rising average sea levels and more frequent extreme sea levels, and increasing specific humidity but decreasing relative humidity. The south east of England will generally experience more intense changes than the north west (Hulme *et al*., 2002). The combination of hot temperatures and dry conditions in summer will become more common (Hulme *et al*., 2002). Increasing urbanisation, in the form of urban expansion and densification, has meant that the proportional cover of green space has declined (EEA, 2002). This places pressure on the urban ecosystem, impacting on surface temperatures, stormwater runoff, carbon storage, and biodiversity (Whitford *et al*., 2001; Pauleit & Duhme, 2000). Both climate change and urban growth and densification are partly dependent upon lifestyle choices, whilst climatic changes themselves may facilitate, inhibit or accentuate lifestyle choices.

The urban system is dynamic and has complex interactions and feedback loops within it. The severity of the impacts of climate change will depend upon the state of the urban environment. The process of urbanisation has strong impacts on the atmosphere, geosphere, hydrosphere and biosphere (Bridgman *et al*., 1995). The state of the urban environment, with respect to the climate (in particular the urban heat island effect and its potential to accentuate and exacerbate climate change impacts), air quality (such as the formation of ozone in the urban environment and the occurrence of winter and summer air pollution episodes), and hydrology (including important factors for assessing flood risk in the urban environment such as the extent of the drainage system, effects of blocked culverts and the surfacing of river channels, and hydraulic capacity of sewers), as well as greenspace (including the built to greenspace ratio, differences in size, composition and function of greenspaces), human well-being (including health, comfort and quality of life) and building integrity (with key considerations such as the soil on which it is built which may affect subsidence), was outlined.

The impacts of climate change on air quality, hydrology, green space, human well-being, and building integrity, as well as their related socio-economic impacts, were explored and it was recognised that there are complex interactions between the different components of the urban environment. There is much literature about how climate affects natural, human and built environments and exploring the potential impacts of climate change is becoming an increasingly popular research topic. There is an abundance of research on the relationship between climate and air quality, and how this impacts on human health (e.g. Anderson *et al*., 2002). Similarly, research into the potential impacts of flooding is plentiful, and many modelling experiments have been undertaken in order to understand the relationship between increased precipitation, river flows and flooding (e.g. Webb, 1996; Pilling & Jones, 1996). There has been little research into the impacts of climate change on urban ecology in particular, but there is a wealth of monitored/observational data concerning species populations and phenology in comparison to climate (e.g. Crick, 1999; Sparks, 1999) and a UKCIP report on climate change impacts on gardens (Bisgrove & Hadley, 2002). The impacts of climate change on health have been well researched (e.g. Donaldson *et al*., 2002; Rogers *et al*., 2002) yet impacts on external human comfort remain a topic for future research. There is a general understanding of the impacts of climate change on building integrity (e.g. Spence *et al*., 1998; Garvin *et al*., 1998), but more directed research is required. The literature concerning the impacts of climate change on socio-economic factors remains scarce (Shackley *et al*., 2001).

The main impacts on air quality resulted from changes in local pollution production, transport and dispersion (O'Hare & Wilby, 1994); anthropogenic and natural emissions; and the distribution and types of airborne allergens (Patz *et al*., 2000). It is likely that there will be a significant decrease in mean and episodic winter ambient concentrations of particles, NO_2 and SO_2 (especially the latter) as a result of warmer, windier winters and a reduction in emissions (Anderson *et al*., 2002). However, there may be a small net increase in summer ozone episodes as the frequency of days with the combination of high temperatures and low windspeeds, characteristic of high ozone concentrations increase (Anderson *et al*., 2002).

Hydrological impacts included decreasing annual and summer average soil moisture contents (especially in the south east); increased winter surface runoff (especially in the north) and decreased summer runoff (especially in the south), although individual catchments vary significantly (with differences in geology, land use, surface and groundwater abstraction); an increased frequency of both high and low river flows which could lead to increased flooding. Other factors of concern for flooding include: sea level rise (combined with severe storms and wave heights which may be more important than the slower changes in mean sea level); more frequent, severe, or prolonged rainfall events; the large size of urban catchments; an increasingly built-up environment which increases surface water runoff, in particular, the rate of development on floodplains; the age, condition and lack of capacity of existing urban drainage infrastructure; and the impact of rising groundwater in conjunction with surface flooding (CII, 2001). Whilst in summer dry periods, especially in consecutive years, reservoir levels could reduce substantially. In clay and urban catchments there may be less opportunity for winter groundwater recharge so baseflows may decline (Davis, 2001).

The main impacts on urban greenspace result from increased pressures on their structure and function. Climate drives the potential ranges of species, phenology, physiology and behaviour, despite the heavy management of gardens and parks (Bisgrove & Hadley, 2002). Climate change will favour certain plants and animals that are better adapted to cope with the new conditions, such as summer drought, winter water logging, changing air quality, and increased windstorms. It has been suggested that wetter soils in winter combined with a higher frequency of storms may lead to higher levels of tree fall (Bisgrove & Hadley, 2002). Additionally, during droughts and in areas subject to subsidence, trees are the biggest cause of soil drying and subsidence, resulting in foundation movement and damage to buildings (Biddle, 2001). The distribution and timing of activities of insects, pests and disease are also strongly dependent on climate. Temperature changes and longer frost-free seasons are extending the UK growing season and this will affect the rate of development of plants. In a changing climate the multifunctional role of trees and greenspaces is likely to become increasingly important for negating erosion and flooding; shelterbelt function; reducing UHI effect; and providing shade, recreational and water storage functions.

Climate change will impact on human well-being. Human comfort levels vary with temperature, wind, precipitation and humidity. Human health is affected by heat, air and water quality, flooding and wind storms. It is likely that there will be more deaths as a direct result of hotter weather, but fewer deaths as a result of colder weather, whilst the importance of acclimatisation is recognised (Martens, 1996; Gawith *et al.*, 1999). Warmer winters would shorten the heating season and have a positive impact on winter comfort, especially for those in fuel poverty (Langford & Bentham, 1995). However, there may be an increased use of air conditioning in summer. Negative health effects include an increased risk of skin cancer; more cases of eye cataracts; an increasing incidence of food poisoning; possible enhanced pollen production increasing the risk of aggravating allergies; an increase in the incidence of vector-borne diseases; as well as health and comfort effects associated with flooding and gales. Changes in air quality will most likely lead to a considerable reduction in the adverse health effects associated with winter concentrations of particles, NO_2 and SO_2 but an increase in adverse health effects as a result of summertime ozone concentrations, with mean ozone concentrations expected to be the most important issue for the impact of climate change on air pollution with its associated health effects (Anderson *et al*., 2002). Changes to the timing and type of illnesses experienced under climate change will result in changes to the pattern of demand placed on the health services.

An increased risk of flooding will be an important threat to building integrity and utility infrastructure. Buildings may also become more prone to subsidence, especially in areas with clay soils subject to shrink-swell. More stormy weather also poses a threat to the integrity of buildings, which may require more maintenance and repairs. In much of England, buildings are not currently designed to withstand the severity of storms experienced in other parts of Europe. Higher winter temperatures could result in fewer burst pipes as a result of freezing, however wetter winters may cause clay expansion and hence more burst pipes and summer leakage may increase due to drier soils and clay subsidence (Doornkamp, 1993). Timber may also become more prone to insect attack as a result of warmer, damper winters with more rain. Climatic changes could severely disrupt transport systems as well as impacting on the preferred modes of transportation.

