london'swarming

The Impacts of Climate Change on London

Technical Report

A High Profile Launch for London's First Climate Change Study

The Mayor of London Ken Livingstone and Environment Minister Michael Meacher launched London's Warming on 24 October 2002.

The launch event was very successful, attracting a large number of people from a wide range of sectors. Many individuals attended who had not previously been involved in the Climate Impacts study but recognised that climate change is an issue that will become increasingly important in the years to come.

At the Launch the Environment Minister said "The UK is leading the way in identifying the effects which climate change will have on all parts of the country, including our capital city. Some climate change is now inevitable, so we are going to have to adapt."

While the Mayor of London pointed out the particular issues that London will have to face, saying "The size of this city's population means that there's already huge pressure on our resources, so we have to plan properly and strategically to deal with these new demands. This report is the start of that process."

If you want to be part of that process please contact the London Climate Change Partnership at climatechange@london.gov.uk.

London Climate Change Partnership

A Climate Change Impacts in London Evaluation Study

Final Report

November 2002

Acknowledgements

The London Climate Change Partnership, a group of stakeholders originally convened by the Government Office for London in July 2001, commissioned this work to take a first look at the impacts that climate change will have on our capital city. The members of the partnership are: The Greater London Authority (GLA), Government Office for London, the Association of London Government (ALG), the Housing Corporation, the Environment Agency, the Assocaition of British Insurers (ABI), the London Development Agency (LDA), Thames Water, the London Electricity Group, the Corporation of London, St. George Plc., Transport for London (TfL), UK Climate Impacts Programme (UKCIP), the London Sustainabiolity Exchange and the Thames Gateway Partnership. A more comprehensive list of organisations who have taken part in meetings related to this study can be found in Appendix A.

This study wsas carried out by a project consortium consisting of Entec UK Ltd, the Tyndall centre for Climate Change research, Meetroeconomica, Dr.Rob Wilby of King's college London and Professor David Crichton, an independent consultant.

The main contributors were: Simon Clarke, Jim Kersey and Emily Trevorrow of Entec UK LTd.; Rob Wilby of King's College, London; Simon Shackley, John Turnpenny and Andy Wright of the Tyndall Centre; Alistair Hunt of Metroeconomica; and David Crichton.

Contents

6. The Potential Social Impacts of Climate Change in London 95

Executive Summary

This study is the first step in understanding what may happen as a result of possible future climate change in London. It was commissioned by the Greater London Authority (the GLA), acting as an agent for the London Climate Change Partnership and has been written by a team led by Entec UK Ltd, comprising Dr. Rob Wilby (Kings' College London), the Tyndall Centre for Climate Change Research, Metroeconomica and Professor David Crichton (Independent Consultant).

The overall objective for the study was to "*outline the threats and opportunities presented by climate change, and start to address the responses needed"*. More specifically this study has aimed to provide an overview of the existing information on the impacts of climate change on the environment and the economy and, to elucidate the social impacts of climate change largely based on existing reviews, research and monitoring studies within and outside of London. The study findings have been discussed in context with existing policies and strategies for London and recommendations for further work made accordingly.

Pivotal to the study has been 'stakeholder engagement' a broad term used to encompass (*inter alia*) the processes of: raising awareness amongst stakeholders; involving stakeholders; stakeholder consultation, and; consensus building amongst stakeholders about the likely direction and level of climate change in London and the impacts of such change on London, its population and businesses. Stakeholder engagement has been addressed in several ways by this project but primarily through a workshop setting.

There are two study reports. This report, the Technical Report, describes in detail the study's findings and is aimed at the more specialised reader and those involved in more detailed planning. A summary report has also been produced that presents the general findings from the study and is aimed at the general reader and policy makers.

The UK Climate Impacts Program (UKCIP) has published four scenarios (Low emissions, Medium-Low emissions, Medium-High emissions and High emissions) of future climates for the 2020's, 2050's and 2080's at a resolution of 50 km^2. These scenarios form the basis for impact analysis in this study. As well as existing published information and key input from a number of stakeholders consulted, the scenarios have been used to predict what impacts climate change is likely to have on London.

Climate change may exacerbate the urban heat island effect (a term used to describe the fact that the temperature of London at its centre is several degrees higher than at its edges; this is because London is a fairly dense, urban settlement and heat emitted from buildings and the characteristics of the airflow contribute to this temperature profile) with resulting impacts of increased summer heat stress and mortality, higher temperatures on the London underground and higher rates of household waste decay.

Further statistical analyses of the UKCIP climate scenarios have been undertaken to predict the specific environmental impacts of climate change on London whilst recognising that certain scientific uncertainties exist. Key environmental impacts identified within London relate to:

- Flood risk - London is vulnerable to three main types of flooding: the inundation of floodplains by river water, local flooding when the drainage network is overwhelmed by intense rainfall, and by tidal surges in the Thames. Climate change could adversely affect all three with the latter leading to more frequent operation of the Thames Barrier.

- Water resources - reduction in summer soil moisture (affecting plants and animals and their habitats), lower summer and higher winter flows in rivers (with lower summer flows aggravating water quality problems, especially following heavy storms) and increased domestic water demand.
- Air quality - a reduction in air quality leading to possible health problems and potential deleterious effects on urban trees and urban fabric.
- Biodiversity - changes in the distribution of species and the places they inhabit.

In relation to social impacts, the study found that:

- on balance the social impacts of climate change upon London are probably more negative than positive.
- there are, however, some potentially significant benefits for a number of sectors such as tourism and leisure where increased temperatures could attract more visitors to London.
- there are some but, in the majority of cases, fairly small benefits for a number of sectors including transport (less ‘cold weather’ disruption), housing (warmer winters should reduce winter fuel bills), history & cultural legacy (changes in flow patterns in the river Thames potentially uncovering more archaeological remnants), jobs (e.g. opportunities in the tourist industry and in emergency services and urban planning and design), health (fewer cold-weather related illnesses) although these are often offset by larger negative impacts.
- the more negative impacts arising from housing, redevelopment, built environment, health, clean city (relating to air quality and decay of household rubbish), cost of living (including insuring properties) and open and green spaces are all uncertain, in part because the scale and precise character of the impact depends on the adjustment and adaptation responses. However, most of the larger negatives are attributable to potentially increased flooding, greater incidence of summer heat waves, exacerbation of existing air pollution problems and increased pressures upon open and green spaces from water shortages and greater water use.
- suitable adaptation policies and management could limit the incidence of the most negative impacts.

The study has also identified the following economic impacts for London:

- the increased flood risk to areas of London, already vulnerable to river and drainage flooding, from higher rainfall intensities predicted in the climate change scenarios, poses a threat to many economic assets, including property and communication infrastructure.
- flood risk to buildings and infrastructure - along with changing atmospheric conditions associated with a warmer climate - present immediate challenges in

building and urban design. These climate change issues do not relate only to London.

- The London insurance industry, as one of the three largest global insurance centres, is particularly exposed to an increased volume of claims from business and domestic customers that are likely to occur in the event of higher and more extreme wind storms and flood events. Since UK insurers offer greater insurance protection for weather-related damage than their competitors elsewhere, they are, consequentially, more exposed to climate change effects.
- the economic costs of weather-related disruption to London transport systems was the economic impact most widely identified by stakeholders in the consultation process.
- the net balance of change in energy demand as a consequence of climate change in London is not clear. The supply infrastructure network is vulnerable to windstorms and clay shrinkage. The economic impacts of disruption to the power supply for extended periods has not been estimated in quantitative terms but is believed to be significant.
- manufacturing is subject to disruption of raw materials (e.g. food stuffs) that are supplied from parts of the world adversely impacted by climate change.
- revenues from tourism may increase as London - and the UK - becomes a more attractive destination in summer relative to those in Southern Europe and elsewhere that are likely to suffer from adverse climate change impacts. However, more trips may be taken from London to escape uncomfortably high temperatures due to heat island impacts.

Increased general awareness of potential and actual climate change impacts in London is likely to focus policy makers minds on the need to mitigate and adapt to such impacts locally and globally in the future. Indeed, many of the key strategic and policy processes have begun to consider the potential impacts of climate change. Awareness of climate change issues amongst stakeholders involved in this study was high and is accelerating. However, most of the strategy and policy responses are of a scoping nature and more work needs to be done to begin to quantify the potential climate change impacts and adaptation options at the local level including impact on water resources, flooding, water quality, settlement patterns, employment, working conditions, open spaces, infrastructure, economic sectors, biodiversity, economic sectors, health and the built environment.

1. Setting the Scene

1.1 Background and Objectives

This study is the first stage in trying to understand what may happen because of possible future climate change in London. It was commissioned by the Greater London Authority (the GLA), acting as an agent for the London Climate Change Partnership (a stakeholder group which has evolved from a meeting originally convened by the Government Office for London to discuss climate change in London in July 2001; a list of organisations that have taken part in meetings of the Partnership from 2001 onwards given in Appendix B). The study has been undertaken by a project consortium consisting of Entec UK Ltd, Dr. Rob Wilby (Kings' College London), the Tyndall Centre for Climate Change Research, Metroeconomica and Professor David Crichton (Independent Consultant).

The overall objectives for the study, as stated in the original tender documents were as follows:

> *"The study should outline the threats and opportunities presented by climate change, and start to address the responses needed. Investigating the policies and programmes needed to adapt to climate change in detail will be the subject of a subsequent (Stage two) study."*

This stage one study has also provided a platform for addressing the principal aims of the London Climate Change Partnership, which are:

1. To provide an overview of the best current information on the likely climate change scenarios for London.
2. To provide an overview of the existing information on the impacts of climate change on the environment and the economy and, to elucidate the social impacts of climate change largely based on existing reviews, research and monitoring studies within and outside the region.
3. To build a consensus view among key stakeholders about the likely direction and level of climate change in London and to assess the impacts of such change on London, its population and businesses.
4. To provide relevant input to ensure that policy responses are appropriate to the needs of London's population and economy.
5. To raise awareness amongst London institutions, businesses and communities that might otherwise not be aware of the implications of climate change and, in this way, ensure an increased understanding of the common issues faced by all of London in the event of various climate change outcomes.
6. To make proposals for further research and information collection to develop a better understanding of the type and extent of potential impacts.
7. To disseminate the results of the study effectively to those who need to take action.

The following sections address these aims.

There are two study reports. This report, the Draft Technical Report, describes in detail the study's findings and is aimed at the more specialised reader and those involved in more detailed planning.

1.2 Why London is Different

There are several features that distinguish this London study from other regional climate change studies:

- This is the first UK climate change impacts study with a distinctly urban focus. As a result, it has identified a number of climate change impacts that have received less attention in previous regional studies - such as impacts on air quality, transport infrastructure, buildings and the financial sector. As an increasing proportion of the world's population lives in cities, how the world's major cities are affected becomes increasingly important;
- London is not only the capital of the UK but a major world city. Changes to the world's climate will affect all parts of our globe. This will fundamentally affect the environmental, economic, social and political drivers that influence London;
- The Urban Heat Island effect exacerbates many impacts of climate change in London;
- Climate change impacts on buildings and the built environment, water resources, transport, parks and gardens, air pollution and tourism, are all exacerbated in London compared to other UK cities and regions. A population density twice that of most other UK cities exerts strong pressures upon these resources, systems and sectors;
- London's population has a diverse social structure and climate change will be likely to affect vulnerable social groups disproportionately (for example those on lower incomes may be more significantly affected).

1.3 Report Structure

This report starts by defining climate change and describing the baseline climate and environmental conditions in London (Section 1 and 2 respectively). This baseline provides the platform for subsequent discussions of regional climate change scenarios (Section 4) and associated environmental, social and economic impacts (Sections 5 to 7 respectively). This structure reflects the project methodology (see Appendix C) whereby environmental, social and economic impacts of climate change on London were addressed as three discreet (but related) workstreams involving key stakeholder workshop discussions. For this reason climate change issues such as flooding appear separately within each of Sections 5 to 7. However, Section 8 provides an overall summary of climate change impacts and possible adaptation options by combining impacts from all workstreams. Section 8 also addresses climate change in relation to policy issues relating to London and also provides recommendations for further research. Overall study conclusions are presented in Section 9.

It should be drawn to the attention of the reader that there are a number of climate change related issues for which little published information was available, or they were not considered as high priority issues by the stakeholders involved in this study, or there was neither the time nor the resources available to cover the issues. Such issues include areas such as infrastructure and food supply. These issues are covered in the report as they arise and have not been drawn out specifically for detailed consideration. However, the LCCP would welcome any comments relating to these and any other issues discussed within this report. It should also be noted that some issues will be found in more than one section.

2. What is Climate Change?

2.1 Climate Change – An Introduction

The earth's climate has been changing throughout its history and, until now, this has been mostly due to natural causes.

The atmosphere maintains the earth's temperature range by trapping a certain amount of the incoming energy from the Sun. The amount of energy that is trapped depends on the proportion of different gases in the atmosphere, which in turn determines the earth's temperature. A particular mixture of gases maintains the temperature within the range that supports life. Changes in the proportion of gases can alter the earth's temperature and hence weather patterns which are also influenced by the earth's geography (oceans, mountains, land masses etc). Thus the atmosphere needs a certain proportion of greenhouse gases (called the greenhouse gas concentration) in order to maintain an acceptable temperature range and hence support life.

There are concerns that because human activities have led to an increase in the levels of greenhouse gases in the atmosphere, the climate is changing beyond its natural variability. Climate change studies try to understand these changes and how they could affect us. This is done by looking at historical meteorological measurements, such as temperature and rainfall, and looking for changes beyond what can be considered natural. Computer based models are then run that try to describe the behaviour of global weather system due to increases in greenhouse gas levels. This is a complex task, as no model can hope to fully describe what is happening or could possibly happen with the weather. However the models are improving and are beginning to be able to more accurately describe what has been recorded historically and thus scientists are becoming more confident that such models are able to predict future changes. These models produce a range of possible events or scenarios, as there is no exact answer to what may happen with the climate. They produce estimates of future climate such as rainfall and temperature. This information can then be used to estimate what the impacts of climate change could be such as the effect on water resources and flooding. Less rainfall could reduce water resources. This in turn could affect agriculture, industry and domestic supplies. More rainfall could increase flooding, leading to damage to buildings and land. Changes in temperature could lead to changes in agriculture with different types of crops being grown and changes in the length of the growing and harvesting season. Many animal and plant species are sensitive to climatic factors, so changes in temperature and rainfall could also affect flora and fauna.

So, the scenarios can be used to help plan future programmes that may be affected by climate change such as where people live, the need for flood defence and water storage. However, climate change is not the only change that is happening. There are other changes brought about by social and economic trends. In some cases climate change may have only a minor impact and in others it may be more significant. In some cases climate changes may be beneficial and in other it may be adverse. Therefore consideration of possible future climate changes should be undertaken as part of the consideration of the wide range of issues that may affect organisations and people in the future.

In this study historical measurements of the London climate are examined to try to identify any trends in climate changes. Computer models have also been run to describe a range of possible scenarios for climate change in the future. The potential impacts of these climate changes are also described. These are presented in the following sections. The first section describes the evidence for climate change at the international and national levels and the organisations that have been set up to monitor and respond to climate change.

2.2 Progress with Climate Change at the International Level

The Intergovernmental Panel on Climate Change (IPCC) was set up in 1988 and is a joint organisation of the United Nations Environment Programme (UNEP) and the World Meteorological Organisation (WMO). It is a group of international scientists and policy makers who have been assessing the latest research and implications of climate change. Their second report on climate change in 1995 stated that observations suggest:

> *"a discernible human influence on global climate". This means that climate change is happening and that human activities (especially those that lead to greenhouse gas emissions) are contributing to this.*

The Chairman of the Intergovernmental Panel on Climate Change (IPCC), Robert T Watson, stated in his report to the Fifth Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) in Bonn, November 1999:

> *"…let me remind you that it is not a question of whether the Earth's climate will change but rather when, where and by how much…"*

Against the background of overall demonstrable climate change, much work is being undertaken to understand the specific "*when, where and how much…*" questions of climate change both at the UK national level and at the sub national/regional level.

In 2001 Working Group I of the IPCC Third Assessment Report (TAR) presented an even stronger case for the link between human influence and climate change. In the Summary for Policymakers' Report of Working Group I of the IPCC (2001a, p19-20), the authors arrived at the following conclusions:

- An increasing body of observations gives a collective picture of a warming world and other changes in the climate system.
- Emissions of greenhouse gases and aerosols due to human activities continue to alter the atmosphere in ways that are expected to affect the climate system.
- Confidence in the ability of climate models to project future climate has increased.
- There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities.
- Human influences will change atmospheric composition throughout the 21st century.
- Global average temperature and sea level are projected to rise under all IPCC scenarios.

Anthropogenic climate change will persist for many centuries. The TAR also emphasises the importance of understanding the implications of climate change at the regional level. One of the organisations that runs computer models to estimate future climate change at the global level is the UK's Hadley Centre for Climate Prediction and Research. These models are used by the IPCC. The work of the Hadley Centre is briefly described in the next section.

2.3 Progress with Climate Change at the National Level

The UK Climate Impacts Program (UKCIP), set up by the Government in 1997, seeks to develop an integrated approach to impact evaluation in the UK by working with decision-makers. UKCIP provides tools for use in impacts studies, notably the UKCIP climate change scenarios, produced by:

- The Hadley Centre for Climate Prediction and Research, which sits within the Met Office and develops computer models to predict future climate changes based on extensive monitoring and research.
- The Tyndall Centre for Climate Change Research, based at the University of East Anglia, which has a focus on trans-disciplinary climate change research - both mitigation and adaptation - within the context of sustainable development.

The latest UKCIP Climate Change Scenarios report, produced in April 2002, presents a set of four scenarios for future climate change in the UK. These are discussed in Section 4. These scenarios are based on our current understanding of climate change as developed by the Hadley Centre and provide a common starting point for assessing climate change vulnerability, impact and adaptation in the UK.

A number of studies have been, or are being, carried out to interpret the impacts of the scenario climate changes at the regional level. These include studies for Scotland, the North West England, the South East England, Wales, East Midlands, West Midlands, Northern Ireland, Yorkshire and Humber as well as a major conference on climate change impacts in South West England. This London scoping study follows on from the other regional studies under the umbrella of the UKCIP. Studies are also being carried out into sectors that could be vulnerable to climate change such as biodiversity, natural resources (the MONARCH study), health, gardens, water demand, built environment and the marine environment. These studies have been reviewed and information from them, where relevant, has been used in this technical report.

3. Baseline Climate and Environment

3.1 Introduction

The south-east of England enjoys a near continental climate that is most pronounced in the Thames Valley. The region is relatively sheltered from the influence of mid-latitude depressions and, as a consequence, is one of the driest and sunniest parts of mainland Britain. Around the Thames estuary annual rainfall totals average just 500 mm, compared with 600-650 mm across the Thames Valley, and over 1000 mm on the South Downs (Mayes, 1997).

Unfortunately, the climate of London also favours the development of photochemical smog arising from the production of ozone in the presence of pollutants from vehicles and the catalysing effect of sunshine. Extensive urban and suburban landscapes mean that under light winds and little cloud cover, a heat island may develop too, further aggravating local heat stress (Oke, 1987). This is because the urban fabric changes the energy and radiation balance, hydrology and airflow characteristics relative to rural and suburban sites.

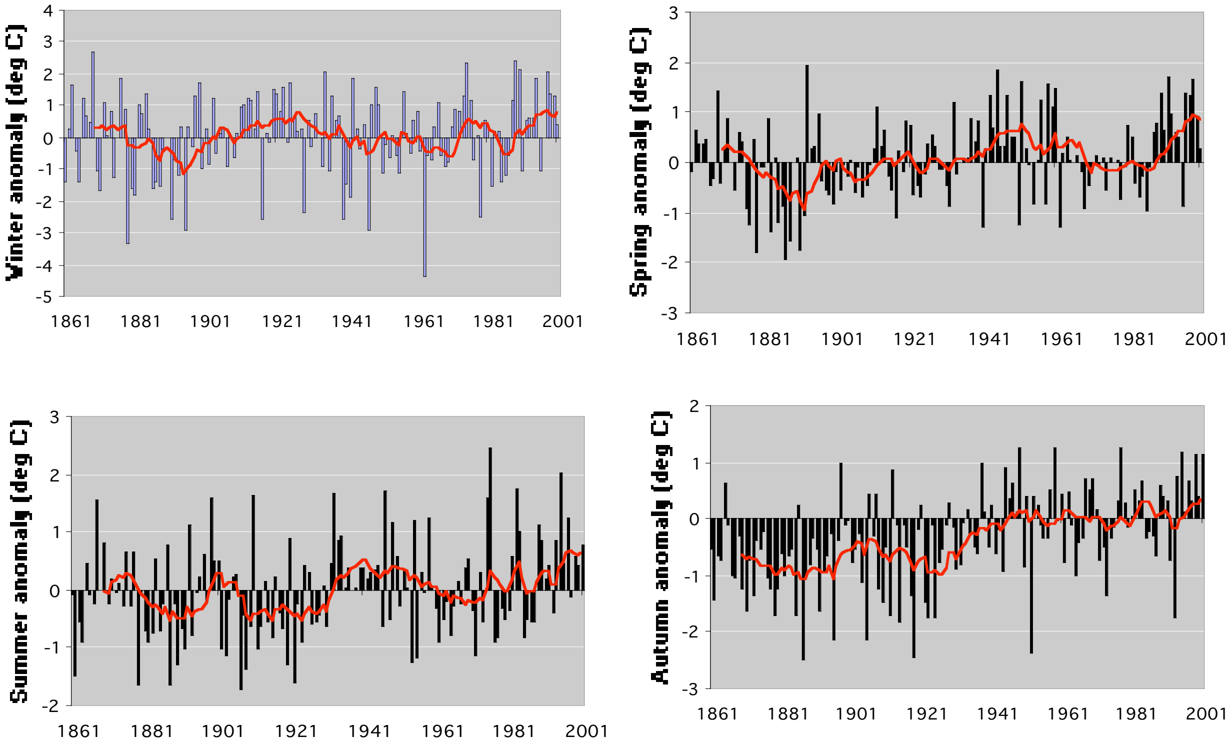
The relatively small area and general paucity of homogeneous climate records for central London, coupled with the artificial heat island, complicates the task of climate change detection and attribution for this urban locale. Where possible, composite records have been employed and/or artificial influences accounted for. However, the importance of recognising data inconsistencies when searching for climate related trends can not be over-stated (Davis, 2000). Regression approaches to trend analysis have also been avoided as the linear form is not necessarily the most appropriate, and because resulting trends can depend on the sub-period of data used.

With these issues in mind, the available evidence has been organised in two parts: Sections 3.2 to 3.5 describe the most important changes in driving climate variables, whilst Sections 3.6 to 3.11 describe contemporaneous changes in selected environmental indices. This information provides the baseline for subsequent discussions of regional climate change scenarios and associated impacts. The section concludes with a summary of the key issues and trends.

3.2 Temperature

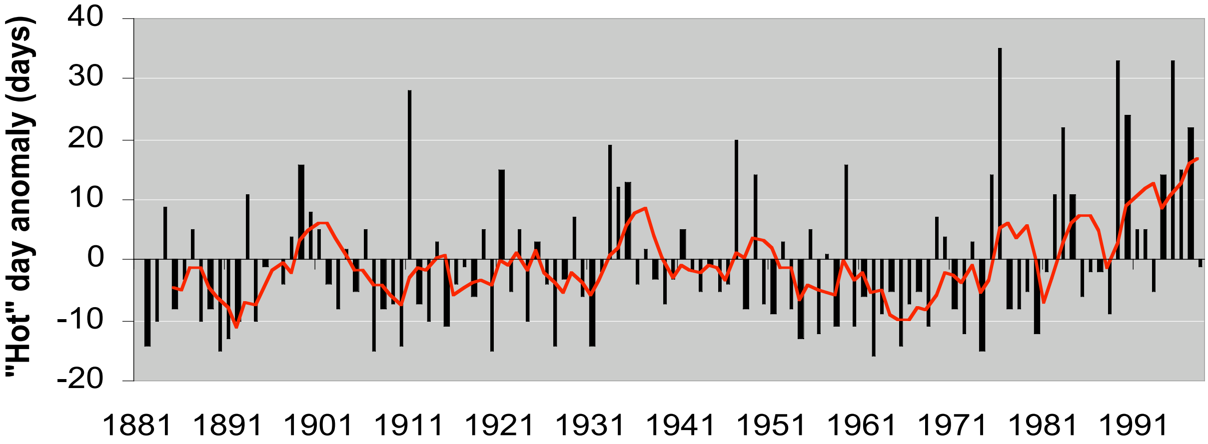
The Central England Temperature (CET) series is the longest instrumental climate record in the world. The monthly catalogue extends back to 1659 and provides a unique insight to climate variability in the UK (Manley, 1953; 1974; Parker et al., 1992). Although the CET record describes temperature changes in the Midlands it is indicative of the signal of temperature change over the Thames Region, and is also untarnished by urban heat island effects. Figure 3.1a shows the record of winter (December to February), spring (March to May), summer (June to August) and autumn (September to November) mean temperature anomalies for the CET from 1861 to 2001. During the 20th Century annual mean temperatures showed a warming of +0.6ºC, with six of the warmest years in the 20th Century occurring since 1989: 1999, 1990, 1997, 1995, 1989 and 1998. Relative to 1961-90 all these years were between 0.9 and 1.2ºC warmer than average. The years 1994 and 2000 were also unusually warm with anomalies close to +0.8ºC. Within the year, warming has been greatest from mid-summer to late autumn: July (+ 0.8ºC), August (+ 1.2ºC), September (+0.9ºC), October (+ 1.2ºC) and November (+1.3ºC) respectively.

Figure 3.1a **Central England Temperature record for the post-industrial period, 1861-2001. The anomalies (or departures from the mean) are relative to the 1961-1990 average.**



The daily CET has been used to investigate the annual frequency of days classified as ‘hot’ (mean temperature above 20ºC) or ‘cold’ (mean below 0ºC) since 1772 (Hulme and Jenkins, 1998). Since the 18th Century, the number of cold days has fallen from around 15-20 per year to around 10 per year presently. Most of this change occurred prior to the 20th Century and is, therefore, probably unrelated to human influences on climate. At the same time, there has been an imperceptible rise in the frequency of hot days in the 20th Century, despite 1976, 1983, 1995 and 1997 returning some of the highest frequencies of such days. Daily maximum temperature data for Kew are also suggestive of a greater number of hot days since the 1970’s (Figure 3.1b), but the site may well reflect urban heat island effects (see below). The daily CET also indicates that the growing season for plants has increased by about 30 days since 1900 (Mitchell and Hulme, 2002), and that central England presently enjoys longer frost-free spells than at any time during the pre-industrial era (Wilby, 2001).

Figure 3.1b **Annual frequency of hot days (daily maximum > 25ºC) at Kew, 1881-1998. Anomalies are relative to the 1961-1990 average.**



As noted above, central London can be several degrees warmer than surrounding rural areas due to the urban heat island effect (Lee, 1992). For example, the average peak temperature difference between the British Museum and a rural reference station in Langley Country Park (about 30 km west) was 3ºC over the summer of 1999 (Graves et al., 2001). Increased urban temperatures have an impact on the summer cooling demand in relation to the 'intensity' of the heat island – defined as the peak difference between urban and rural temperatures. Detailed monitoring indicates that the heat island is most pronounced at night, that it weakens with increasing wind speed and distance from central London, and that the location of the thermal maximum shifts with changes in wind direction (Graves et al., 2001). Figure 3.2a shows that the heat island is also highly changeable from one day to the next (as a consequence of variable weather patterns), attaining differences of up to 7ºC between St James's Park and Wisley on some nights. The annual number of nights with intense heat islands (defined herein as greater than 4ºC) has been climbing at a rate of over four days per decade since the late 1950's (Figure 3.2b). The average nocturnal heat island intensity increased at the rate of 0.1ºC per decade over the same period. Conversely, the number of intense day-time heat-islands has declined to about one event per year since the mid 1980's (Figure 3.2c).

Figure 3.2a Difference in nocturnal minimum (left column) and day-time maximum (right column) daily temperatures between St James's Park (central London) and Wisley (rural Surrey), July to August 1995.

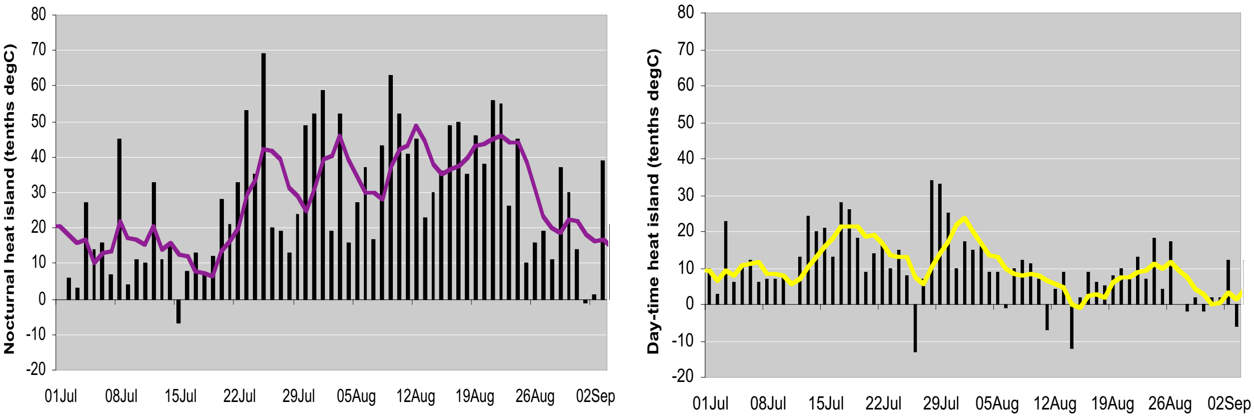


Figure 3.2b Annual frequency of days with nocturnal heat island intensity greater than 4ºC (left column), and annual average nocturnal heat island intensity (right column) between St James's Park (central London) and Wisley (rural Surrey), 1959-1998. Note: data for November-December 1998 are missing.

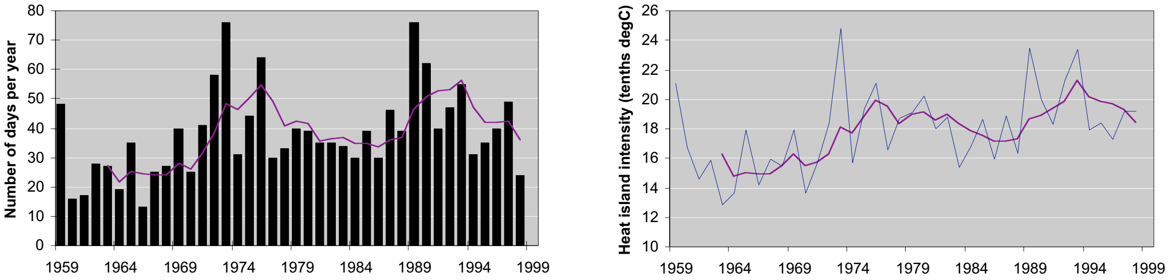
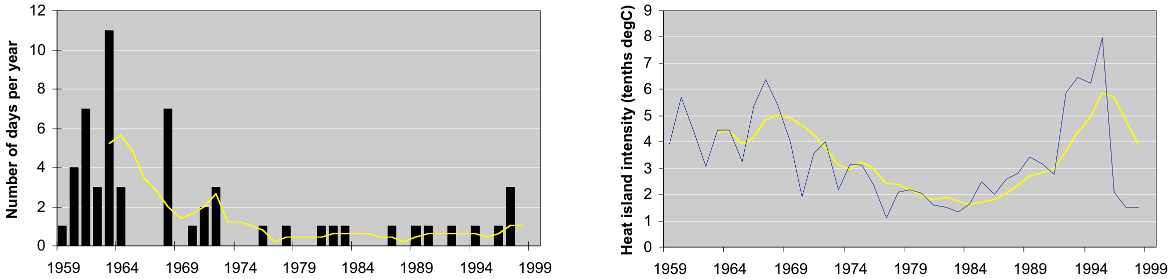


Figure 3.2c As in Figure 3.2b, but for day-time maximum temperatures

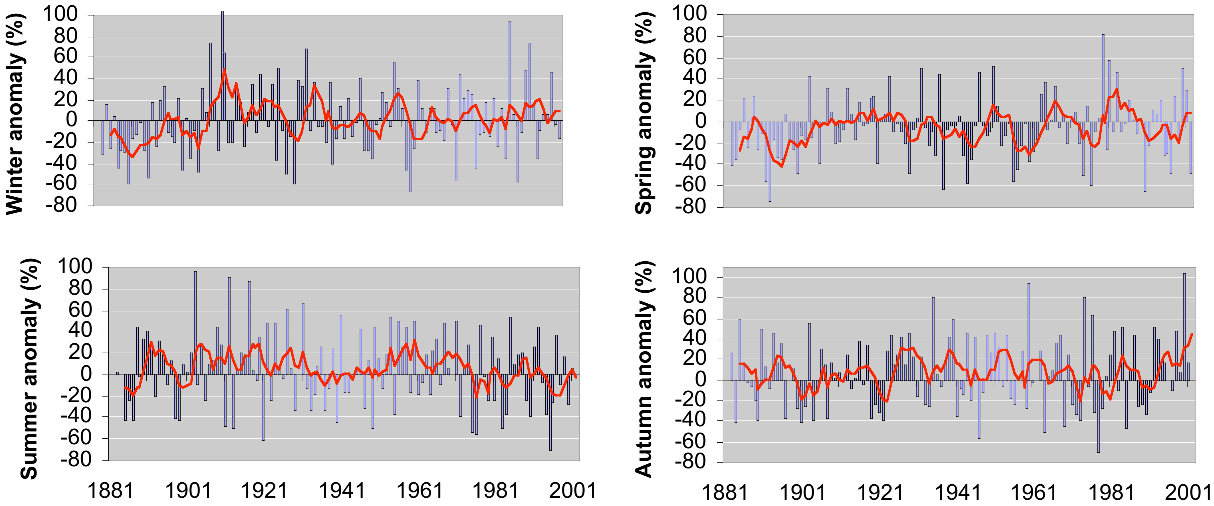


3.3 Precipitation (including snowfall)

Individual precipitation records are particularly susceptible to local conditions, instrumentation and observer practices. The detection of precipitation trends at single stations is also confounded by inter-annual variability (i.e., there is a high level of 'noise' relative to 'signal'). Therefore, recent precipitation trends for the Thames Region were analysed using a composite record of 12 gauges from 1883 (Davis, 2000). This data set also better reflects the Thames-wide water resource context of London.