The main socio-economic impacts of climate change include increased temperatures resulting in more year round domestic tourism and possibly less international tourism (Giles & Perry, 1998). There will be potential opportunities for the renewable energy markets, as well as other environmental businesses. However, businesses and/or the workforce may relocate from the city. Transport disruption may affect the manufacturing industry, causing delays to the arrival of raw materials that may be needed for 'just-in-time' industrial processes. Whilst the insurance industry can expect more claims as a result of flooding, subsidence and wind storms (Austin *et al*., 2000). A perceived flood risk may affect the attractiveness of an area, meaning that higher income businesses and households can move to other areas and thereby forcing lower income households to inhabit areas at a greater risk from flooding, where mortgage and insurance difficulties may blight communities.

The possible adaptation responses to the impacts of climate change have not been explored here and will be a topic of further research within the ASCCUE project.

6.2 Interactions

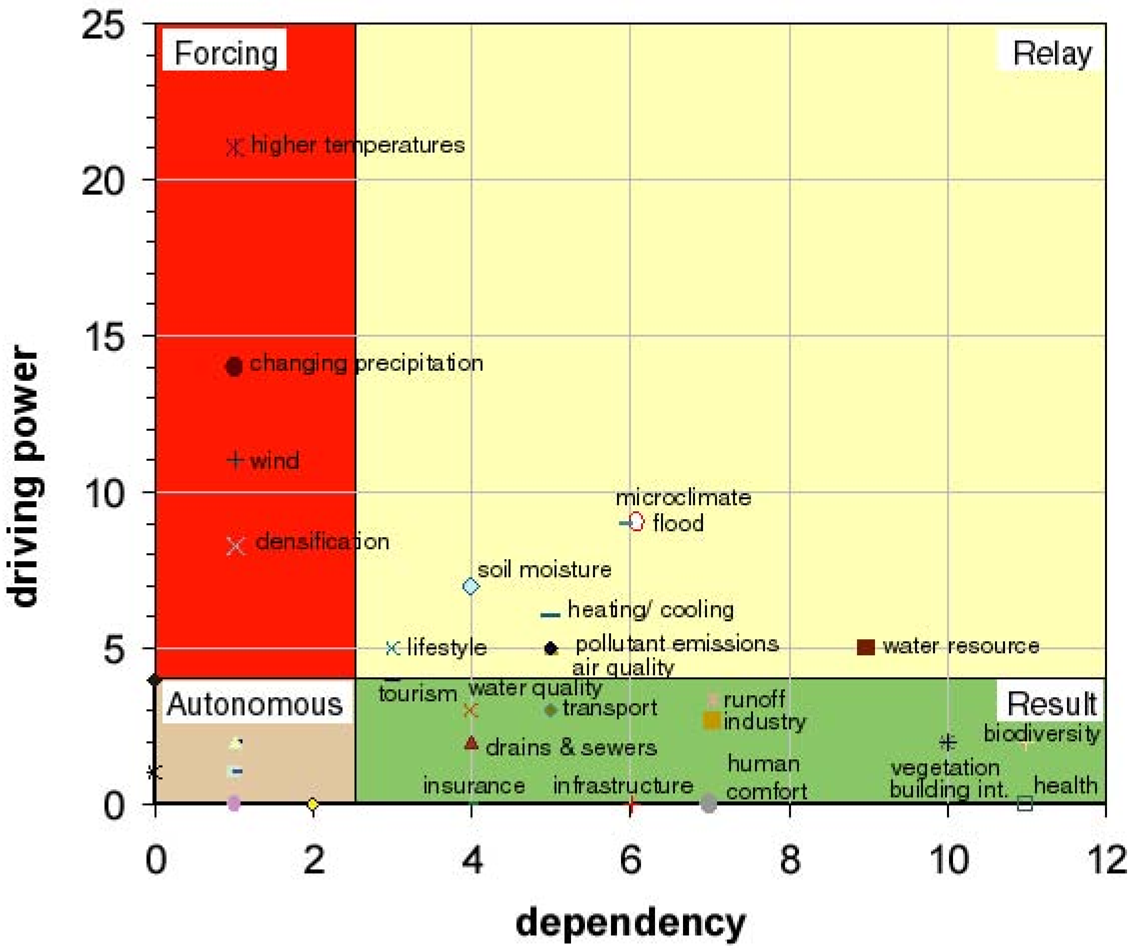
The ASCCUE project is also interested in exploring and understanding the complex interactions between both the pressures and the impacts of climate change in the different components of the urban environment. Whilst the literature review begins to draw out some of these interactions it is helpful to present the information in an interaction matrix (table 10) in order to understand the driving-dependency properties of the different components (fig. 29) (Parry & Carter, 1998). The relationships between key variables identified in this literature review were used to produce figure 29. It highlights the strong forcing or driving power of higher temperatures, changing precipitation patterns, wind and urban densification. Similarly, the main result or dependency variables are shown to be health, biodiversity, vegetation, and building integrity. Whilst runoff, industry, human comfort, infrastructure, transport, water quality, drains and sewers, insurance and tourism are also dependent variables, but are less strong. It is interesting that human comfort and building integrity, chosen by the ASCCUE project as vulnerability exposure units fall into this category, whilst vegetation and biodiversity, two components of greenspace (the third vulnerability exposure unit) also fall into this category. Microclimate, flooding, soil moisture, heating and cooling, water resources, pollutant emissions, air quality and lifestyle are the relay variables, which have both high driving and dependency values, and therefore could be good indicators of climate change.

The process of determining the interaction matrix highlighted certain issues concerning the approach. Firstly, only influences mentioned in the literature review were recorded. Secondly, any number of variables could be used. It was thought that too few variables would make such an exercise pointless, whilst too many could make the task unwieldy. The variables chosen were believed to be the main ones highlighted in the literature review, but the choice of individual variables will determine the number of influences that can be recorded for it. For example, if greenspace was chosen as a variable it would have more influences assigned to it than if greenspace were split up into more variables such as biodiversity, soil, vegetation health etc. Thirdly, only *direct* influences were recorded but in some instances it is difficult to determine the nature of the influence. For example, greenspace demand was found to be solely dependent on lifestyle, which in turn was dependent on higher temperatures, precipitation changes and wind, yet it could be argued that these variables also directly influence greenspace demand.

Table 10. An interaction matrix for climate change impacts in the urban system (after Parry & Carter, 1998)

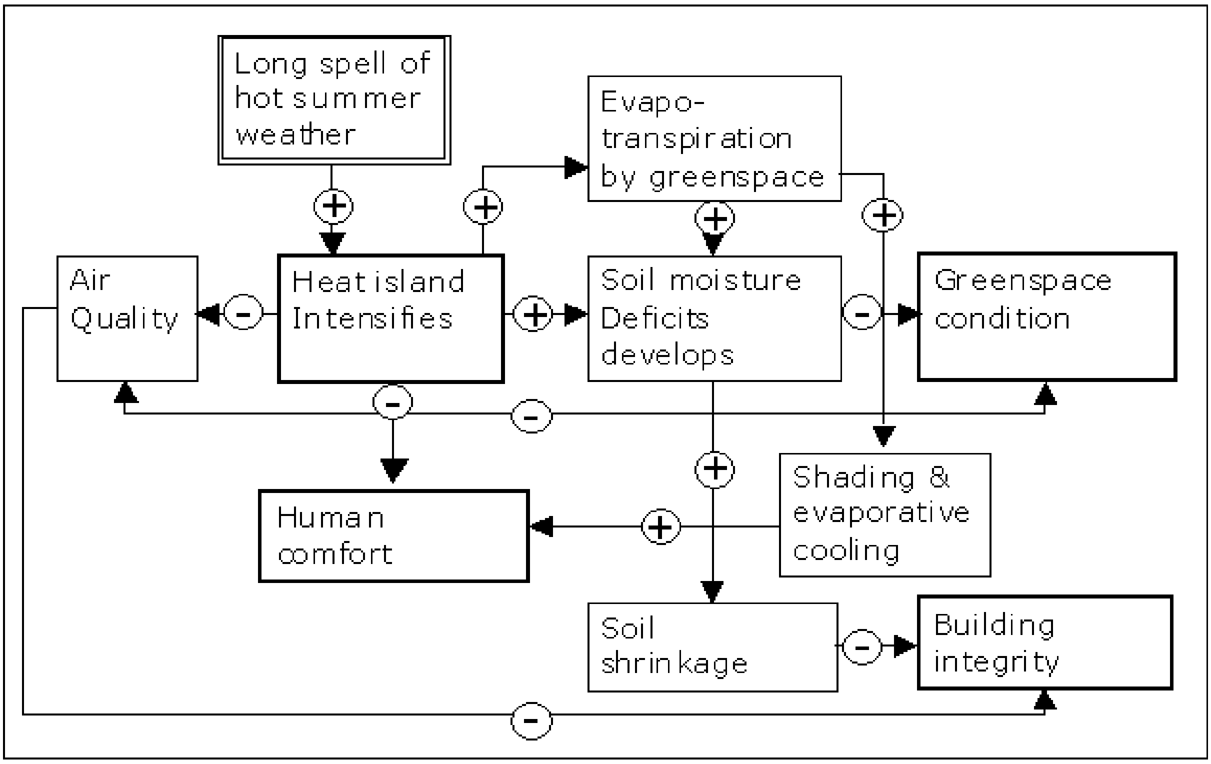
	GHG/pollutant emissionns	socio-economic scenario	densification	lifestyle	higher temperatures	changing precipitation	wind	growing season	heating/cooling	soil moisture	rising sea level	humidity	runoff	C storage	biodiversity	greenspace demand	UHI/microclimate	transport	industry	air quality	water quality	veg (health/phenology)	human comfort	building integrity	health	building design	soil type/geology	water resource	drains/sewers	culverts	river surfacing	Flood	infrastructure	insurance	tourism	crime	*Row sum (driving power)*
GHG/poll. emissions					1	1	1													1		1															5
socio-ec. scenario	1																																				1
densification													1	1	1		1			1					1			1				1					8
lifestyle		1	1													1			1						1												5
higher temps.	1			1				1	1	1	1	1			1		1	1	1	1	1	1	1	1	1			1					1		1	1	21
changing precip.				1						1			1		1			1	1		1	1	1	1				1	1			1	1				14
wind				1											1			1	1	1		1	1	1	1								1	1			11
growing season															1							1															2
heating/cooling	1																1						1	1	1								1				6
soil moisture													1									1		1				1	1				1	1			7
rising sea level																																1					1
humidity																							1		1												2
runoff																												1	1			1					3
C storage																																					0
biodiversity																						1		1													2
greenspace demand															1																						1
UHI/microclimate									1						1				1	1	1	1	1		1										1		9
transport	1																1		1																		3
industry	1																1											1									3
air quality									1													1		1	1										1		5
water quality															1										1			1									3
veg (health/phen.)										1					1																						2
human comfort																																					0
building integrity																										1								1			2
health																																					0
building design									1								1							1													3
soil type/geology										1			1											1				1									4
water resource																			1			1			1				1			1					5
drains/sewers													1																			1					2
culverts													1																								1
river surfacing													1																								1
flood															1			1			1		1	1	1								1	1		1	9
infrastructure																																					0
insurance																																					0
tourism									1						1			1										1									4
crime																																					0
Column sum (dependency)	5	1	1	3	1	1	1	1	5	4	1	1	7	1	11	1	6	5	7	5	4	10	7	10	11	1	0	9	4	0	0	6	6	4	3	2	

Fig. 29. Outcome of the climate change impacts in the urban system structural analysis (after Parry & Carter, 1998), autonomous variables are: socio-economic scenario, thermal growing season, rising sea level, humidity, carbon storage, building design, soil type/ geology, culverts, river surfacing, crime



Whilst these considerations are important, the approach is still potentially very useful in understanding the relationships between key elements of the system. The method should not be taken to provide absolute values about the driver-dependency nature of each variable, but should be used as a general guide to their nature. It would be beneficial to repeat the process for the three exposure units: greenspace, building integrity and human comfort, in turn. This would allow for a more detailed look at each of these components. However, using such an interaction matrix only indicates the presence or absence of an influence and does not inform us of whether the interactions are positive or negative. For this purpose, it may be useful to use conceptual models, demonstrating the relationships for a given pressure on the system (fig. 30). The ASCCUE project will further explore and develop such approaches.

Fig. 30. Conceptual model demonstrating possible interactions between urban greenspace, building integrity, and human comfort



Bibliography

ABI (2000). *Inland Flooding Risk – Issues Facing the Insurance Industry*. Research Report No. 10, Association of British Insurers. (cited by Austin *et al.*, 2000).

ABI (2001). *Flooding: A Partnership Approach to Protecting People*. London, Association of British Insurers.

ABI (2002a). *London Assembly Flooding Scrutiny*. London, Association of British Insurers. (cited by LCCP, 2002).

ABI (2002b). *Renewing the Partnership – How the insurance industry will work with others to improve protection against floods*. London, Association of British Insurers.

Akasaka, H., Nimiya, H. and Soga, K. (2002). Influence of heat island phenomenon on building heat load. *Building Services Engineering Research and Technology*, 2, 269-278.

Akbari, H., Rose, L. S. and Taha, H. (2003). Analyzing the land cover of an urban environment using high-resolution orthophotos. *Landscape and Urban Planning*, 63: 1-14.

Alberti, M. (2001). Urban form and ecosystem dynamics. In *Achieveing Sustainable Urban Form* (ed. K. Williams, E. Burton and M. Jenks). London: E & E Spon, pp. 84-96.

Anderson, H. R., Limb, E. S., Bland, J. M., Ponce de Leon, A., Strachan, D. P. and Bower, J. S. (1995). Health effects of an air pollution episode in London, December 1991. *Thorax*, 50, 1188-1193. (cited by Anderson *et al*., 2002).

Anderson, H. R., Ponce de Leon, A. and Bland, J. M. (1996). Air pollution and daily mortality in London: 1987-92. *British Medical Journal*, 312, 665-669. (cited by LCCP, 2002).

Anderson, H. R., Derwent, R. G. and Stedman, J. (2002). Air Pollution and Climate Change. In *Health Effects of Climate Change*. Department of Health, www.doh.gov.uk.

Antrop, M. (2000). Changing patterns in the urbanized countryside of Western Europe. *Landscape Ecology*, 15: 257-270.

Argotrade (2003). http://www.argotrade.com/wind. (site accessed 13th October 2003).

Arnell, N. W. and Reynard, N. S. (1996). The effects of climate change due to global warming on river flows in Great Britain. *Journal of Hydrology*, 183, 397-424.

Arnell, N. W. (1998). Climate change and water resources in Britain. *Climatic Change*, 39, 83-110.

Ashie, Y., Thanh Ca, V. and Asaeda, T. (1999). Building canopy model for the analysis of urban climate. *Journal of Wind Engineering and Industrial Aerodynamics*, 81, 237-248.

Ashmore, M., Bell, N. and Rutter, J. (1985). The role of ozone in forest damage in West Germany. *Ambio*, 14, 81-87. (cited by LCCP, 2002; cited by O'Hare & Wilby, 1995).

Austin, B., Cheesman, P. and Maggs, C. (2000) United Kingdom Floods. London, Guy Carpenter, Instrat UK.

Baxter, P. J., Moller, I., Spencer, T., Spence, R. J. and Tapsell, S. (2002a). Flooding and climate change. In *Health Effects of Climate Change*. Department of Health, www.doh.gov.uk.

Baxter, P. J., Lee, B. E., Wyatt, T. A. and Spence, R. J. (2002b). Windstorms and climate change. In *Health Effects of Climate Change*. Department of Health, www.doh.gov.uk.