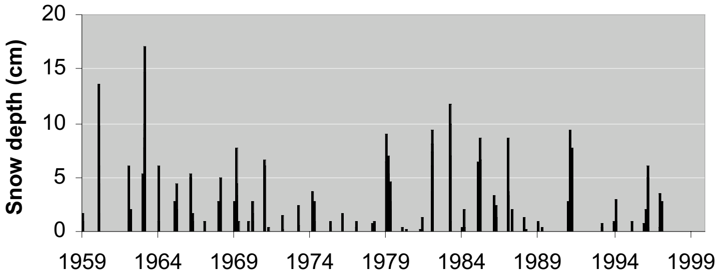
Annual water year precipitation totals (October through following September) for the Thames region indicate a slight but statistically insignificant increase since the 1880's. However, relative to the 1880's winter precipitation has increased by 11% and summer has declined by 10% over the same period (Figure 3.3). The largest changes in monthly precipitation totals have occurred in January (+28%), April (+27%), September (+36%), and July (-26%), but much of the apparent increase is due to the cluster of dry winters and springs in the first few decades of the record (see Brugge, 1993).

Figure 3.3 River Thames seasonal precipitation totals, 1883-2001



Nonetheless, the summers of 1995 and 1976 were still two of the three driest since the 1880's, with seasonal totals respectively –70% and –56% below the 1961 to 1990 average. The second driest summer on record occurred in 1921 and had an anomaly of –62% (see Table 3.1). Conversely, the wettest winters were 1914/15 (+ 112%), followed by the much celebrated winters of 1989/90 (+94%) and 1994/95 (+73%) (see Marsh and Monkhouse, 1993; Marsh and Turton, 1996). A further feature of recent winters has been the steady decline in snowfalls. Since the 1960's the frequency of snowfall in south east England has fallen from 45 days per decade, to 39 in the 1970's and 1980's, to just 23 in the 1990's (see also Wild et al, 1996; 2000). Average areal snowfall depths across the region have also declined in recent decades (see Figure 3.4).

Figure 3.4 Snowfall depths in southeast England, 1959-1999. The composite was derived from observations at Cambridge, Dover and Oxford.



Source: O'Hare and Wild (pers. comm.)

Table 3.1 The five most severe droughts of different duration in the Thames Region defined using the Standard Precipitation Index (from Wade et al., 2001)

Rank	Duration				
	3 months	6 month	12 months	24 months	48 months
1	1938	1976	1976	1992	1891
2	1929	1921	1921	1935	1976
3	1893	1929	1922	1934	1901
4	1976	1938	1934	1997	1992
5	1989	1892	1898	1922	1890

Changes in daily precipitation occurrence and wet-day amounts are also relevant to many environmental processes. Since the 1900's there has been no trend in either the frequency of winter rain days or the average length of wet-spells, or persistence of rainfall in the Thames Region (Figure 3.5a). The observed inter-annual variability is consistent with large-scale, atmospheric circulation changes over the North Atlantic (Wilby et al., 1997). Similarly, neither summer rainfall frequencies nor dry-spell persistence exhibit clear trends since the 1900's (Figure 3.5b). However, the 1980's witnessed above average numbers of summer rain days, whilst dry-spell persistence has increased slightly since the 1960's. This suggests that the downward trend in summer rainfall totals (Figure 3.3) is partly driven by fewer rain days.

Figure 3.5a River Thames winter rain day frequencies and wet-spell persistence, 1904-2001. Anomalies are relative to 1961-1990 average. A wet-day is defined as >0.3 mm/day.

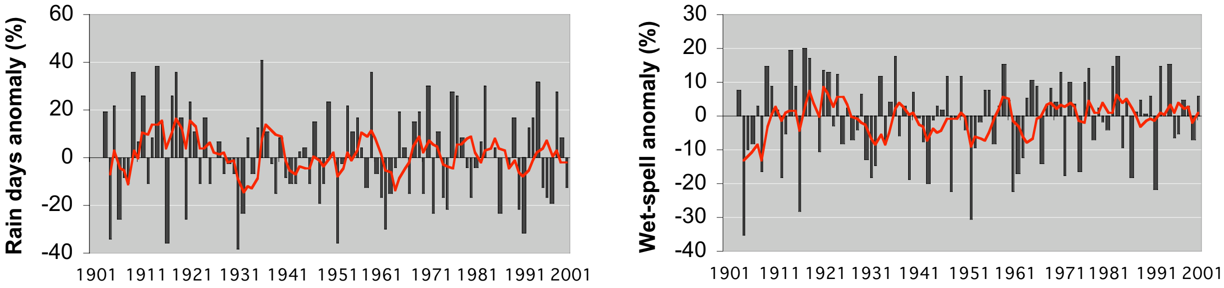
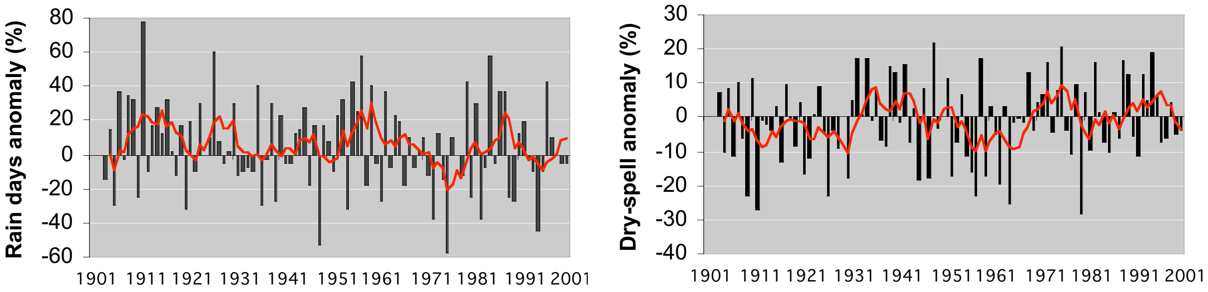
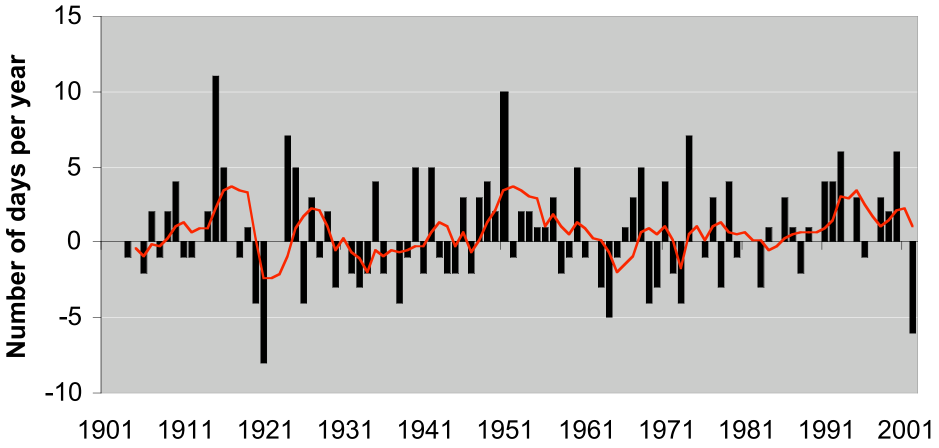


Figure 3.5b River Thames summer rain day frequencies and dry-spell persistence, 1904-2001. Anomalies are relative to 1961-1990 average. A wet-day is defined as >0.3 mm/day.



The variability in Thames rainfall should be viewed alongside other studies showing that heavy rainfall events have contributed proportionately more to winter, spring and autumn precipitation totals than light or intermediate storms since the 1960's (Osborne et al., 2000). Conversely, summer rainfall totals have been increasingly dominated by light and moderate precipitation events, leading to a slight reduction in mean intensities during this season.

Figure 3.6 **Number of days with precipitation above 12.5 mm/d across the Thames Region, 1904-2001. Anomalies are relative to 1961-1990 average.**



The frequency and seasonality of heavy rainfall events contributes to riverine flooding and the exceedence of sewerage capacity. Figure 3.6 shows no consistent trend in the number of heavy rainfall events (over 12.5 mm in a day averaged across the Thames Region – an event that on average occurs 9 times per year). Even when broken down to individual seasons, only autumn shows a small but statistically insignificant increase in such events, amounting to less than one extra day per century.

3.4 Gales

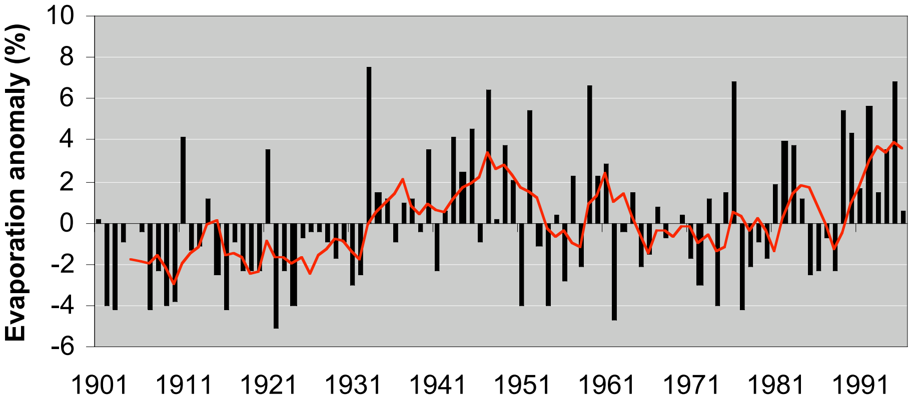
On 16 October 1987 the south east was struck by arguably the most severe storm since 1703 resulting in several fatalities, widespread loss of electrical power, and destruction of woodland (Burt and Mansfield, 1988). However, record wind speeds of 1987 at Kew Gardens (59 knots), were soon surpassed during the storm of 25 January 1990 (71 knots) which struck during daylight hours, leading to severe traffic disruption in London. Despite their significance to infrastructure, long homogeneous records of gale activity are difficult to develop. Nonetheless, Jones et al. (1999) used adjusted grid–point mean–sea–level pressure data to calculate a simple index of gale activity over the UK for the period 1881–1997. This record shows no long–term trend, but the average frequency of severe gales did attain a maximum in the 1990's (corresponding to the pronounced westerly phase of the North Atlantic Oscillation during that decade).

3.5 Potential Evaporation and Relative Humidity

Changes in actual and potential evaporation (PE) have implications for effective rainfall volumes, soil moisture and water resources. However, accurate, long term estimates of these water balance terms are seldom available because of station closures, changes in instrumentation and data inconsistencies. A thorough review of potential evaporation (PE) data was recently undertaken for the Thames Region (Davis, 2000). This analysis concluded that there have been significant increases in PE (Penman method) at Kew since 1871, and for PE (Thornthwaite method) using CETs since 1659. The strongest trends exist in spring and autumn, although all seasons and annual totals show significant increases (Figure 3.7), consistent with observed temperature rises. Indeed, annual PE totals in southern England often exceeded 700 mm in the 1990's – values more typical of western France (Marsh, 2001a).

In contrast, summer relative humidity has generally declined since the 1920's, with exceptionally low humidity values in August during the last two decades (Carter and Robertson, 1998). The Cranwell–Waddington relative humidity series indicates that occurrences of low humidities are becoming more frequent but not necessarily more intense (Lockwood, 2000). However, exceptionally low summer humidities in 1933/34, 1975/76 and 1989/90 were all connected with widespread regional drought.

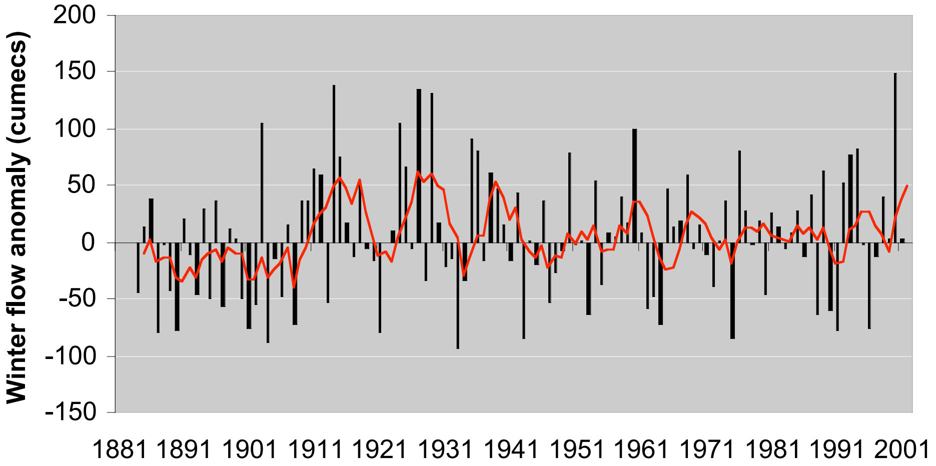
Figure 3.7 **Oxford annual potential evaporation anomaly estimated using a modified Thornthwaite method, 1901-1996. Anomalies are relative to 1961-1990 average.**



3.6 River Flows

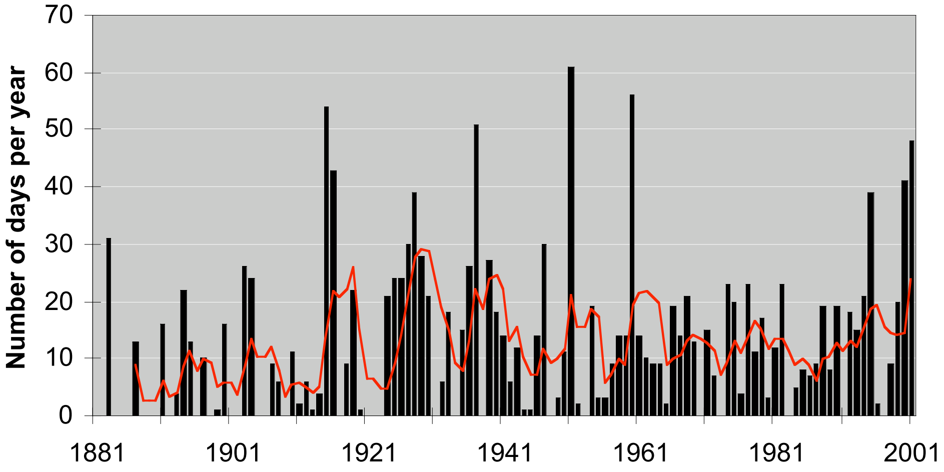
The detection of trends in river flow series is highly problematic because most hydrological records tend to be short (<30 years duration), river flows are typically highly variable from year to year, land-use changes may amplify or conceal climate change signals, and flow regulation, surface and groundwater abstraction mean that the flow regimes of most rivers are dominated by artificial influences (Littlewood and Marsh, 1996; McCabe and Wolock, 1997). Following an analysis of river flows from 29 gauging stations in the Thames Region it was concluded that none have any significant climatically induced trends in terms of water year average flows over the period of record (Davis, 2000). Where trends were detected, they could be explained in terms of water imports, urbanisation or changes in gauging structures. With these caveats in mind, Figure 3.8 shows winter and summer flow anomalies in the naturalised record for the non-tidal Thames at Teddington since the 1880's. Although there are no discernible trends in either series, clusters of summers with below average flow are clearly evident in the 1890's, 1900’s, 1940’s, 1970’s and 1990’s. Conversely, the winter of 2000/01 had the highest 90-day river flow volume on record.