BBC News (15 August 2002). *New Legionnaires' Cases Reported*. http://news.bbc.co.uk.

BBC News UK Edition (19 August 2003). *Thousands without water*. http://news.bbc.co.uk.

BBC News UK Edition (20 August 2003). *Water restored to thousands*. http://news.bbc.co.uk.

Bentham, G. (2002a). UV Radiation. In *Health Effects of Climate Change*. Department of Health, www.doh.gov.uk.

Bentham, G. (2002b). Food poisoning and climate change. In *Health Effects of Climate Change*. Department of Health, www.doh.gov.uk.

Berry, P. M., Vanhinsberg, D., Viles, H. A., Harrison, P. A., Pearson, R. G., Fuller, R. J., Butt, N. and Miller, F. (2001). Impacts on terrestrial environments. In *Climate Change and Nature Conservation in Britain and Ireland: Modelling Natural Resource Responses to Climate Change (the MONARCH project)* (eds. P. A. Harrison, P. M. Berry and T. E. Dawson). UKCIP Technical Report, Oxford.

Berz, G. & Loster, T. (2001). *Climate Change – Threats and Opportunities for the Financial Sector*. Munich, Munich Reinsurance Company.

Biddle, G. (2001). Tree root damage to buildings. *Expansive Clay Soils and Vegetative Influence on Shallow Foundations*, pp. 1-23. Conference Paper.

Bisgrove, R. and Hadley, P. (2002). *Gardening in the Global Greenhouse: The Impacts of Climate Change on Gardens in the UK*. UKCIP Technical Report, Oxford.

Bower, J. S., Broughton, G. F. J., Stedman, J. R. and Williams, M. L. (1994). A winter NO_2 smog episode in the UK. *Atmospheric Environment*, 28, 461-475. (cited by LCCP, 2002; Anderson *et al*., 2002).

Bretz, S., Akbari, H. and Rosenfeld, A. (1998). Practical issues for using solar-relfective materials to mitigate urban heat islands. *Atmospheric Environment*, 32(1), 95-101.

Bridgman, H., Warner, R. and Dodson, J. (1995). *Urban Biophysical Environments*. Oxford, Oxford University Press.

Bronstert, A., Niehoff, D. and Burger, G. (2002). Effects of climate and land-use change on storm runoff generation: present knowledge and modelling capabilities. *Hydrological Processes*, 16, 509-529.

Brown, R. D. and Gillespie, T. J. (1995). *Microclimate Landscape design: Creating Thermal Comfort and Energy Efficiency.* Chichester, John Wiley & Sons.

Burroughs, W. J. (2002). Gardening and climate change. *Weather*, 57, 151-157. (cited by LCCP, 2002).

Burt, P. J. A. (2002). Weather and pests. *Weather*, 57, 180-183. (cited by LCCP, 2002).

Cannell, M. G. R. and Sparks, T. H. (1999). Health of beech trees in Britain. In *Indicators of Climate Change in the UK* (Eds. M. G. R. Cannell, J. P. Palutitkof and T. H. Sparks). Department of the Environment, Transport and Regions, UK. http://www.nbu.ac.uk/iccuk (site accessed August 2003).

Carvel, J. (2003). Heatwave may have claimed 2000 lives. The Guardian, October 4th 2003. http://www.guardian.co.uk.

CEH (undated). (cited by CURE & Tyndall Centre, 2003, no reference)

CEH Wallingford and Meteorological Office (2001). *To what degree can the October/November 2000 flood events be attributed to climate change?* Department for Environment, Food and Rural Affairs, DEFRA FD2304 Final Report. (cited by LCCP, 2002).

Chestnut, L. G., Breffle, W. S., Smith, J. B. and L.S. Kalkstein, L. S. (1998). Analysis of differences in hot-weather-related mortality across 44 U.S. metropolitan areas. *Environmental Science and Policy*, 59, 59–78. (cited by IPCC, 2001).

CII (2001). *Climate Change and Insurance*. London, Chartered Institute for Insurance.

CIRIA (2003). *Sustainable Drainage Systems*. http://www.ciria.org.uk. (site accessed 13th October 2003).

COMEAP (1998). *Quantification of the Effects of Air Pollution on Health in the United Kingdom*. Great Britain Committee on the Medical Effects of Air Pollutants. London, HMSO. (cited by LCCP, 2002).

Connor, S. (2002). Building for a future that's hotter and wetter. *Green Futures*. Feb/March 2002. (cited by LCCP, 2002).

CRES (undated). *RUROS – Rediscovering the Urban Realm and Open Spaces*. Centre for Renewable Energy Sources, Passive Solar and Hybrid Systems Department, Greece.

Crick, H. Q. P., Dudley, C., Glue, D. E. and Thomson, D. L. (1997). UK birds are laying eggs earlier. *Nature*, 388, 526. (cited by LCCP, 2002).

Crick, H. Q. P. (1999). Small bird population changes. In *Indicators of Climate Change in the UK* (Eds. M. G. R. Cannell, J. P. Palutitkof and T. H. Sparks). Department of the Environment, Transport and Regions, UK. http://www.nbu.ac.uk/iccuk (site accessed August 2003).

Crowe, P. R. (1962). Climate. In *Manchester and its Regions: a Survey Prepared for the British Association* (ed. C. F. Carter), Manchester, Manchester University Press, pp. 17-46.

CURE & Tyndall Centre (2003). *Spatial Implications of Climate Change for the North West*. Main Report, Consultation Draft.

Davis, R. J. (2001). The effects of climate change on river flows in the Thames Region. *Water Resources, Hydrology and Hydrometry Report 00/04*. Reading, Environment Agency. (cited by LCCP, 2002).

de la Vega-Leinert, A. C. and Nicholls, R. J. (2002). Potential implications of sea-level rise for Great Britain. *Journal of Coastal Research*, in press. (cited by LCCP, 2002).

DETR (2000a). *Development and flood risk (PPG25) Consultation Draft*. Department of the Environment Transport and the Regions, London. (cited by LCCP, 2002).

DETR (2000b). *Potential UK adaptation strategies for climate change*. Department of Environment, Transport and Regions. (cited by Austin *et al.*, 2000).

Dlugolecki, A. (2001). Introduction. In *Climate Change and Insurance*, pp.1-3. CII, London.

Donaldson, G., Kovats, R. S., Keatinge, W. R. and McMichael, A. J. (2002). Heat- and cold-related mortality and morbidity and climate change. In *Health Effects of Climate Change in the UK*. Department of Health, www.doh.gov.uk.

Doornkamp, J. C. (1993). Clay shrinkage induced subsidence. *Geographical Journal*, 159, 196-202. (cited by LCCP, 2002).

Dukes, J. S. and Mooney, H. A. (1999). Does global change increase the success of biological invaders? *Trends in Ecology and Evolution*, 14, 135-139.

Edholm, O. G. (1978). *Man - Hot and Cold*. Studies in Biology No. 97. London, Edward Arnold.

Edwards (1999). (cited by LCCP 2002, no reference).

EEA (2002). Towards an urban atlas – assessment of spatial data on 25 European cities and urban areas. *Environmental Issue Report*, 30, Copenhagen.

EEA (2003). European Environment Agency. http://glossary.eea.eu.int/EEAGlossary/D/DPSIR.

Eliasson, I. (2000). The use of climate knowledge in urban planning. *Landscape and Urban Planning*, 48: 31-44.

Emberlin, J. (1994). The effects of patterns in climate and pollen abundance on allergy. *Allergy*, 94, 15-20. (cited by LCCP, 2002).

Emberlin, J. (1997). The trend to earlier birch pollen seasons in the UK: a biotic response to changes in weather conditions. *Grana*, 36, 29-33. (cited by LCCP, 2002).