Figure 3.8 **River Thames flow anomalies at Teddington in winter and summer (naturalised), 1883-2002. Anomalies are relative to 1961-1990 average.**



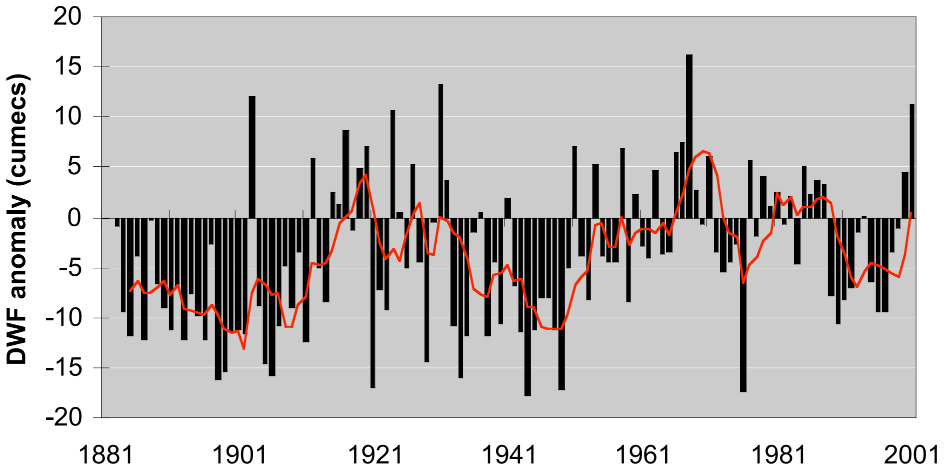
Daily data for Teddington provide an indication of the changing pattern of high flows on the Thames (defined herein as mean daily flows exceeding 250 cubic metres per second, or cumecs). Although the last 30-50 years show strong evidence of increases in the number of high flows, this period is not particularly unusual in the context of the entire record – there have been flow rich periods in the past, most notably the 1920's (Figure 3.9). This is consistent with the national picture of no clear long-term trend in flood peaks, flood volumes or duration of flood flows (Marsh, 2001a, b; Robson et al., 1998). However, the flows of October to December 2000 were the most extreme in terms of England and Wales 90-days totals (CEH and Meteorological Office, 2001). In London two hundred households in Woodford, 75 in Edmonton and Wanstead were flooded (ABI, 2002). In terms of the maximum recorded mean daily flows at Teddington since 1900, the snowmelt event of 1947 was the highest on record (714 cumecs), with the maximum flow of 2000 (464 cumecs) ranked just 50th. The longest duration of flows above 250 cumecs occurred in the winter of 1951 following the wettest February on record (+174% of the 1961-1990 average).

Figure 3.9 **Days with River Thames flow at Teddington exceeding 250 cumecs (naturalised), 1883-2002. Anomalies are relative to 1961-1990 average.**



There is no single definition of hydrological drought (Mawdsley et al., 1994), however, the annual series of seven-day minimum dry weather flows (DWF) is widely employed. Figure 3.10 shows the DWF for the Thames since the 1880’s. The most prominent era of low flows occurred between the 1880’s and early 1900’s, followed by notable droughts in 1921/22, 1933/34, 1943/44, 1975/76, 1988-92 and 1995-97 (see also Jones and Lister, 1998). Using this index of drought, 1976 is ranked 2nd and 1995 as 50th in the entire record. Although the DWF has declined since the late 1960’s there is, again, no clear trend in the overall series for the Thames.

Figure 3.10 Seven-day Dry Weather Flow (DWF) of the River Thames at Teddington (naturalised), 1883-2001. Anomalies are relative to 1961-1990 average.



Note: unmeasured leakage at the Teddington complex prior to 1951 is known to have caused an underestimation of drought flows (Marsh, 2001a).

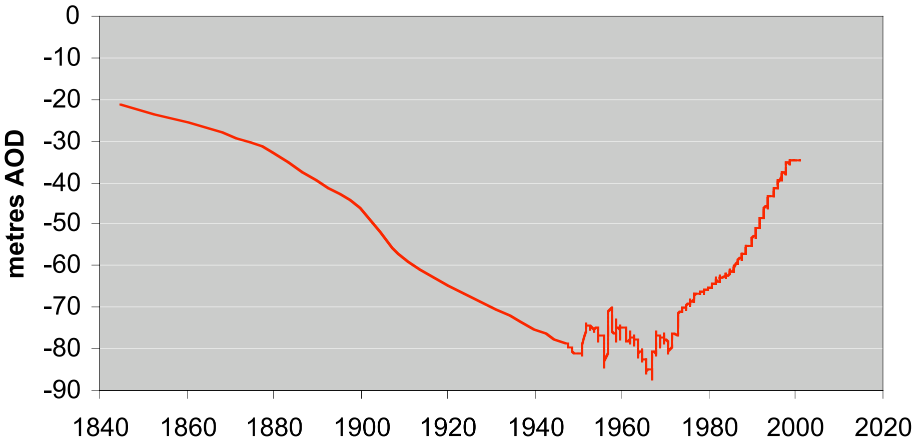
3.7 Groundwater

London is located at the eastern side of the London Basin Syncline, the most extensive chalk aquifer in Britain. For nearly two centuries groundwater has been abstracted from the aquifer mainly for commercial and industrial uses. Groundwater is an essential source of high quality water accounting for 40% of public supply in the Thames Region. Groundwater discharges also contribute to the health of many rivers in the upper catchment (EA, 2001a). Past abstractions resulted in a progressive dewatering of the aquifer under London, and a fall in groundwater levels to a minimum in the 1940's and 1950's (Figure 3.11).

Thereafter, reduced abstractions lead to a reversal of this trend, such that water levels are now rising at up to 2.5 m per year, threatening tunnels and building foundations in central London (EA, 2001b). The General Aquifer Research Development and Investigation Team (GARDIT) is an informal group of interested parties derived from its three original members, Thames Water, London Underground Ltd and the Environment Agency. This group was set up to address the rising groundwater problem. One of the proposals of the GARDIT group was controlling the rise by pumping which could yield an additional source of 30-50 Ml/d water to supply (EA, 2001c).

Conversely, the chalk aquifer to the north east of the Thames Region has been adversely affected by groundwater abstraction at unsustainable levels and by periods of prolonged dry weather (EA, 2001a). Long-term records at the Cholgrove House borehole in West Sussex and at Therfield in Hertfordshire (where artificial influences are minimal), in contrast, are characterised by remarkable stability throughout the 19th and 20th Centuries (Marsh, 2001a).

Figure 3.11 Groundwater levels at Trafalgar Square, 1845-2001

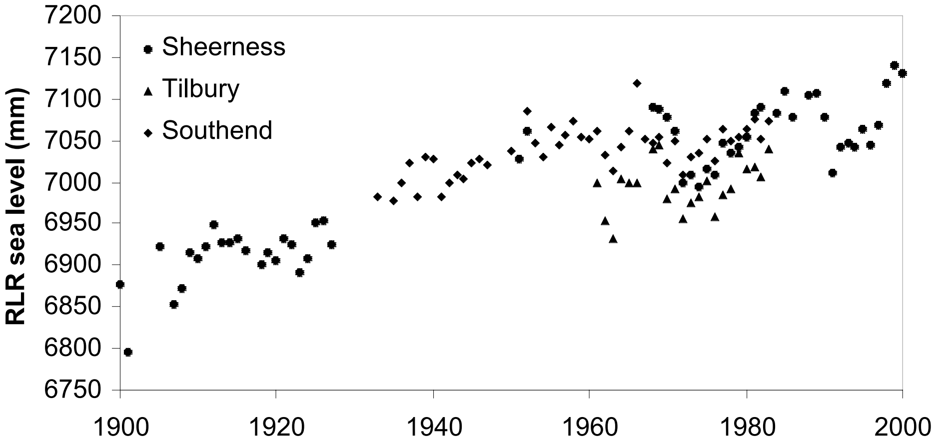


Potable groundwater resources may be impacted adversely by a range of residues originating from agriculture, landfill or accidental spills. Concentrations of nitrates, phosphates and total organic carbon are generally low in the London chalk aquifer due to the clay cover protection from surface pollutants. However, localised contamination by solvents and hydrocarbons has occurred via existing boreholes and other conduits. Shallow groundwater has also been contaminated by urban waste within the gravels aquifer (EA, 2001b).

3.8 Tidal Levels

An anticipated consequence of global warming is a rise in mean sea-level, due to the thermal expansion of ocean water and the melting of land glaciers (Woodworth et al., 1999; Shennan, 1993). Since 1933, the Permanent Service for Mean Sea Level (PMSL) has been responsible for the collection, archiving, and analysis of sea level data from a global network of tide gauges (Woodworth, 1991). This data set currently holds records for over 50 stations around the British Isles, of which about a dozen have records that are at least 30 years in length.

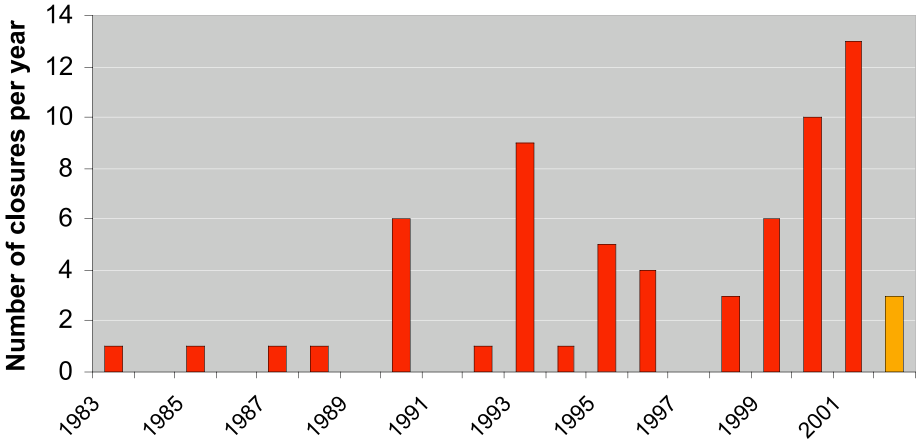
Figure 3.12 Annual mean sea level at Sheerness, Southend and Tilbury, 1901-1999.



Note: in order to construct time series of sea level measurements at each station, the monthly and annual means have to be reduced to a common datum: the 'REVISED LOCAL REFERENCE' (or 'RLR'). This reduction is performed by the PSMSL making use of the tide gauge datum history provided by the supplying authority. The RLR datum at each station is defined to be approximately 7000mm below mean sea level, with this arbitrary choice made many years ago in order to avoid negative numbers in the resulting RLR monthly and annual mean values (see: http://www.pol.ac.uk/psmsl/datainfo/psmsl.hel).

The closest tide gauges to London are at Tilbury, Southend and Sheerness. Figure 3.12 shows the annual mean sea-level at these station since 1901. The combined effects of tectonic subsidence and thermal expansion of the ocean has resulted in an average change in sea-level of +1.44 mm/year. Rising sea levels combined with increased storminess and changes in wave direction and energy, tectonic subsidence and settlement of London on its bed of clay mean that high tide levels in London are rising by about 60 cm per century (EA, 2001b). The Thames Barrier, upstream sea walls, and 32 km of embankments downstream were designed to provide a 1 in 1000 year level of protection to 2030 for London and surrounding areas. Between 1983 and 2001 the Thames Barrier was closed 62 times to protect London from tidal flooding (Figure 3.13). Although the frequency of closure rose steadily during this period(since construction), care should be taken in interpreting this trend, since it is not a long period of record to assess data. The prolonged high river flows of winter 2000/01 resulted in a higher number of closures, since fluvial flow is one parameter by which the need for closure is determined. At present however, it is difficult to determine long term trends based on operating conditions.

Figure 3.13 Number of Thames Barrier closures against tidal surges, 1983-2001

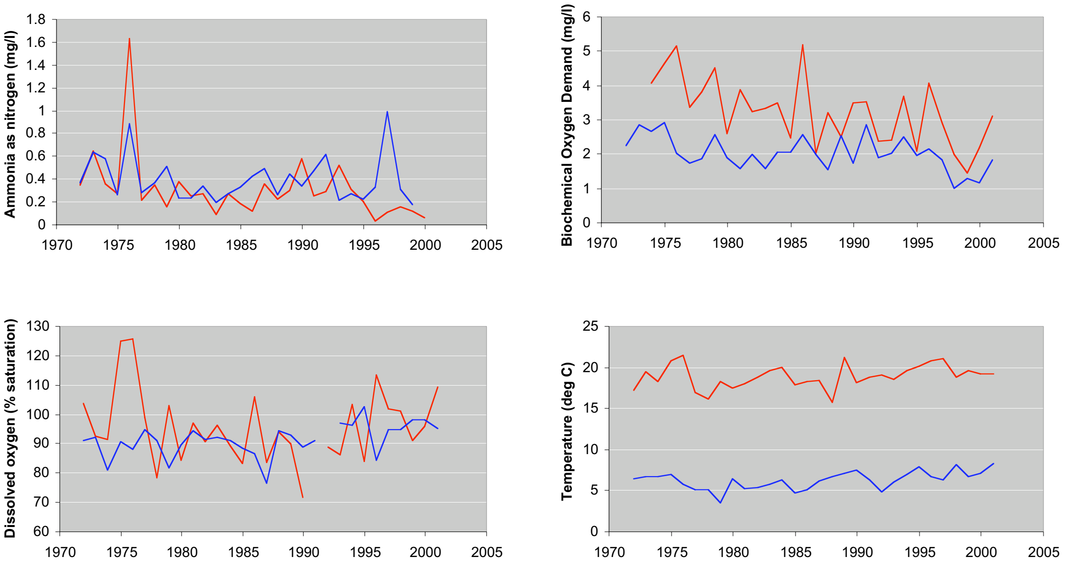


Note: data for 2002 is up to and including 27 April 2002

3.9 Surface Water Quality

The River Thames is now regarded as one of the cleanest metropolitan rivers in the world (EA, 2001b). However, the chemical and biological quality of the London's rivers and estuary is variable due to factors such as changing river flows and urban runoff. The General Quality Assessment (GQA) scheme is used to monitor and assess water quality trends over time and to compare rivers in different areas. The chemical markers of the GQA are defined by standards of dissolved oxygen, biochemical oxygen demand and total ammonia. Overall chemical river quality showed a marked improvement between 1990 and 1995 as flows recovered from the 1989-91 drought, but between 1995 and 1997 quality deteriorated once again as a consequence of the low flows of the 1995 drought (see Figure 3.14). Summary GQA chemical quality data for Thames region shows further improvements in quality for the region's rivers with approximately 60% of monitoring sites showing improvements in water quality from 1990 to 2001 (www.environment-agency.gov.uk) In line with national trends, river water temperatures in the Thames have risen since the 1970's. Rising river water temperatures, particularly in low elevation and slow moving lengths (Webb, 1996) have also been linked to apparent declines in some fish populations and changes in macrophyte communities. For example, at the end of July 2000 extensive algal blooms were recorded between Tower Bridge and Putney.

Figure 3.14 River water quality trends at Teddington in summer (red) and winter (blue), 1972-2001



The GQA scheme for biological quality was introduced in 1995, and monitoring has since shown that the highest quality is found in headwaters, and lowest directly below sewage treatment works outfalls (EA, 2001b). Since 1989, the Agency has used invertebrates and dissolved oxygen as key indicators of chemical water quality of the tidal Thames (and Estuary). Following summer rainfall events, river oxygen levels in the upper and middle reaches of the tideway are severely depleted by increased bacterial activity as organic matter in storm runoff is broken down. As a result of several major fish mortalities between 1973 and 1986, the Thames Bubbler and Thames Vitality have been injecting up to 30 tonnes of oxygen each day at critical locations in the river. Between 1999 and 2000 the vessels were deployed on 55 days, compared with 24 days over the preceding three years. The recent increased usage reflects a combination of higher rainfall and accompanying storm runoff. The organic load discharged during severe storms will, however, be reduced by scheduled improvements to Hammersmith, Western, Lots Road and Abbey Mills pumping stations and at Putney Bridge by 2005 (EA, 2001a). Thames Water's Thames Tideway Strategic Study is currently assessing the environmental impact of storm sewage discharges to the tideway and is also considering what improvements (and associated costs) may be desirable with a view to developing technical solutions. This study recognises that climate change predictions for more frequent storms could, inevitable aggravate water quality problems.