Environment Agency (2001a). *Water Resources for the Future: A Summary of the Strategy for North West Region*. Environment Agency.
http://www.environment-agency.gov.uk/subjects/waterres/

Environment Agency (2001b). *Water Resources for the Future: A Summary of the Strategy for the Southern Region*. Environment Agency.
http://www.environment-agency.gov.uk/subjects/waterres/.

Environment Agency (2001c). *State of the Environment Report for London*. Reading, Environment Agency. (cited by LCCP, 2002).

EPSRC & UKCIP (2003). *Building Knowledge for a Changing Climate: The Impacts of Climate Change on the Built Environment*. UK Climate Impacts Programme.

Fanger, P. O. (1970). *Thermal Comfort*: Analysis and Applications in Environmental Engineering. Copenhagen, Danish Technical Press.

Fordham, M. and Ketteridge, A.-M. (1995). *Flood Disasters – Dividing the Community*. Paper presented at the Emergency Planning Conference, 2-6 July 1995, Lancaster, UK.

Forestry Commission (2000). *Climate Change – Implications for Forestry in Britain*. Forestry Commission information note, Edinburgh, Forestry Commission. (cited by CURE & Tyndall Centre, 2003).

Futter, M. and Lang, I. (2001). *Implications for Scotland of Recent Developments in Design, Rainfall Estimation and Climate Change*. Scottish Wastewater Planning Users Group (WaPUG) Meeting, 12th June 2001, Dunblane. (cited by LCCP, 2002).

Garvin, S., Phillipson, M., Sanders, C., Hayles, C. and Dow, G. (1998). *Impact of Climate Change on Building*. Building Research Establishment, Scottish Laboratory. (cited by Shackley *et al.*, 2001).

Gawith, M., Downing, T. and Karacostas, T. (1999). Heatwaves in a changing climate. In *Climate Change and Risk* (eds. T. E. Downing, A. A. Olsthoorn and R. S. J. Tol), London, Routledge, pp. 279-307. (cited by LCCP, 2002).

Giles, A. R. and Perry, A. H. (1998). The use of temporal analogue to investigate the possible impact of projected global warming on the UK tourist industry. *Tourism Management*, 19: 75-80.

Givoni, B. (1991). Impact of planted areas on urban environmental quality: a review. *Atmospheric Environment*, 25B: 289-299.

Goldsmith, J. R. (1986). Three Los Angeles heatwaves. In *Environmental Epidemiology: Epidemiological Investigation of Community Environmental Health Problems* (Ed. J. R. Goldsmith), pp. 73-81. CRC Press, Boca Raton, FL. (cited by Sartor *et al.*, 1995).

Gómez, F., Tamarit, N. and Jabaloyes, J. (2001). Green zones, bioclimatics studies and human comfort in future development of urban planning. *Landscape and Urban Planning*, 55: 151-161.

Grambsch, A. (2002). Climate change and air quality. In *The Potential Impacts of Climate Change on Transportation: Workshop Summary and Proceedings*. U.S. Department of Transportation, Centre for Climate Change and Environmental Forecasting. http://climate.volpe.dot.gov/workshop1002/index.html.

Graves, H. M. and Phillipson, M. C. (2000). *Potential Implications of Climate Change in the Built Environment*. East Kilbride, BRE.

Graves, H. M., Watkins, R., Westbury, P., and Littlefair, P. (2001). *Cooling Buildings in London: Overcoming the Heat Island*. London, CRC Ltd.

The Guardian (26th November 2003). *Save water or risk drought, official warns*.

Hardwick, N. V. (2002). Weather and plant diseases. *Weather*. 57, 184-190. (cited by LCCP, 2002).

Hassan, H., Aramaki, T., Hanaki, K., Matsuo, T. and Wilby, R. L. (1998). Lake stratification and temperature profiles simulated using downscaled GCM output. *Journal of Water Science and Technology*, 38, 217-226. (cited by LCCP, 2002).

Henry, J. A. and Dicks, S. E. (1987). Association of urban temperatures with land use and surface materials. *Landscape and Urban Planning*, 14: 21-29.

Herrington, P. (1996). *Climate Change and the Demand for Water*. London, HMSO. (cited by LCCP, 2002).

HMSO (1991). Department of Health, advisory group on medical aspects of air pollution episodes, first report. *Ozone*. London, HMSO. (cited by O'Hare & Wilby, 1995).

Holt, T. (1999). A classification of ambient climatic conditions during extreme surge events off Western Europe. *International Journal of Climatology*, 19, 725-744.

Höppe, P. (2002). Different aspects of assessing indoor and outdoor thermal comfort. *Energy and Buildings*, 34, 661-665.

Hough, E., Kessler, H., Lelliott, M., Price, S. J., Reeves, H. J. and McBridge, D. (2003). Look before you leap: the use of geoenvironmental data models for preliminary site appraisal. In *Land Reclamation* (eds. Moore, Fox & Elliott), Lisse, Swets & Zeitlinger, pp. 369-375.

Hulme, M., Jenkins, G. J., Lu, X., Turnpenny, J. R., Mitchell, T. D., Jones, R. G., Lowe, J., Murphy, J. M., Hassell, D., Boorman, P., McDonald, R. and Hill, S. (2002). *Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report*. Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK. http://www.ukcip.org.uk/scenarios/sci_report/sci_report.html.

Humphreys, M. A. and Nicol, J. F. (2002). The validity of ISO-PMV for predicting comfort votes in every-day life. *Energy and Buildings*, 34, 667-684.

International Society of Biometeorology (2003). *Commission 6: Development of a 'Universal Thermal Climate Index'*. http://arbmed.klinikum.uni-muenchen.de/biomet/Commission6.htm (site accessed 28th January 2004).

IPCC (2000). *Emissions Scenarios*. Special Report of the Intergovernmental Panel on Climate Change. Cambridge, Cambridge University Press.

IPCC (2001). *Climate Change 2001: Impacts, Adaptation, and Vulnerability*. Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge. http://www.ipcc.ch.

Jendritzky, G. and Nübler, W. (1981). A model analysing the urban thermal environment in physiologically significant terms. *Archives for Meteorology, Geophysics, and Bioclimatology*, B29: 313-326.

Kaufman, M. M. and Marsh, W. M. (1997). Hydro-ecological implications of edge cities. *Landscape and Urban Planning*, 36: 277-290.

Keleher, C. J. and Rahel, F. J. (1996). Thermal limits to salmonid distributions in the Rocky Mountain region and the potential habitat loss due to global warming: a geographic information system (GIS) approach. *Transactions of the American Fisheries Society*, 125, 1-13. (cited by LCCP, 2002).

Kettlewell, P. S., Atkinson, M. D., Stephenson, D. B., Easey, J. A. & Hollins, P. D. (2003). Potential predictability of soil moisture deficits in Britain from the North Atlantic Oscillation. *Geophysical Research Abstacts*, 5: 12222. European Geophysical Society, 2003. http://www.cosis.net/abstracts/EAE03/12222/EAE03-J-12222.pdf.

Kilbourne, E. M. (1990). Atmospheric change and temperature-related health effects. In *Global Atmospheric Change and Public Health* (Eds. J. C. White, W. Wagner and C. N. Beal), pp. 89-100. New York, Elsevier. (cited by Sartor *et al.*, 1995).

Krupa, S. V. and Manning, W. J. (1988). Atmospheric ozone: formation and effects on vegetation. *Environmental Pollution*, 50, 101-137. (cited by LCCP, 2002; cited by O'Hare & Wilby, 1995).

Kunst, A. E., Looman, C. W. N. and Mackenbath, J. P. (1993). Outdoor air temperature and mortality in the Netherlands: a time-series analysis. *American Journal of Epidemiology*, 137, 331-341. (cited by LCCP, 2002; Sartor *et al.*, 1995).