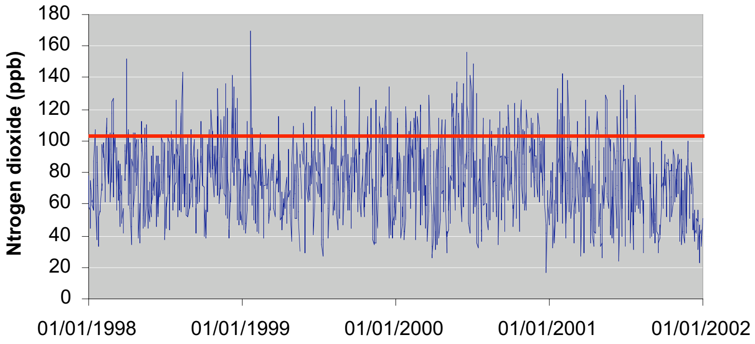
3.10 Air Quality

The Government's National Air Quality Standards (NAQS) represent defined levels of air quality which avoid significant risks to health for eight pollutants (benzene, 1,3-butadiene, carbon monoxide, lead, nitrogen dioxide, ozone, particulates (PM_{10}), and sulphur dioxide). Air quality is monitored by the National Automated Monitoring Networks and Non-automatic Networks at over 1500 sites across the UK, with data available as far back as 1972 for some sites. The reliable detection of air quality trends is complicated by the brevity of data sets, changes in instrumentation, representativeness of monitoring sites and the strong control exerted by weather patterns on pollution episodes (Crabbe et al., 1999; McGregor and Bamzelis, 1995; Scaperdas and Colvile, 1999; Comrie, 1992).

According to the Sustainable Development Unit, DEFRA, there has been a decline in the number of days nationally when air pollution was classified as moderate or high at urban sites from an average of 59 days per site in 1993, to 21 days in 2001. However, air quality remains at unacceptable levels in many parts of London. For example, in Marylebone particulate concentrations exceeded NAQS on over 30 days in 1998 and 1999 (EA, 2001b). Furthermore, a positive correlation has been shown between air pollution and social deprivation in London, with higher concentrations of nitrogen dioxide and particulates found in areas exhibiting higher social deprivation (Pye et al., 2001).

Traffic emissions of nitrogen dioxide and particulates have replaced sulphur dioxide from coal-burning as the most significant air quality problems currently facing London (Eagleson et al., 1992). The highest concentrations of nitrogen dioxide are found in central London (Figure 3.15) and along busy road corridors. Background concentrations of particulates are highest in the east of the Thames Region due to secondary particles, such as sulphate and nitrate formed from chemical reactions in the atmosphere, that originate from mainland Europe. Concentrations of sulphur dioxide are also highest in the East Thames Corridor due to emissions from a number of power stations and a refinery (EA, 2001b). Maximum concentrations of ozone, however, tend to occur at weekends outside of central London due to transportation by wind (Wilby & Tomlinson, 2000), as well as lower concentrations of ozone destroying pollutants (principally nitric oxide) in rural areas. Peak ozone concentrations in central London typically occur under stable summer anticyclonic weather which favours photochemical action (O'Hare & Wilby, 1994).

Figure 3.15 Daily maximum hourly average nitrogen dioxide concentrations (ppb) kerbside at Marylebone Road, 1998-2001. Note: the National Air Quality Standard for nitrogen dioxide is 105 ppb for a one hour mean. This limit should not be exceeded more than 18 times per year.



Data source: National Environmental Technology Centre

3.11 Biodiversity

The word biodiversity has figured prominently in discussions of the environment since the Earth Summit at Rio de Janeiro in 1992, when over 150 countries adopted a Biodiversity Convention. In the present context biodiversity is taken to mean the whole variety of life supported by the wildlife habitats of London. As Table 3.2 indicates, the City contains a number of nationally and internationally important habitats, species of plants and animals. Despite the City's urban character, nature conservation designations apply to 16% of its area, covering a range of habitats including wetlands, woodland, water bodies, heathland, urban wasteland, marshes, and mudflats (Table 3.3). The gardens and parks of London also have an important role in the conservation of wildlife species, not least for their part in the Green Corridor network of the Mayor's Biodiversity Strategy (2002). It is hoped that this network of waterways, canals and railsides will allow some species with specialised habitat requirements to extend their distribution across the City. London is also home to important populations of several nationally rare plants and animals including the stag beetle, greater yellow-rattle, black redstart, burrowing bee and wasp, serotine and noctule bats, the kingfisher, and rare species of fish such as smelt, sea lamprey and the protected twaite shad.

Obvious threats to biodiversity include the degradation and/or loss of wildlife habitats, the introduction and spread of problem species that threaten other wildlife, water pollution, unsympathetic management, and encroachment of inappropriate development (Table 3.4). The recent declines of wildlife species, such as the house sparrow and starling, however, are much harder to explain (Robinson et al., 2001; RSPB, 2000). In addition, many terrestrial and aquatic species are sensitive to the direct effects of climate variability, and/or indirectly through changes in related environmental processes such as river flow (Cannell et al., 1999). For example, several species have recently colonised south-east England or expanded their distribution northward (e.g., the Lesser Emperor dragonfly, Roesel's Bush Cricket, and the Little Egret). Conversely, the salmon population of the Thames suffered a dramatic decline from the peak in 1993 — at least partially due to the recent dry summers and their effect on river flows — but has been making a gradual recovery since 1998 (EA, 2001b). Changes in river flow regimes can, in turn, affect the thermal and chemical quality of waters, on in stream habitat availability, salinity, and on rates/patterns of fluvial and estuarine deposition (e.g., Owens and Walling, 2002; Webb, 1996). Alterations to river flows, substrates, salinity or tidal exposure also have the potential to modify invertebrate communities (Wood et al., 2000).

Table 3.2 Nature conservation designations in London

Status	Location(s)	Importance
Special Protection Area under the European Union Birds Directive.	Walthamstow Reservoirs; Kempton Park Reservoirs.	Internationally important populations of waterfowl.
Special Areas of Conservation under the European Union Habitats Directive (pending).	Wimbledon Common, Richmond Park and Epping Forest.	Stag beetle.
Ramsar sites.	Lee Valley and South West London Waterbodies Special Protection Areas.	Wetlands
Important Bird Areas	Walthamstow Reservoirs, Chingford Reservoirs and Walthamstow Marshes; Kempton Park Reservoirs; Rainham and Wennington Marshes	Bird populations
UNESCO World Heritage Sites (nominated)	Kew Gardens; Down House in Bromley Borough	Natural history resource; Charles Darwin's former home.
Sites of Special Scientific Interest in London (38)	Including Richmond Park and the Inner Thames Marshes; Ruislip Woods and Richmond Park have recently been designated National Nature Reserves.	Ancient woodlands (10), grassland (7), mixed woodland and grassland (3), wetlands (10), heathland and bog (2), parkland (1), and geological interest (5).
Sites of Importance for Nature Conservation	About 140 Metropolitan sites, with a total area of nearly 16,000 Ha (10% of London's land area).	Important wildlife sites as recognised by the London Borough councils.
Sites of Borough Importance	310 Grade I sites, 460 Grade II sites, with a total area of about 12,000 hectares (almost 8 per cent of London's land area).	Local importance, providing people with access to nature close to home.
Countryside Conservation Areas	Various	Small fields with good hedgerows, surviving field ponds, copses and green lanes
Green Corridors	Links between sites and to Green belt by rivers, canals and railside land.	Enabling some species to extend their distribution.
Local Nature Reserves (76)	Various	Intrinsic biodiversity value and local importance.

Source: Mayor's Biodiversity Strategy (2002)

Table 3.3 Selected wildlife habitats in London, their biodiversity significance, associated threats and opportunities

Habitat	Area (Ha)	Location(s)	Importance	Threats	Opportunities
Woodland	7,300	Outer Boroughs such as Bromley; <20 Ha amongst the seven Boroughs along the Thames from Hammersmith/Fulham to Barking/Dagenham.	One of the most diverse habitats; one third classified as ancient; yew, beech and hornbeam; hawfinch, marsh tit, spotted flycatcher; bird's nest orchid, coral-root bittercress.	Threat of clearance; damaged by amenity management and/or public over-use; changes in water regime through drainage or flood control; water and air pollution.	Sympathetic and appropriate woodland planting; promote natural succession to wet woodland at disused mineral workings; pond creation.
Grassland (pasture/meadow)	 11,000	Frequently mown amenity grass widespread; acid grassland in Richmond; chalk grassland in southern Boroughs such as Croydon, Bromley, and Sutton.	Common birds such as blackbird and mistle thrush; unique invertebrate communities; wild flowers, including orchids.	Agricultural improvement; mowing and drainage of rough grasslands; poor management, over-grazing; fragmentation and isolation of habitat; tree-planting; development.	Relaxation or modification of mowing regimes; uncut areas of perennial grasses; sympathetic grazing regime; harvesting of grass as a crop.
(acidic)	1,200				
(chalk)	300				
River Thames and tributaries	2400	Within Greater London boundaries; wetland habitats in the catchments of the Colne, Ingrebourne, Cray and Roding.	Supports 118 species of fish; 450 species of invertebrate in tidal zone; significant populations of ringed plover, dunlin and redshank (downstream), grebes, ducks, herons, gulls, cormorants and terns (upstream).	Water pollution by huge organic loads from storm drains during summer storms; accidental oil or chemical spills; disturbance of sensitive riverside species; encroachment by development; reconstruction of river walls.	Habitat restoration and re-creation; creation of shingle beaches and salt marsh; curtailing of dredging; appropriate riverside development and flood defence schemes; environmental education resource.
Ponds, canals and lakes	1,500+	Former farm ponds; canals to the north of Thames; lakes on former country estates; gravel pits and storage reservoirs.	Diverse populations of fish and common dragonflies; great crested and palmate newts; over-wintering wetland birds; kingfisher.	Redevelopment of canalsides; increased disturbance and recreational pressure; desilting and vegetation clearance; water pollution; infilling and nutrient enrichment; operational activities.	Habitat enhancement and creation schemes; integration within Green Corridor network; pond restoration; flooding of former gravel pits; sympathetic management of operational reservoirs.

Habitat	Area (Ha)	Location(s)	Importance	Threats	Opportunities
Heathland	80	Wimbledon Common and Putney Heath, Poor's Field in Hillingdon, Stanmore Common in Harrow, the Addington area of Croydon and Hayes Common in Bromley.	Scarce and declining habitat; dwarf gorse, petty whin, cotton grass; black darter dragonfly, green hairstreak, yellow underwing.	Lack of appropriate management; nutrient enrichment from air pollution; inappropriate tree planting; limited opportunities for expansion.	Heathland restoration and re-creation in suitable areas adjacent to existing habitat; re-instatement of grazing; sympathetic management of patches on golf courses.
Farmland	12,000	Mainly in the Green Belt of the outer London Boroughs	Brown hare and birds such as tree sparrow, skylark, corn bunting and grey partridge.	Agricultural intensification; fertiliser, herbicide and insecticides; neglect of hedgerows and ponds; inappropriate tree-planting; change of land-use to leisure activities.	Set-aside and stewardship schemes; organic farming and reversion to 'traditional' farming methods; biodiversity conservation as part of housing planning.
Marshland	273	Ingrebourne Marshes; Denham Lock wood; Farm Bog; Walthamstow Marsh; The Chase Nature Reserve	Wet terrestrial habitat (bog, swamp, fen, wet marginal vegetation, wet marshy grassland and ditches); important for breeding birds such as sedge warbler, reed warbler, reed bunting; dragonflies; water vole; grass snake; frogs and bats.	Development, water abstraction, pollution, lack of, or inappropriate management; summer droughts and/or hydrological changes through drainage schemes; fragmentation; succession to woodland.	Rehabilitation and restoration under Local Environment Agency Plans (LEAPs); incorporating habitats in new flood defence or surface water drainage schemes; Water Level Management Plans; restoration of former gravel pits.
Parks and squares	~12,500	Royal Parks and smaller local parks e.g. Richmond, Regents, Battersea.	Common birds, butterflies and animals; heronries in park lakes.	Unsympathetic management; piece-meal disposal for development; recreational pressure.	Restoration of relic features and habitats; creation of ponds or wildflower meadows; relaxing mowing regimes; integration within Green Corridor network.
Cemeteries and churchyards	1,300	Victorian cemeteries such as Highgate, Nunhead, Kensal Green and Abney Park	Less intensively managed than parks; uncommon ferns and lichens; relict grassland with rare wild flowers.	Increasing pressure for re-use of burial space; well-ordered 'tidy' appearance.	Reduction of mowing frequency; introduction of bird and bat boxes; promotion of 'green burials'; habitat restoration; educational resource.

Habitat	Area (Ha)	Location(s)	Importance	Threats	Opportunities
Gardens and allotments	31,000	Ubiquitous	Habitats similar to hedgerows or edges of woodlands; garden ponds; breeding linnet and goldfinch on allotments; common birds and butterflies in gardens.	Lack of appreciation of habitat value; cutting hedges during bird breeding season; removal of leaf-litter and dead wood; paving of front-gardens; chemical pesticides; backland development and infilling.	Wild-life friendly gardens; vast and intricate network of green corridors; point of contact with the natural environment.
Railway land, line sides & road sides	1,000+ (Sites of Importance for Nature Conservation)	Examples include Sydenham Hill station and New Cross Gate cutting managed as nature reserves.	Network of a variety of habitats, chiefly woodland, scrub and rough grassland; locally important bird and insect populations.	Habitat loss through development or operational requirements; clear-felling of trees to reduce leaf-litter; herbicide treatments; fly-tipping.	Management guidance taking account of ecology; restoration of grassland habitats and woodland edges; high potential for raising awareness of biodiversity value.
Wasteland	Unknown	Incompatible definitions; but disappearing habitat due to redevelopment.	Rare insects and birds, such as the black redstart; rapid colonisers; invertebrates.	Proposals for redevelopment and/or decontamination; lack of awareness of nature conservation value; existing value assumed less than that of improvements.	Establishment/maintain urban wasteland nature reserves; opportunities to research biodiversity in the built environment; create roof-top urban wastelands; promote natural colonisation by wasteland flora and fauna.

Sources: Mayor's Biodiversity Strategy (2002) and London Biodiversity Partnership (2002).

Table 3.4 Exemplar biodiversity issues currently facing London

Species/habitat	Trend	Distribution	Key issues
Water Vole	Disappeared from over 72% of sites occupied prior to 1997.	Rainham Marshes, Crayford-Erith Marshes, River Cray, Lee Valley.	Predation by feral American mink; sensitive habitat management.
Noctule and serotine bats	Significant decline since the mid-1980's	Buildings, bridges, trees and underground roosts.	Disturbance, damage or destruction of roosts; loss of insect-rich feeding habitats such as wetlands, woodlands and grasslands; loss of flight line features; artificial lighting.
Reed Bunting	Fluctuation in response to weather.	Rainham Marshes, inner Thames Marshes SSSI, Walthamstow Marshes, Walthamstow Reservoir, Brent Reservoir SSSI.	Deterioration of wetland habitats; intensification of agricultural practices.
Bittern	National decline since 1960's; numbers boosted by continental migrants.	Visitor to London Wetland Centre in 2002, over winters in Lee Valley Park.	Loss and fragmentation of reedbed habitat; small population size; pesticide and heavy metal pollution.
House sparrow	Dramatic decline in recent years across many parts of the United Kingdom.	Completely disappeared from large areas of London where it was common until only a few years ago.	More intensive agriculture has affected most farmland birds, but causes of urban decline are not known.
Black redstart	Currently declining.	Abandoned industrial sites in the east Thames corridor.	Habitat loss through urban regeneration.
Bumblebee	Drastic decline in range in recent decades	Wasteland sites with sandy substrates, open conditions and low nutrient status.	Habitat loss through urban regeneration.
Coastal Salt Marsh	Currently declining.	Tidal Thames.	Development pressures; erosion; over-grazing; tidal defences.
Chinese Mitten Crab	Problem species, increasing unchecked.	River Thames as far as Staines, Rivers Roding, Lee, Darent, Cray, Mole, Crane, Brent, Hogsmill, Wandle, Quaggy, & Ash.	Destruction of natural banks and reed beds; possible predation of the White-clawed Crayfish.
Floating Pennywort	Introduced, problem species, spreading rapidly throughout the waterways and wetlands of Greater London.	River Lee south of M25, Rivers Roding and Wandle, Marsh Dykes, Brent Reservoir SSSI, Wetland Centre at Barnes, Epping Forest.	Out competes other plants forming dense mats; deoxygenates water; restricts flow; hampers navigation, flood control, surface abstraction & recreation.
Salmon	Significant decline between 1993 and 1998, slight recovery since.	River Thames	Excellent indicator of water quality; fish rearing and stocking; construction of fishes passes; recent decline attributed to dry summers and lower flows; If the temperature of the river increases significantly, conditions will become increasingly unsuitable for salmon.

Sources: Environment Agency (2001b), London Biodiversity Partnership (2002), and the Mayor's Biodiversity Strategy (2002).

3.12 Summary

The preceding sections provide a review of the recent trends and changes in key environmental indices. The benchmarks, summarised in Table 3.5, form the basis for subsequent discussions of future climate scenarios and potential environmental impacts facing London.

Table 3.5 Key climate and environmental trends in London and the wider Thames Region

Climate indicators	Recent trend
Air temperature	Annual average has risen by +0.6ºC since 1900's
	Several of the warmest years on record have occurred since 1989
	Most rapid warming in period July to November
	Fewer 'cold' days and longer frost free season
	Growing season +30 days since 1900's
	Nocturnal urban heat island intensifying
Rainfall	Decreasing summer rainfall since 1880's
	Increasing winter rainfall over last 150-200 years
	Two of three driest summers were 1995 (1st), 1976 (3rd)
	Two of three wettest winters were 1989/90 (2nd), 1994/95 (3rd)
	More winter rain days and longer wet-spells since 1960's
	Heavy storms contribute more to winter rainfall totals since 1960's
	Lighter, more frequent summer storms
Snowfall	Fewer snowfall events and smaller snowfalls since 1960's
Gales	Record wind speeds in 1987 and 1990
	No long-term trend but cluster of severe gales in the 1990's
Evaporation and relative humidity	Increases in PE in all seasons but especially spring and autumn
	Decline in summer RH since 1920's
River flow	No discernible trends that may be linked exclusively to climate
	Notable low flows in the 1880's to 1900's, 1940's, 1970's, 1990's
	Flood rich period in the 1920's
	Increases in number of high flows in last 30-50 years
	Winter 2000/01 highest 90-day flow volume in the Teddington record
Groundwater	Levels increasing by up to 2.5 m/yr in central London
	Local declines due to unsustainable abstraction and dry weather

Climate indicators	Recent trend
Tidal levels	High tide levels rising by 6 mm/yr (includes subsidence)
	Frequency of Thames Barrier closure increased during the 1990's
River water quality	Water quality trends reflect fluctuations in rainfall intensity and river flow volume
	Droughts of 1989-91/1995-97 led to deterioration of river quality
	River water temperatures have risen in the Thames
	Combined sewer outflows severely deplete oxygen levels following severe summer storms
Air quality	Air quality is failing standards in many parts of London principally due to traffic emissions
	Key pollutants are nitrogen dioxide, particulates, ozone, and sulphur dioxide
	Weather patterns strongly affect ambient pollution levels
Biodiversity	Decline in some species due to predation, e.g. Water Vole
	Decline in some species due to agricultural intensificaton, e.g. House Sparrow
	Decline in some species due to loss of habitat, e.g. Bumblebee
	Loss of habitats due to redevelopment e.g. marshland and urban wasteland
	Spread of problem species, e.g. Floating Pennywort, Chinese Mitten Crab
	Increasing pressures from recreation and amenity, e.g. woodland, waterways
	Fragile, but generally recovering Salmon population

3.13 Bibliography

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4. Future Climate Scenarios

4.1 Introduction

In 1995 the Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report (SAR), concluded that the observed rise in global average temperature over the 20th Century '*is unlikely to be entirely natural in origin*" and that "*the balance of evidence suggests that there is a discernible human influence on global climate*". As state previously in Section 2.2 in 2001 Working Group I of the IPCC Third Assessment Report (TAR) presented an even stronger case for the link between human influence and climate change.

4.2 Global Climate Projections

Climate model projections of future global–mean temperature and sea level change depend on future estimates of greenhouse–gas and sulphate aerosol emissions. In 2000, the IPCC approved a new set of emission scenarios to update and replace the IS92 scenarios used in the IPCC SAR. The new scenarios, presented in the IPCC *Special Report on Emission Scenarios* (SRES), have much lower emissions of sulphur dioxide than the IS92 scenarios. Although the scenarios cover a total of 40 future demographic, economic and technological 'storylines', just four marker scenarios have received most attention within the scientific community (Table 4.1). It is not possible to attach probabilities to any of the SRES scenarios; they are all plausible descriptions of socio–economic trends that could affect future emissions of greenhouse gases.

Table 4.1 SRES storylines used by the IPCC for future greenhouse gas emission scenarios

Scenario	Outline
A1F1	Very rapid economic growth, a global population that peaks in mid–21st Century and thereafter declines, and the rapid introduction of new and efficient technologies. The scenario also envisages increased cultural and social interaction, with a convergence of regional per capita income.
A2	A very heterogeneous world, characterised by self–reliance and preservation of local identities. Population continues to grow but economic growth and technological change are slower than other storylines.
B1	The same population dynamics as A1, but a transition toward service and information economies, with lower material consumption and widespread introduction of clean and efficient technologies.
B2	A world with lower population growth than A2, accompanied by intermediate levels of economic development, with less rapid and more diverse technological change than in B1 and A1.

Table 4.2 summarises the key features of observed and projected climate changes presented in the *Summary for Policymakers' Report* (IPCC, 2001a). Table 4.3 focuses on extreme events and the levels of confidence attached to observed global trends and model projections.

Table 4.2 Consensus about future changes in the climate system

Temperature

- The global average surface temperature has increased by 0.6±0.2ºC since 1861, although most of the warming occurred during two periods, 1910 to 1945 and 1976 to 2000.
- Globally, it is likely that the 1990s was the warmest decade and 1998 the warmest year in the instrumental record, since 1861.
- Proxy data for the Northern Hemisphere indicate that the increase in temperature in the 20th century is likely to have been the largest of any century during the past 1000 years.
- Between 1950 and 1993 night-time daily minimum temperatures over land increased by about 0.2ºC per decade (about twice the rate of increase in daytime daily maximum air temperatures).
- Since 1950 it is very likely that there has been a reduction in the frequency of extreme low temperatures, with a smaller increase in the frequency of extreme high temperatures.
- Globally averaged surface temperature is projected to increase by 1.4 to 5.8ºC over the period 1990 to 2100.

Precipitation

- It is very likely that precipitation has increased by 0.5 to 1% per decade in the 20th century over most mid- and high-latitudes of the Northern Hemisphere continents.
- It is likely that there has been a 2 to 4% increase in the frequency of heavy precipitation events in the latter half of the 20th century over mid- and high-latitudes of the Northern Hemisphere.
- Over the 20th century (1900 to 1995), there were relatively small increases in global land areas experiencing severe drought or severe wetness.
- There has been a 2% increase in cloud cover over mid- to high-latitude land areas during the 20th century.
- Northern Hemisphere snow cover and sea-ice extent area projected to decrease further.
- Global water vapour concentration and precipitation are projected to increase during the 21st century.
- Larger year to year variations in precipitation are very likely over most areas where an increase in mean precipitation is projected.
- No systematic changes in the frequency of tornadoes, thunder days, or hail events are evident in the limited areas analysed.

Sea level

- Tide gauge data show that global average sea level rose between 0.1 and 0.2 metres during the 20th century.
- Global sea level is projected to rise by 0.09 to 0.88 metres between 1990 and 2100, for the full range of SRES scenarios.

Source: IPCC (2001a)

Table 4.3 Estimates of confidence for selected observed and projected changes in extreme weather and climate events

Changes in phenomenon	Confidence* in observed changes (latter half of 20th century)	Confidence* in projected changes (during the 21st century)
Higher maximum temperatures and more hot days over nearly all land areas	Likely	Very likely
Higher minimum temperatures, fewer cold days and frost days over nearly all land areas	Very likely	Very likely
Reduced diurnal temperature range over most land areas	Very likely	Very likely
Increase of heat index over land areas	Likely, over many areas	Very likely, over most areas
More intense precipitation events	Likely, over many NH land areas	Very likely, over many areas
Increased summer continental drying and associated risk of drought	Likely, in a few areas	Likely, over most mid-latitude continental interiors

* IPCC qualitative classification of confidence levels: Likely (66 to 90%), Very likely (90 to 99%)
Source: IPCC (2001a)

4.3 Climate Change Scenarios for the UK and London

Since the publication of the UKCIP98 scenarios (Hulme and Jenkins, 1998), significant advances in computing power have enabled a greater number of climate model experiments to be conducted at higher spatial resolutions. The Hadley Centre global climate model (HadCM3) was used to drive a high resolution atmospheric model (HadAM3H) and, in turn, a regional climate model (HadRM3) for Europe. These experiments resulted in the development of the UKCIP02 scenarios (Hulme et al., 2002) which describe how the climate of the UK land area may change in the 21st Century at a resolution of ~50 km (as opposed to the ~300 km resolution of UKCIP98). The new scenarios also provide more information about changes in extremes of weather and sea level, and are explicitly linked to the four SRES storylines described in Table 2.1 (B1~**Low Emissions**, B2~**Medium-Low Emissions**, A2~**Medium-High Emissions**, A1F1~**High Emissions**). In contrast, the UKCIP98 scenarios were based on much simpler descriptions of future population and fossil fuel use.

Table 4.4 **Summary of results presented in the UKCIP02 Scientific Report**

- The UK climate will become warmer by between 1 to 2ºC by the 2050 and by up to 3.5ºC by the 2080's, with parts of the south-east warming by as much as 5ºC in summer.
- Higher summer temperatures will become more frequent and very cold winters will become increasingly rare.
- Winters will become wetter and summers may become drier everywhere.
- Summer soil moisture may be reduced by 40% or more over large parts of England by the 2080s.
- Daily maximum temperatures of 33ºC, which occur about 1 day per summer in the south-east, could occur 10 days per summer by the 2080's.
- Snowfall amounts will decrease throughout the UK.
- Heavy winter precipitation (rain and snow) will become more frequent.
- Relative sea level will continue to rise around most of the UK's shoreline.
- Extreme sea levels will be experienced more frequently.
- The Gulf Stream may weaken in the future, but it is unlikely that this weakening would lead to a cooling of UK climate within the next 100 years.
- In central London the urban heat island effect could add a further 5 to 6ºC to temperatures during summer nights.

Source: Hulme et al., 2002

Despite these advances, the UKCIP98 and UKCIP02 scenarios (Table 4.4) are qualitatively very similar. The main differences in UKCIP02 are: a) slightly higher warming rates over the UK; b) smaller rates of sea level rise; c) summers are now projected to become drier over the *whole* UK, and by a larger amount; d) changes in the patterns of average wind speed; e) less marked increase in the frequency of heavy rainfall days. Tables 4.5 and 4.6 show changes in temperature, precipitation, cloud cover, relative humidity, average wind speed and sea level for HadRM3 grid points close to London. Changes are all with respect to the mean 1961-1990 climate, for the UKCIP02 **Low Emissions** and **High Emissions** scenarios respectively. The scenarios presented in Tables 4.5 and 4.6 should be regarded only as indicative because the regional climate model treats London as a vegetated surface. Furthermore, the use of model results from individual grid points is generally discouraged by the climate modelling community.

Table 4.5 Climate changes for Greater London* under the UKCIP02 Low Emissions scenario

Variable	2020s			2050s			2080s		
	Summer	Winter	Annual	Summer	Winter	Annual	Summer	Winter	Annual
Temperature (ºC)	1 to 1.5	0.5 to 1	0.5 to 1	2 to 2.5	1 to 1.5	1.5 to 2	2.5 to 3	1.5 to 2	2 to 2.5
Precipitation (%)	-10 to -20	0 to 10	-10 to 0	-30 to -20	10 to 15	-10 to 0	-30 to -20	10 to 15	-10 to 0
Cloud cover (%)	-4 to -3	nv	-3 to -2	-6 to -5	nv	-4 to -3	-9 to -6	nv	-6 to -3
Relative humidity (%)	-4 to -3	-1 to 0	-2 to -1	-6 to -5	-1 to 0	-4 to -2	-9 to -6	-3 to 0	-6 to -3
Wind speed (%)	0 to 1	1 to 2	0 to 1	0 to 1	2 to 3	0 to 1	0 to 3	3 to 5	nv
Net sea level change (cm)	12			19			26		

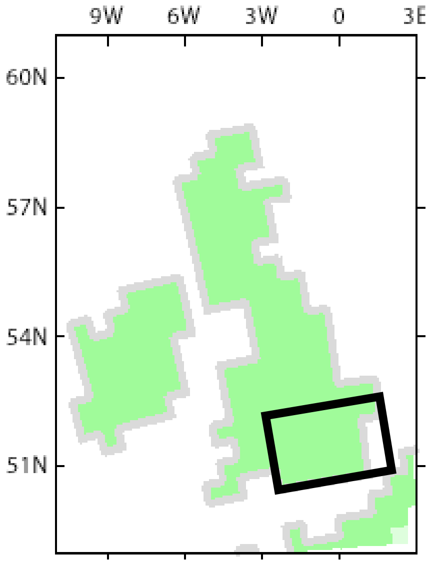
* estimated from the model grid points closest to Greater London
nv indicates changes within the bounds of 'natural variability'

Table 4.6 Climate changes for Greater London under the UKCIP02 High Emissions scenario

Variable	2020s			2050s			2080s		
	Summer	Winter	Annual	Summer	Winter	Annual	Summer	Winter	Annual
Temperature (ºC)	1 to 1.5	0.5 to 1	1 to 1.5	3 to 3.5	1.5 to 2	2 to 2.5	>4.5	3 to 3.5	4 to 4.5
Precipitation (%)	-20 to -10	0 to 10	-10 to 0	-40 to -30	15 to 20	-10 to 0	<-50	25 to 30	-10 to 0
Cloud cover (%)	-4 to -3	nv	-3 to -2	-10 to -8	nv	-6 to -4	<-15	0 to 3	-9 to -6
Relative humidity (%)	-4 to -3	-1 to 0	-3 to -2	-10 to -8	-2 to 0	-6 to -4	-15 to -12	-3 to 0	-9 to -6
Wind speed (%)	0 to 1	2 to 3	0 to 1	0 to 2	3 to 5	0 to 2	0 to 3	7 to 9	0 to 3
Net sea level change (cm)	22			48			86		

In addition, UKCIP02 projections of temperature and precipitation changes were extracted for a domain covering south-east England (Figure 4.1). Patterns are presented for the **Low Emissions** and **High Emissions** scenarios, for different seasons, and for three future periods: 2020s (years 2011 to 2040), 2050s (2041 to 2070), and 2080s (2071 to 2100). All changes are expressed with respect to the average 1961-1990 climate, which itself may incorporate some climate change. The **Low Emissions** and **High Emissions** scenarios represent the full range of precipitation and temperature change under the UKCIP02 scenarios, but not the full range of emission scenarios shown in the IPCC TAR.

Figure 4.1 **Reference map showing the south-east region used herein with respect to the UKCIP02 domain**



Temperature

By the 2080s, annual temperatures average across the south-east UK may rise by about 2.2ºC for the **Low Emissions** and by about 4.2ºC for the **High Emissions** scenario (see Figure 4.2). In general, there may be a greater warming in summer and autumn than in winter and spring, and there may be greater warming during night in winter and during day in summer. This implies that heating degree days will decrease, and that cooling degree days will increase. The likelihood of extreme temperatures is also expected to increase. For example, the summer maximum temperature that has a 5% chance of occurring on a given day under the current climate may increase from about 28ºC to 36ºC by the 2080s under the **Medium-High Emissions**.