Landsberg, H. (1981). *The Urban Climate*. Vol. 28, International Geophysics Series. New York, Academic Press. (cited by Bridgman *et al*., 1995).

Langford, I. H. and Bentham, G. (1995). The potential effects of climate change on winter mortality in England and Wales. *International Journal of Biometeorology*, 38, 141-147. (cited by LCCP, 2002).

Laschewski, G. and Jendritzky, G. (2002). Effects of the thermal environment on human health: an investigation of 30 years of daily mortality data from SW Germany. *Climate Research*, 21, 91-103. (cited by LCCP, 2002).

LCCP (2002). *London's Warming: The Impacts of Climate Change on London*. London Climate Change Partnership.

Lee, D. O. (1993). Climatic change and air quality in London. *Geography*, 78, 77-79. (cited by LCCP, 2002).

Lee *et al.* (1999). (cited by CURE & Tyndall Centre, 2003, no reference).

LHC (2002). *Health in London 2002: Review of the London Health Strategy High-Level Indicators*, London Health Commission, www.londonshealth.gov.uk. (cited by LCCP, 2002).

Lippmann, M. (1989). Health effects of ozone: a critical review. *Journal of Air and Waste Management Assoc.*, 39, 672-695. (cited by O'Hare & Wilby, 1995).

Lowe, J. A., Gregory, J. M. and Flather, R. A. (2001). Changes in the occurrence of storm surges around the UK under a future climate scenario using a dynamic storm surge model driven by the Hadley Centre climate models. *Climate Dynamics*, 18, 179-188.

Macfarlane, A., Haines, A., Goubet, S., Anderson, H. R., Ponce de Leon, A. and Limb, E. S. (1997). Air pollution, climate and health: short-term effects and long-term prospects. In *The Health of Adult Britain: 1841-1994, Vol. 1* (eds. J. Charlton & M. Murphy). London, The Stationary Office, 187-204. (cited by Anderson *et al*., 2002).

Magnuson, J. J., Webster, K. E., Assel, R. A., Bowser, C. J., Dillon, P. J., Eaton, J. G., Evans, H. E., Fee, E. J., Hall, R. I., Mortsch, L. R., Schindler, D. W., and Quinn F. H. (1997) Potential effects of climate changes on aquatic systems: Laurentian great lakes and Precambrian shield region. *Hydrological Processes*, 11, 825-871.

Magnuson, J. J. *et al.* (2000). Historical trends in lake and river ice-cover in the Northern hemisphere. *Science*, 289, 1743-1746. (cited by LCCP, 2002).

Marchant, J. H., Hudson, R., Carter, S. P. and Whittington, P. (1990). *Population trends in British Breeding Birds*. British Trust for Ornithology. (cited by LCCP, 2002).

Marchant, P., Eling, W., van Gemert, G-J., Leake, C. J. and Curtis, C. F. (1998). Could British mosquitoes transmit falciparum malaria? *Parisitology Today*, 14, 344-345.

Marmor, M. (1978). Heatwave mortality in nursing homes. *Environmental Research*. 17, 102-115. (cited by Sartor *et al.*, 1995).

Marsh (2001). (cited by LCCP, 2002, no reference).

Martens, W. (1996). *Vulnerability of Human Population Health to Climate Change: State-of-Knowledge and Future Research Directions*. Dutch National Research Programme on Global Air Pollution and Climate Change, Maastricht, University of Limburg. (cited by LCCP, 2002).

Matzarakis, A., Mayer, H. and Iziomon, M. (1999). Applications of a universal thermal index: physiological equivalent temperature. *International Journal of Biometeorology*, 43: 76-84. (cited by Svensson & Eliasson, 2002).

Matzarakis, A. (2001). Die thermische Komponente the Stadtklimas. *Berichte des Meteorologischen Instituts der Universität Freiburg*, 6.

McPherson, E. G. (1998). Structure and sustainability of Sacramento's urban forest. *Journal of Arboriculture,* 24: 174–190.

Milly, P. C. D., Wetherald, R. T., Dunne, K. A. and Delworth, T. L. (2002). Increasing risk of great floods in a changing climate. *Nature*, 415, 514-517. (cited by LCCP, 2002).

Morris, R. E., Gery, M. W., Liu, M. -K., Moore, G. E., Daly, C., and Greenfield, S. M. (1989). Sensitivity of a regional oxidant model to variations in climate parameters. In *The Potential Effects of Global Climate Change on the United States, Appendix F: Air Quality*. (Ed. J. B. Smith and D. A. Tirpak). Washington, DC, Environmental Protection Agency. (cited by IPCC, 2001).

Morris, R. E., Guthrie, P. D. and Knopes, C. A. (1995). Photochemical analysis under global warming conditions. In *Proceedings of the 88th Air and Waste Management Association Annual Meeting*. Pittsburgh, Air and Waste Management Association. (cited by IPCC, 2001).

Murdoch, P. S., Baron, J. S. and Miller, T. L. (2000). Potential effects of climate change on surface water quality in North America. *Journal of the American Water Resources Association*, 36, 347-366. (cited by LCCP, 2002).

Nachbarschaftsverband Stuttgart (1992). *Klimaatlas. Klimauntersuchung für den Nachbarschaftsverband Stuttgart und angrenzende Teile der Region Stuttgart*. Stuttgart.

National Research Council (1991). *Rethinking the Ozone Problem in Urban and Regional Air Pollution*. Washington, National Academy Press. (cited by O'Hare & Wilby, 1995).

National Statistics (2001). Greater Manchester, Census 2001. http://www.statistics.gov.uk/census2001/pyramids/pages/2a.asp (site accessed 25th November 2003).

Newson, R., Strachan, D., Archibald, E., Emberlin, J., Hardaker, P. and Collier, C. (1998). Acute asthma epidemics, weather and pollen in England, 1987-1994. *European Respiratory Journal*, 11, 694-701. (cited by LCCP, 2002).

Nichol, J. E. (1996). High-resolution surface temperature patterns related to urban morphology in a tropical city: a satellite-based study. *Journal of Applied Meteorology*, 35: 135-146.

Nicol, F. (1993). *Thermal Comfort* - A Handbook for Field Studies Toward an Adaptive Model. University of East London.

Nikolopoulou, M., Baker, N. and Steemers, K. (2001). Thermal comfort in outdoor urban spaces: understanding the human parameter. *Solar Energy*, 70(3) 227-235.

N'Jai, A., Tapsell, S. M., Taylor, D., Thompson, P. M., Witts, R. C., Parker, D. J. and Penning-Rowsell, E. C. (1991). *Flood loss assessment report*. London: Middlesex Flood Hazard Research Centre, Middlesex University. (cited by Baxter *et al*., 2002).

NPI (2000). *Food Access*, Briefing paper from seminar on food access, New Policy Institute, London. http://www.www.npi.org.uk/reports.