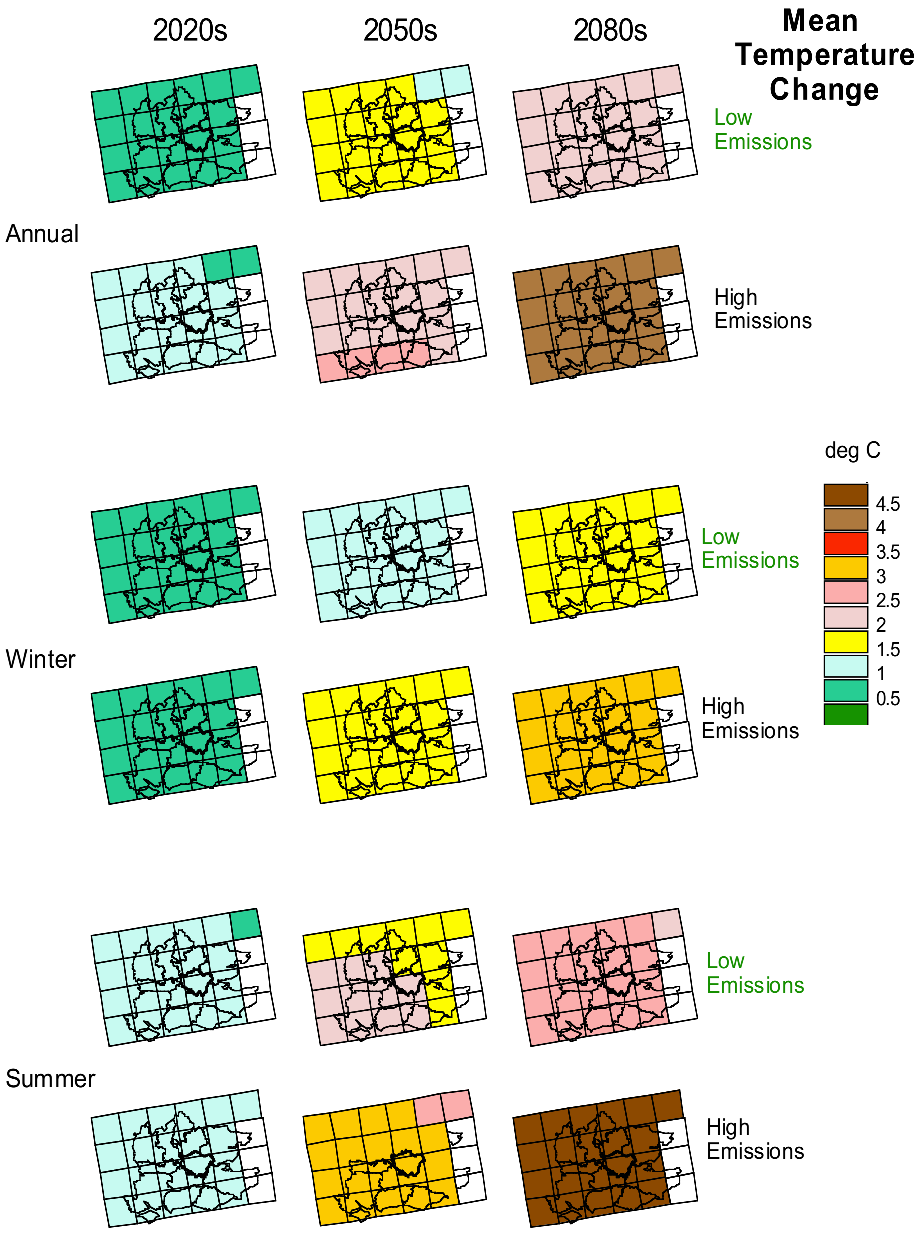


Figure 4.2 **Changes in south-east England average annual, winter and summer temperature for the 2020s, 2050s and 2080s for the UKCIP02 Low Emissions and** High Emissions **scenarios**

Note: Although the colour code is consistent with UKCIP02 figures, there are slight differences between the plots shown above and those in the UKCIP02 report. This is because the monthly mean data held on the UKCIP02 website has been smoothed using a 1-2-1 filter (e.g., smoothed Jan mean = [Dec mean + 2*Jan mean + Feb mean]/4) to reduce step changes between months. This smoothing was not undertaken for data used in the maps of the UKCIP02 report (Turnpenny, pers. comm.)

Precipitation

By the 2080s, winter precipitation in the south-east may increase by 10 to 20% for the **Low Emissions** scenario, to between 25 to 35% for the **High Emissions** scenario (see Figure 4.3). The pattern is reversed in summer, with a decrease in rainfall for the **Low Emissions** scenario of up to 30%, and by 50% or more for the **High Emissions** scenario. The net effect on annual precipitation totals, is a reduction of 5 to 10%. There will also be less snowfall over the south-east – perhaps up to 90% reductions by the 2080s for the **High Emissions** scenario, and 50-70% reductions for the **Low Emissions** scenario. The frequency of heavy winter precipitation, however, is projected to increase. For example, the maximum daily precipitation amount that currently occurs once every two winters may increase in intensity by between 10 to 20% for the **Low Emissions** scenario and by more than 20% for the **High Emissions** scenario.

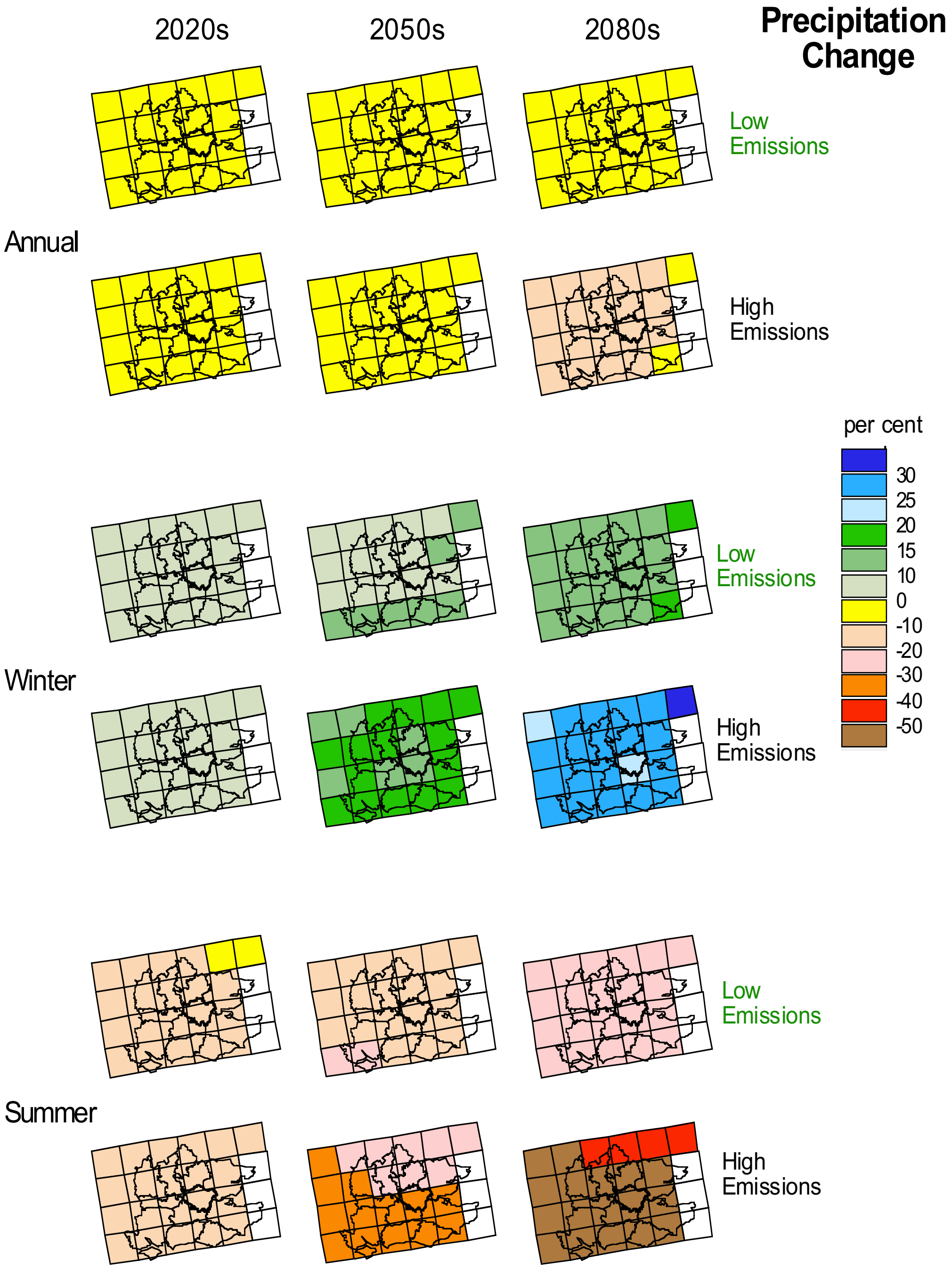


Figure 4.3 As in Figure 4.2, but for precipitation

Sea Level

Rates of change in mean sea level around the UK depend on natural land movements as well as on the thermal expansion of the world's oceans and melting of land glaciers. By the 2080s the net sea-level rise (taking vertical land movements into account) for London may be 26 cm under the **Low Emissions** scenario and 86 cm under the **High Emissions** scenario, relative to 1961-1990. These values were derived using the low end of the **Low Emissions** scenario (9 cm global sea-level rise) and the high end of the **High Emissions** scenario (69 cm rise), plus an assumed vertical land change of 1.5 cm/decade. However, most coastal damage is caused during storm surges. According to the Proudman Oceanographic Laboratory model, the 1 in 50 year extreme sea level increases by more than 1.1 metres by the 2080s under the **Medium-High Emissions** scenario. Unfortunately, much uncertainty is associated with this result, because the projections depend very much on the particular ocean model used.

Other Variables

Tables 4.5 and 4.6 provide summary information on projected changes in other climate variables for the south-east. By the 2080s, cloud cover may decrease in summer by more than 15% for the **High Emissions** scenario, with concomitant increases in summer sunshine. Summer relative humidities reduce by 10% or more for the **High Emissions** scenario, with fewer fog days expected in winter. Wind speeds are highly problematic to estimate from climate models, however, the UKCIP02 scenarios suggest that more frequent depressions cross the UK in winter leading to stronger winds in southern England. Finally, average soil moisture will decrease by 40% or more under the **High Emissions** scenario, and by about 20% for the **Low Emissions** scenario.

4.4 Climate Change Analogues

The future weather will continue to display much natural year-to-year and decade-to-decade variability. Indeed, for some aspects of climate, such as precipitation, natural variations are expected to be greater than changes due to increased greenhouse gas emissions until the second half of the 21st century. One helpful approach to visualising future probabilities of selected seasonal climate extremes is to describe their occurrence with reference to Table 4.3 events in the past. Climate change analogues are thus constructed by identifying climate records that could typify the future climate of the region. A major advantage of the approach is that the future climate scenario (and accompanying environmental impacts) may be described in far greater temporal and spatial detail than might otherwise be possible (see Subak et al., 1999). For example, the hot/dry summer of 1995 and the wet winter of 1994/95, provide useful analogues of the projected climate of the 2050s (Table 4.7). Thus, by the 2050s, the '1995-type' summer might be expected to occur in one year out of five, and by the 2080s, two in every three years.

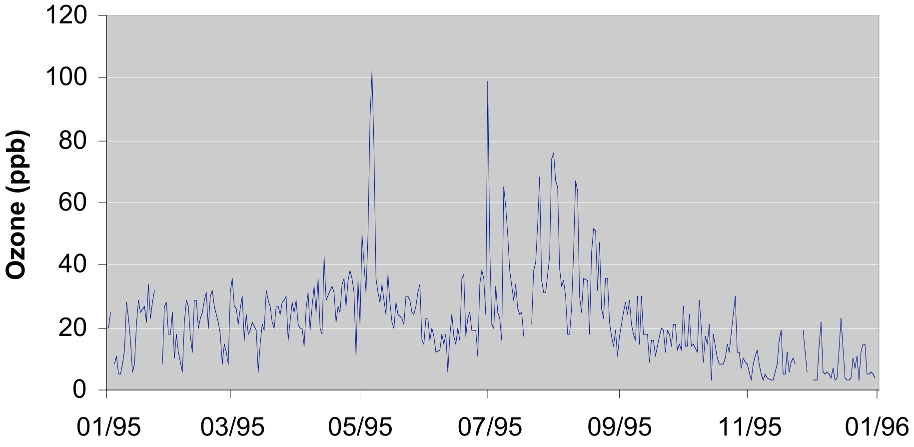
Table 4.7 Percentage of years experiencing extreme seasonal anomalies across central England and Wales for the Medium-High Emissions scenario

Analogue	Anomaly	2020s	2050s	2080s
A hot '1995-type' August	3.4ºC warmer	1	20	63
A warm '1999-type' year	1.2ºC warmer	28	73	100
A dry '1995-type' summer	37% drier	10	29	50
A wet '1994/95-type' winter	66% wetter	1	3	7

The anomalies shown are relative to the average 1961-1990 climate.
Source: Hulme et al. (2002)

A major disadvantage of the analogue approach is that the associated impacts of the weather extreme are unlikely to be the same in the future. For example, the summer of 1995 resulted in several serious ozone episodes in London (Figure 4.4). The development of similar pollution episodes in the summers of the 2050s, presupposes that the historic combination of emissions and large-scale weather systems are repeated.

Figure 4.4 Maximum hourly mean ozone concentrations at Russell Square Gardens, Bloomsbury, London during the hot-summer year of 1995. The World Health Organisation (WHO) guideline of 76 ppb was breached on five occasions during 1995.



4.5 Statistical Downscaling

Climate change scenarios for individual sites may differ from those represented by the climate model grid-boxes shown in Figures 4.2 and 4.3. This is because the former are point statistics, whereas the latter are area-averages. Statistical downscaling (SDS) methods are relatively simple procedures for translating large-scale climate model information into station scale data representing the unique 'local' climate of target sites (for a review see Wilby and Wigley, 1997). This enables the development of climate change scenarios of higher resolution than available through UKCIP02, and at scales commensurate with many impact sectors. The technique involves two main steps. Firstly, statistical relationships are established between the target variable of interest (e.g., maximum daily temperatures in St James Park, London) and indices of regional weather (e.g., wind direction, atmospheric pressure, etc., over southern England) for the *current* climate (Figure 4.5). Secondly, the same statistical relationships are employed to estimate the local variable for the *future* climate, using data supplied by a climate model. SDS techniques are not computationally demanding and require orders of magnitude *less* computer time than RCMs to produce equivalent scenarios. However, SDS scenarios are dependent on the stability of the local–regional scale relationship(s), and on the choice of predictor variable(s) used for downscaling future climate change (see Winkler et al., 1997).

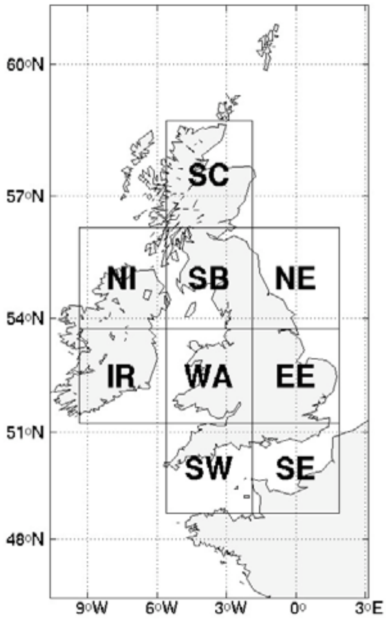
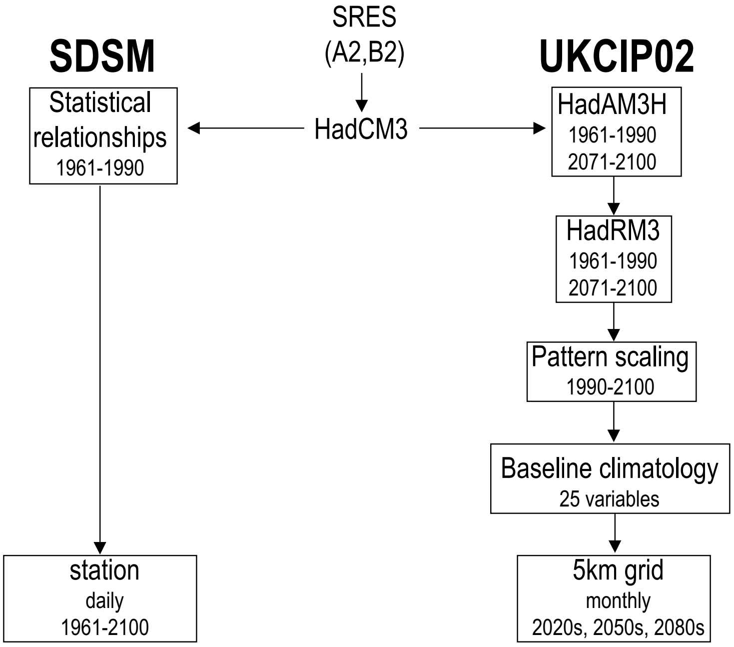


Figure 4.5 **The location and nomenclature of the nine climate model grid boxes used for downscaling current and future climate scenarios to individual sites across the UK. Downscaling for London was undertaken using climate information taken from the EE and SE grid-boxes.**

The local climate scenarios used for impacts assessment in subsequent sections of this report were developed using the **S**tatistical **D**own**S**caling **M**odel (SDSM) version 2.2 (Wilby et al., 2002). This software facilitates the rapid development of multiple, low–cost, single–site scenarios of daily surface weather variables under current and future climate conditions. An important feature of the SDSM package is the data archive: a set of daily climate variables prepared for model calibration and downscaling to any site across the UK (Figure 4.5). This archive contains variables describing atmospheric circulation, thickness, stability and moisture content at several levels in the atmosphere, under climate conditions observed between 1961 and 2000. Equivalent predictor variables are provided for HadCM3 experiments of transient climate change between 1961 and 2099, for the A2 (**Medium-High Emissions**) and B2

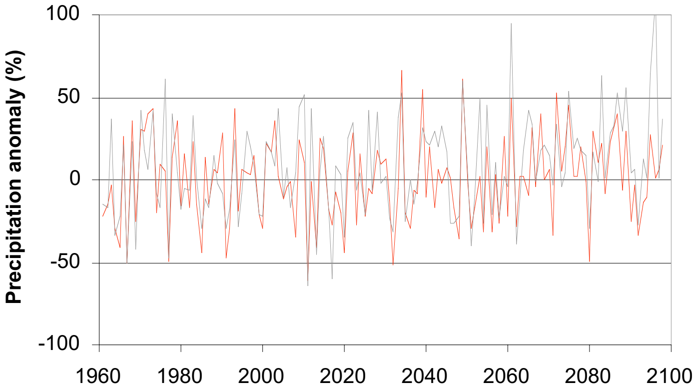
(**Medium-Low Emissions**) SRES scenarios. As Figure 4.6 shows, both the SDSM and UKCIP02 scenarios ultimately derive from the same climate model experiments – what is different is the means by which the HadCM3 climate model output is translated to finer spatial scales. The former yields point and sub-grid scale (<50 km) information from statistical relationships; the latter uses a combination of nested dynamical modelling (via HadAM3H and HadRM3) and pattern-scaling techniques.