ODPM (2002). *Planning Policy Guidance Note 3 (PPG 3)*. Office of the Deputy Prime Minister, London: HMSO.
ODPM (2003). *Sustainable communities: building for the future*. Office of the Deputy Prime Minister, London: HMSO.
http://www.odpm.gov.uk/stellent/groups/odpm_communities/documents/page/odpm_comm_022184.hcsp.
Oechsli, F. W. and Buechley, R. W. (1970). Excess mortality associated with three Los Angeles September hot spells. *Environmental Research*. 3, 277-284. (cited by Sartor *et al.*, 1995).
O'Hare, G. P. and Wilby, R. L. (1994). Ozone pollution in the United Kingdom: an analysis using lamb circulation types. *Geographical Journal*, 161, 1-20. (cited by LCCP, 2002).
O'Hare, G. P. and Wilby, R. (1995). A review of ozone pollution in the United Kingdom and Ireland with an analysis using Lamb Weather Types. *Geographical Journal*, 161, 1-20.
Oke, T. R. (1982). Overview of Interactions between Settlements and their Environments. WMO Experts Meeting on Urban and Building Climatology. WCP-37. Geneva, World Meteorological Organization. (cited by Graves *et al.*, 2001).
OST (forthcoming). *Foresight: Flood and Coastal Defence Phase 3*. Office of Science and Technology, London.
Palutikof, J., Subak, S. and Agnew, M. (eds.**) (1997)**. *Economic Impacts of the Hot Summer and Unusually Warm Year of 1995*. Norwich, CRU. (cited by LCCP, 2002).
Pan, W. –H., Li, L.-A. and Tsai, M. –J. (1995). Temperature extremes and mortality from coronary heart disease and cerebral infarction in elderly Chinese. *Lancet*, 345, 353-355. (cited by Sartor *et al.*, 1995).
Parmesan, C., Ryrholm, N., Stefanescu, C., Hill, J. K., Thomas, C. D., Descimon, H., Huntley, B., Kaila, L., Kullberg, J., Tammaru, T., Tennent, W. J., Thomas, J. A. and Warren, M. (1999). Poleward shifts in geographical ranges of butterfly species associated with regional warming. *Nature*, 399, 579-583. (cited by LCCP, 2002).
Parmesan, C., Root, T. L. and Willig, M. R. (2000). Impacts of extreme weather and climate on terrestrial biota. *Bulletin of the American Meteorological Society*, 81, 443-450. (cited by LCCP, 2002).
Parry, M. and Carter, T. (1998). *Climate Impact and Adaptation Assessment: A Guide to the IPCC Approach*. London, Earthscan.
Parsons, K. (2003). *Human Thermal Environments - The Effects of Hot, Moderate and Cold Environments on Human Health, Comfort and Performance* (2nd ed.). London, Taylor & Francis.
Patz *et al.* (2000). (cited by CURE & Tyndall Centre, 2003, no reference).
Pauleit, S. and Duhme, F. (1995). Developing quantitative targets for urban environmental planning. *Land Contamination and Reclamation*, 3: 64–66.
Pauleit, S. and Duhme, F. (2000). Assessing the environmental performance of land cover types for urban planning. *Landscape and Urban Planning*, 52: 1-20.
Penner, J. E., Connell, P. S., Wuebbles, D. J. and Covey, C. C. (1989). Climate change and its interaction with air chemistry: perspectives and research needs. In *The Potential Effects of Global Climate Change on the United States, Appendix F: Air Quality*. (Ed. J. B. Smith and D. A. Tirpak). Washington, DC, Environmental Protection Agency. (cited by IPCC, 2001).
Pielke, R. (1999). Nine fallacies of floods. *Climatic Change*, 42, 413-438. (cited by LCCP, 2002).
Pielke, R. (2000). Flood impacts on society, in *Floods* (ed. D. Parker). London, Routledge. (cited by LCCP, 2002).
Pilgrim, J. M., Fang, X. and Stefan, H. G. (1998). Stream temperature correlations with air temperatures in Minnesota: implications for climate warming. *Journal of the American Water Resources Association*, 34, 1109-1121. (cited by LCCP, 2002).
Pilling, C. and Jones, J. A. A. (1999). High resolution climate change scenarios: implications for British runoff. *Hydrological Processes*, 13, 2877-2895. (cited by LCCP, 2002).

Pilling, C. and Jones, J. A. A. (2002). The impact of future climate change on seasonal discharge, hydrological processes and extreme flows in Upper Wye experimental catchment, mid-Wales. *Hydrological Processes*, 16, 1201-1213. (cited by LCCP, 2002).

Quattrochi, D. A. and Ridd, M. K. (1998). Analysis of vegetation within a semi-arid urban environment using high spatial-resolution airborne thermal infrared remote sensing data. *Atmospheric Environment*, 32: 19-33.

Radevsky, R., Crichton, D. & Loster, T. (2001). Property Insurance. In *Climate change and Insurance*, pp. 54-68. London, CII.

Ramos, M. C. and Steemers, K. (2003). Comfort in urban spaces: the roles of physiological and psychological parameters. Paper presented at *PLEA 2003* - The 20th Conference on Passive and Low Energy Architecture, Santiago, Chile, 9-12 November 2003.

Robertson, D. J., Taylor, K. G. and Hoon, S. R. (2003). Geochemical and mineral magnetic characterisation of urban sediment particulates, Manchester, UK. *Applied Geochemistry*, 18: 269-282.

Roetzer, T., Wittenzeller, M., Haeckel, H. and Nekovar, J. (2000). Phenology in central Europe – differences and trends of spring phenophases in urban and rural areas. *International Journal of Biometeorology*, 44: 60-66.

Rogers, D. J., Randolph, S., Lindsay, S. and Thomas, C. (2002). Vector-borne diseases and climate change. In *Health Effects of Climate Change in the UK*. Department of Health, www.doh.gov.uk.

Rogot, E., Sorlie, P. D. and Backlund, E. (1992). Air-conditioning and mortality in hot weather. *American Journal of Epidemiology*. 136, 106-116. (cited by Sartor *et al.*, 1995).

Rooney, C., McMichael, A. J., Kovats, R. S. and Coleman, M. (1998). Excess mortality in England and Wales, and in Greater London, during the 1995 heatwave. *Journal of Epidemiology and Community Health*, 52, 482-486.

Rose, C. (1990). *The Dirty Man of Europe*. London, Simon and Schuster. (cited by O'Hare & Wilby, 1995).

Rosenfeld, A. H., Akbari, H., Bretz, S, Fishman, B. L., Kurn, D. M., Sailor, D and Taha, H. (1995). Mitigation of urban heat islands: materials, utility programmes, updates. *Energy and Buildings*, 22(3) 255-265.

Rounsevell, M. D. A., Evans, S. P. and Bullock, P. (1999). Climate change and agricultural soils: impacts and adaptation. *Climate Change*, 43, 683-709. (cited by LCCP, 2002).

Samson, P. J., Augustine, S. J., and Sillman, S. (1989). Linkages between global climate warming and ambient air quality. In *Global Change Linkages: Acid Rain, Air Quality, and Stratospheric Ozone* (ed. J. C. White). New York, Elsevier. (cited by IPCC, 2001).

Santos, R. and Boas, M. (2000). Urban morphology and thermal comfort conditions in the central area of Belo Horizonte. *Architecture, City, Environment, Proceedings of PLEA 2000*, Cambridge, UK, July 2000, pp. 630-631.

Sartor, F., Snacken, R., Demuth, C. and Walckiers, D. (1995). Temperature, ambient ozone levels, and mortality during summer, 1994, in Belgium. *Environmental Research*, 70, 105-113.

Schimel, D. D., Kittel, T. G. F. and Parton, W. J. (1991). Terrestrial biogeochemical cycles: global interactions with atmosphere and hydrology. *Tellus*, 43AB, 188-203. (cited by LCCP, 2002).

Schindler, D. W. (1997). Widespread effects of climatic warming on freshwater ecosystems in North America. *Hydrological Processes*, 11, 825-871. (cited by LCCP, 2002).

Scottish Executive (2001). (cited by CURE & Tyndall Centre, 2003, no reference).

Sefton, C. E. M. and Boorman, D. B. (1997). A regional investigation into climate change impacts on UK streamflows. *Journal of Hydrology*, 195, 26-44.

Shackley, S. and Wynne, B. (1994). Viewpoint: Climatic reductionism, the British character and the greenhouse effect. *Weather*, 49 (3), 110-111. (cited by LCCP, 2002).

Shackley, S., Kersey, J., Wilby, R. and Fleming, P. (2001). Changing by Degrees: The Potential Impacts of Climate Change in the East Midlands. Aldershot, Ashgate.