Figure 4.6 Comparison of SDSM and UKCIP02 methodologies and scenario products. Note that HadAM3H predictors were not used for statistical downscaling in the present study, but these may become available in due course.



Although the UKCIP02 and SDSM scenarios will be broadly consistent, subtle variations are expected on a season-to-season basis (see Figure 4.7), with greatest differences for extreme events occurring at daily time-scales (e.g. precipitation). The year-to-year (transient) evolution of the climate scenario is also of interest. For example, in the case of Kew, both the downscaled and coarse resolution climate model scenarios show that large negative winter precipitation anomalies can still occur in the 2080s even though the underlying trend in winter precipitation is upwards. Extreme seasons that 'buck' the underlying trend would be overlooked by any downscaling method that simply reports thirty-year climate averages for the 2020s, 2050s and 2080s.

Figure 4.7 **Winter (December to February) precipitation anomalies (%) for the Eastern England grid box of HadCM3 (grey) compared with a downscaled (red) scenario for Kew, both from the** Medium-High Emission **scenario. The downscaled scenarios were produced using the Statistical DownScaling Model (SDSM) forced by HadCM3 predictor variables from the A2 experiment (http://www.sdsm.org.uk/). Anomalies were calculated with respect to the 1961-1990 averages.**



4.6 Key Uncertainties

Before the potential impacts of the UKCIP02 and SDSM climate changes for London are discussed, it is imperative that the key uncertainties attached to the scenarios be identified:

- Although the emissions used as the basis of the UKCIP02 scenarios represent the full range reported by the IPCC (2001), the scenarios available herein for statistical downscaling (just the **Medium-High Emissions** and **Medium-Low Emissions** scenarios) represent a narrower range. It is also currently impossible to assign probabilities to the various emission scenarios.

- There are a large number of scientific uncertainties concerning the future behaviour of emitted greenhouse gases, the significance of aerosols and soot particles, carbon-cycle feedbacks and ocean responses to greenhouse gas forcing. Different global and regional climate models will, therefore, produce different results depending on the treatment of these factors. The HadCM3 model produces rainfall changes close to the model range for winter, but simulates a larger reduction in summer rain than most models. Such inter-model differences over the UK may be expressed as uncertainty margins to be applied to the UKCIP02 scenarios of *change* in temperature and precipitation (Table 4.8).

Table 4.8 Suggested uncertainty margins to be applied to the UKCIP02 scenarios of changes in average winter and summer temperature and precipitation

	Low Emissions	**Medium-Low Emissions**	**Medium-High Emissions**	**High Emissions**
Average Temperature				
Winter (ºC)	±0.5	±1.0	±1.5	±2.0
Summer (ºC)	±0.5	±1.0	±1.5	±2.0
Average Precipitation				
Winter (%)	±5	±10	±15	±20
Summer (%)	+10	+15	+30	+40

Note: all summer rainfall sensitivities are positive because UKCIP02 summer rainfall changes are already considered to be at the drier end of the inter-model range.
Source: Hulme et al. (2002).

- The realism of the UKCIP02 and SDSM scenarios ultimately depend on the realism of the HadCM3 model output from which both are derived. Fortunately, the performance of this model, when assessed using a range of pattern correlation techniques, is consistently amongst the world's best for the current climate (Wigley and Santer, *pers. comm.*).
- There is little agreement amongst different models about regional patterns of sea-level rise. This is because of regional variations in the warming of ocean water (and associated thermal expansion), ocean circulation and atmospheric pressure. In UKCIP02, future changes in mean sea level were derived using local rates of natural land movement (subsidence) together with the full range of UKCIP02 global sea level rise for the three future periods. This idealised approach does not include any variations in regional sea level rise due to changing estuary shape, sediment consolidation or wave heights, so an uncertainty margin of ±50% is attached to each scenario of sea level rise in Table 4.5 and 4.6.
- Most climate models, including HadCM3, suggest a weakening (but not a shut-down) of the north Atlantic Gulf Stream over the next 100 years. However, changes in the salinity and temperature profile of north Atlantic surface waters, could in theory lead to a shut-down of the Gulf Stream. Although a cooling of UK climate over the next 100 years because of a shut-down of the Gulf Stream is considered unlikely, it can not be completely ruled out.

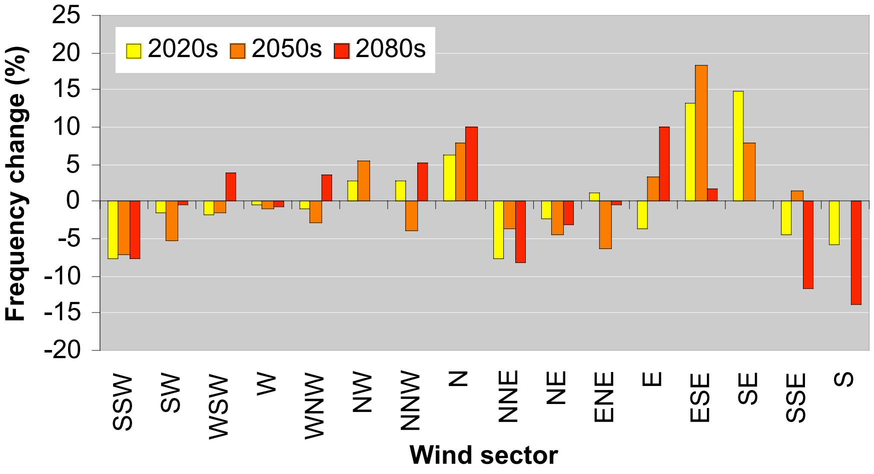
These factors should be borne in mind when considering the following set of climate change impacts for London.

4.7 Statistical Downscaling Case Study: Changes to London's Heat Island Intensity

The existing models of climate change assume a rural land cover. This makes them of limited use for estimating the climate change impacts in urban areas, especially London. This project has estimated changes to the Heat Island Effect, but obviously given the limitations in time and resources available in this project, this has not been a comprehensive remodelling of climate change for London. It is to be hoped that the effects of urban areas will be included in future climate change modelling work. Most people live in cities and urban areas and it is therefore critical to accurately determine the effects of climate change to these built up areas.

Early surveys of London's heat island indicated that the peak usually lies north-east of central London in Hackney and Islington, reflecting the density of urban development, and the displacement of the heat-island by prevailing south-westerly winds (Chandler, 1965). More recent monitoring has highlighted the mobility of the peak in relation to hourly shifts in wind direction (Graves et al., 2001). The thermal centre typically moves by several kilometres in line with the change in wind direction, therefore, future changes in the frequency of different wind directions could have an impact on the future location of the thermal centre. Figure 4.8 indicates a general increase in airflows from the east and south-east at the expense of airflows from the south and south-west under the Medium-High Emissions scenario. This implies that the thermal centre could lie more often over the west and north-west sectors of the City. However, this inference should be treated with extreme caution because the storm tracks in HadCM3 are known to be displaced too far south over Europe, adversely affecting the realism of modelled airflows over southern England (Hulme et al., 2002). Furthermore, projected changes in airflow are generally small relative to natural variability.

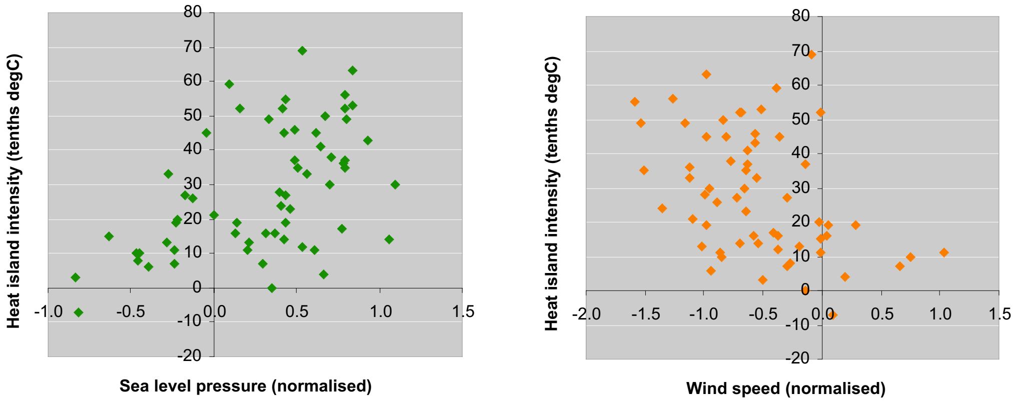
Figure 4.8 **Per cent changes in the frequency of daily airflows over the Eastern England grid box (see Figure 4.5) under the Medium-High Emissions scenario by 2020s, 2050s and 2080s. Changes are with respect to the 1961 to 1990 average**



The intensity of London's nocturnal heat island has been modelled using daily minimum temperatures for St James's Park (urban site) and Wisley in Surrey (rural reference station 30 km to the southwest). The average nocturnal heat island intensity for the period 1961 to 1990 was +1.8ºC, ranging from +10.0ºC (on 14 January 1982) to –8.9ºC (on 31 May 1970), with 5% of days having an intensity of 5ºC or more. In comparison, the average day-time heat island intensity was just +0.3ºC, ranging between +11.7ºC (on 30 May 1963) and –6.7ºC (on 12 December 1963).

The statistical downscaling model SDSM was calibrated using 1961 to 1990 daily minimum temperature differences between St James's and Wisley, and climate variables for the Eastern England (EE) grid-box (Figure 4.5). Significant correlations were found between the intensity of the heat island and several regional climate indices (most notably mean sea level pressure, strength of airflow, vorticity and near surface relative humidity). For example, Figure 4.9 shows the relationship between the nocturnal heat island intensity and pressure/wind speed during the summer of 1995. The scatterplots show that the intensity is greater under conditions of high pressure and low wind speeds (i.e., anticyclonic weather). Interestingly, the nocturnal heat island intensity is only weakly correlated with regional temperatures, suggesting that future changes in the heat island will be largely independent of projected temperature changes.

Figure 4.9 The relationship between London's nocturnal heat island intensity and sea level pressure, and wind speed, July to August 1995



Having established the historic relationship between the nocturnal heat island intensity and regional weather, the statistical downscaling software SDSM (Wilby et al., 2002) was then used to produce future estimates of the heat island under the Medium-High Emissions and Medium-Low Emissions scenarios. Under both scenarios there are progressives increases in both the intensity (i.e., annual average temperature difference between the sites) and number of days on which the intensity exceeded 4ºC (Table 4.9). In line with past experience, there remains considerable interannual variability in both measures (Figure 4.10). Under the Medium-High Emissions scenario, the nocturnal heat island intensity increases by 0.26ºC and the number of intense urban-rural differences by 15 days/year by the 2080s. Note that these heat island temperature changes are in *addition* to the regional warming shown in Figure 4.2, and relate to annual averages (Table 4.9). For example, as a first-order approximation for introducing heat island effects, the additional annual average temperature increase for London relative to rural sites in the region could be ~ 2.1ºC under the Medium-Low Emissions scenario (i.e., 1.8ºC from

1961-90 plus 0.26ºC intensification by the 2080s). However, observed data suggest that the most intense nocturnal heat islands develop in summer, and that these could have more adverse consequences for London in the future, including reduced night-time relief during heat-waves, and reduced ambient cooling of the underground system.

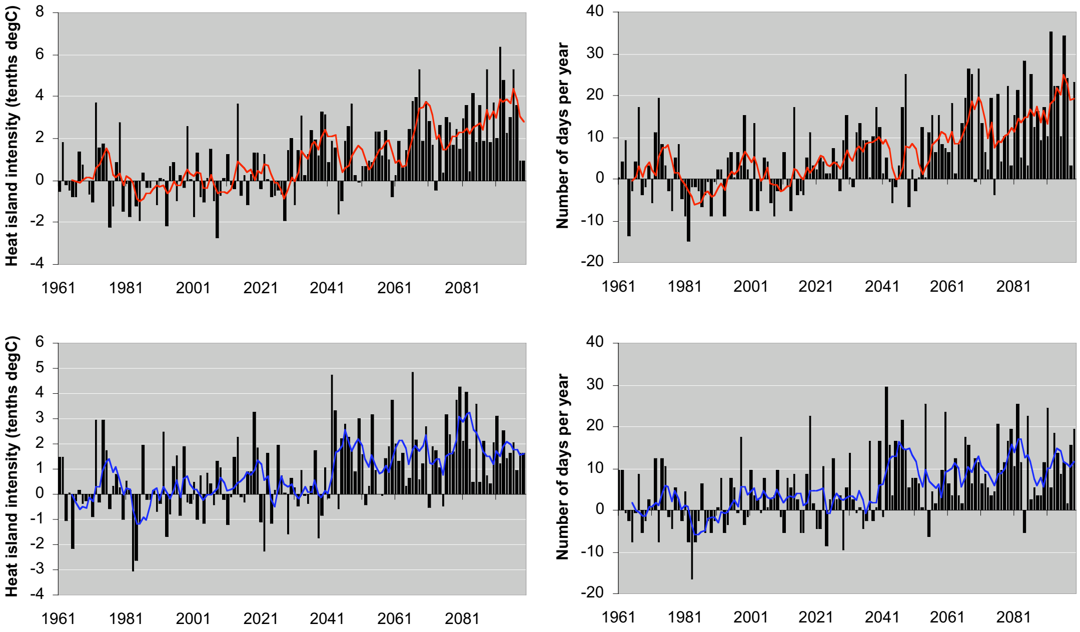


Figure 4.10 Change in annual average nocturnal heat island intensity (left column) and the number of intense (>4ºC urban-rural difference) heat island days (right column) in central London (Medium-High Emissions [top row], and Medium-Low Emissions [bottom row], downscaled), with respect to the 1961 to 1990 average

Table 4.9 Changes in the average nocturnal heat island intensity, net temperature[†] and, change in the number of intense (>4ºC urban-rural difference) heat island days in central London (Medium-High Emissions, and Medium-Low Emissions, downscaled), for the 2020s, 2050s and 2080s with respect to the 1961 to 1990 average

	Medium-High Emissions			**Medium-Low Emissions**		
Scenario	**_Intensity (ºC)**	**_Temperatur (ºC)**	**_Frequency (days)**	**_Intensity (ºC)**	**_Temperature (ºC)**	**_Frequency (days)**
2020s	0.07	2.4 – 2.9	5	0.03	2.3 –2.8	3
2050s	0.16	4.0 – 4.5	9	0.17	3.5 – 4.0	10
2080s	0.26	5.6 – 6.1	15	0.19	4.5 – 5.0	11

[†] Change in net temperature = baseline heat island (1961-1990) + heat island intensification (by date) + regional warming (by date)

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