Shimoda, Y. (2003). Adaptation measures for climate change and the urban heat island in Japan's built environment. *Building Research and Information*, 3/4, 222-230.

Sillman, S. and Samson, P. J. (1995). Impact of temperature on oxidant photochemistry in urban, polluted rural, and remote environments. *Journal of Geophysical Research*, 100, 11497-11508.

Skarby, L. and Selden, G. (1984) The effects of ozone on crops and forests. *Ambio*, 13, 68-72. (cited by O'Hare & Wilby, 1995).

Sparks, T. H. (1999). Date of leaf emergence on trees in spring. In *Indicators of Climate Change in the UK* (eds. M. G. R. Cannell, J. P. Palutitkof and T. H. Sparks). Department of the Environment, Transport and Regions, UK. http://www.nbu.ac.uk/iccuk (site accessed August 2003).

Sparks, T. H. and Loxton, R. G. (1999). Arrival date of the swallow. In *Indicators of Climate Change in the UK* (eds. M. G. R. Cannell, J. P. Palutitkof and T. H. Sparks). Department of the Environment, Transport and Regions, UK. http://www.nbu.ac.uk/iccuk (site accessed August 2003).

Sparks, T. H. and Potts, J. M. (1999). Late summer grass production. In *Indicators of Climate Change in the UK* (eds. M. G. R. Cannell, J. P. Palutitkof and T. H. Sparks). Department of the Environment, Transport and Regions, UK. http://www.nbu.ac.uk/iccuk (site accessed August 2003).

Sparks, T. H. and Woiwod, I. P. (1999). Dates of insect appearance and activity. In *Indicators of Climate Change in the UK* (eds. M. G. R. Cannell, J. P. Palutitkof and T. H. Sparks). Department of the Environment, Transport and Regions, UK. http://www.nbu.ac.uk/iccuk (site accessed August 2003).

Sparks, T. H., Jeffree, E. P. and Jeffree, C. E. (2000). An examination of the relationship between flowering times at the national scale using long-term phonological records from the UK. *International Journal of Biometeorology*, 44: 82-87.

Sparks, T. H. and Smithers, R. J. (2002). Is spring getting earlier? *Weather*, 57, 157-166. (cited by LCCP, 2002).

Spence, R., Brown, A. J. and Fawcett, W. (1998). The windstorm vulnerability of the UK building stock. *4th Conference on Wind Engineering*. (cited by Baxter *et al*., 2002).

Stanwell-Smith, R. (2002). Water-borne diseases and climate change. In *Health Effects of Climate Change*. Department of Health, www.doh.gov.uk.

Stern and Zehavi (1989). (cited by LCCP, 2002, no reference).

Subak, S. (1999). Incidence of Lyme disease in humans. In *Indicators of Climate Change in the UK* (eds. M. G. R. Cannell, J. P. Palutitkof and T. H. Sparks). Department of the Environment, Transport and Regions, UK. http://www.nbu.ac.uk/iccuk (site accessed August 2003).

Svensson, M. K. and Eliasson, I. (2002). Diurnal air temperatures in built-up areas in relation to urban planning. *Landscape and Urban Planning*, 61: 37-54.

Takahashi, Y., Kawashima, S. and Aikawa, S. (1996). Effects of global climate change on Japanese cedar pollen concentration in air – estimated results obtained from Yamagata City and its surrounding area. *Arerugi*, 45, 1270-1276. (cited by LCCP, 2002).

Tan, S.- A. and Fwa, T.- F. (1992). Influence of pavement materials on the thermal environment of outdoor spaces. *Building and Environment*, 27(3), 289-295.

Thomas and Lennon (1999). (cited by LCCP, 2002, no reference).

Thornes (1997). (cited by LCCP, 2002, no reference).

UKCIP (2001). *Socio-Economic Scenarios for Climate Change Impact Assessment: A Guide to Their Use in the UK Climate Impact Programme*. Oxford, UK Climate Impacts Programme. (cited by LCCP, 2002).

UKCIP (2003). UK Climate Impacts Programme. http://www.ukcip.org.uk.

URGENT (2003). Urban Regeneration of the Environment. http://urgent.nerc.ac.uk/about.htm (accessed 24th October 2003).

UKWIR (2002). *Climate Change and Hydraulic Design of Sewerage Systems*. [Accessed 8/7/02: http://www.ukwir.org.uk/frameset.asp] (cited by LCCP, 2002).

UNCHS (1999). *Global Urban Indicators Database*. United Nations Centre for Human Settlements (HABITAT), Oxford, Oxford University Press. http://www.urbanobservatory.org/indicators/database. (cited by IPCC, 2001).

Vaze, J. and Chiew, F. H. S. (2002). Experimental study of pollutant accumulation on an urban road surface. *Urban Water*, 4, 379-389.

Visser, M. E., Vannoordwijk, A. J., Tinbergen, J. M. and Lessells, C. M. (1998). Warmer springs lead to mistimed reproduction in Great Tits (Parus major). *Proceedings of the Royal Society of London B*, 265, 1867-1870. (cited by LCCP, 2002).

Von Storch, H. and Reichardt, H. (1997). A scenario of storm surge statistics for the German Bight at the expected time of doubled atmospheric carbon dioxide concentration. *Journal of Climate*, 10, 2653-2662. (cited by LCCP, 2002).

Walker, T. (2001). Developments since 1994. In *Climate Change and Insurance*, pp. 4-14. London, CII.

Webb, B. W. (1996). Trends in stream and river temperature behaviour. *Hydrological Processes*, 10, 205-226. (cited by LCCP, 2002).

White, J. E. J. (1994). New tree species in a changing world. *Arboricultural Journal*, 18: 99-112. (cited by Bisgrove & Hadley, 2002).

White, M. A., Nemani, R. R., Thornton, P. E. and Running, S. W. (2002). Satellite evidence of phenological differences between urbanized and rural areas of the eastern Urnited States deciduous broadleaf forest. *Ecosystems*, 5: 260-277.

Whitford, V., Ennos, A. R. and Handley, J. F. (2001). "City form and natural process" – indicators for the ecological performance of urban areas and their application to Merseyside, UK. *Landscape and Urban Planning*, 57: 91-103.

WHO (1987). *Air Quality Guidelines for Europe*. Regional Publications European Series, No 23. Copenhagen, World Health Organisation. (cited by O'Hare & Wilby, 1995).

Wilby, R. L. (1994). *Modelling the relative impact of weather, landuse and groundwater abstraction on low flows*. National Rivers Authority, R&D Note 268. (cited by LCCP, 2002).

Wilby, R. L. (2003). Past and projected trends in London's urban heat island. *Weather*, 58(7), 251-260.

Wilby, R. L., Cranston, L. E. and Darby, E. J. (1998). Factors governing macrophyte status in Hampshire chalk streams: implications for catchment management. *The Journal of the Chartered Institution of Water and Environmental Management*, 12, 179-187. (cited by LCCP, 2002).

Wilson, J. S., Clay, M., Martin, E., Stuckey, D. and Vedder-Risch, K. (2003). Evaluating environmental influences of zoning in urban ecosystems with remote sensing. *Remote Sensing of Environment*, 86: 303–321.

Wolf, A. T., (1998). Conflict and cooperation along international waterways. *Water Policy*, 1(2), 251–265. (cited by IPCC, 2001).

Zacharias, J., Stathopoulos, T. and Wu, H. (2001). Microclimate and downtown open space activity. *Environment and Behavior*, 33: 296-315.

Zaninovic, K. and Raos, M. (2001). The influence of meteorological parameters on asthmatic attacks in children. *Hravatski Meteoroloski Casopis*, 37, 89-94.

Zierl, B. (2002). Relations between crown condition and ozone and its dependence on environmental factors. *Environmental Pollution*, 119, 55-68. (cited by LCCP, 2002).