Department of Health

Health Effects of Climate Change in the UK

HEALTH EFFECTS OF CLIMATE CHANGE IN THE UK

PREFACE

There is growing and widely accepted evidence that the climate of the earth is changing, in part due to human activity. It is also becoming clear that climate change will affect health. This effect will be felt more strongly in some countries than others but there is a clear need to understand the likely effects in the UK in order to develop strategies to mitigate such effects and to understand the extent of adaptation that may occur. In addition, the increased burden likely to be imposed on the National Health Service should be understood. The need for medical facilities to cope with the increased demands produced by more patients suffering from familiar disorders such as heat stroke or skin cancer and perhaps from comparatively unfamiliar disorders such as malaria and Lyme disease, should be addressed.

It is clearly important that the impacts on health should be addressed both qualitatively and quantitatively. It is appreciated that considerable effort has been put into the former and that the list of potential problems has been well defined. The quantitative approach has, however, lagged behind. At the request of Ministers at the Department of Health the Expert Group on Climate Change and Health in the UK was formed in early 1999. The group included experts from the meteorological and climate change fields and also from physiology, public heath, epidemiology and microbiology. A series of meetings were held to identify key areas of concern and, in particular, those areas likely to be susceptible to quantitative study and analysis.

It was not the purpose of the group to predict the likely extent of climate change in the UK. It was recognised that a set of widely accepted climate change scenarios for the UK had already been developed under the UK Climate Impacts Programme (UKCIP). The existence of the UKCIP has been an important factor in enabling the work of this group to proceed smoothly.

The group adopted the UKCIP climate scenarios for the 2020s, 2050s and 2080s and considered the likely impact of variables such as increased temperatures, increased storminess and raised sea levels on health. Both primary effects, for example, the direct effects of warmer summers, and secondary effects, for example increased prevalence of ticks and insect vectors of disease, were considered.

It was accepted from the outset that this report would represent only a first look at a difficult problem. It was agreed that a preliminary analysis, carried out over a short period leading to a series of tentative conclusions and firm recommendations should further work be considered necessary, would be the aim of the group. It is recognised that new studies in a number of relevant areas, underway during the preparation of this report, are nearing completion and will need to be taken into account. That the work was completed in such a short time reflects the commitment and expertise of the group: the Department of Health is grateful for the time and effort that members of the group devoted to this work. The Department is also grateful to the staff of the MRC Institute for Environment and Health who carried the administrative burden of producing the report and aided members throughout: Emma Green and Emma Livesley made particularly important contributions. Julia Cumberlidge, Emma Jenkins and Claire Townsend have also made important contributions.

The report was completed in 2000 and published for comment, in early 2001. A small number of individuals and organisations commented upon the report. The tone of the comments was favourable though some omissions and a few errors were detected. The time allowed for comment was extended at the request of several organisations. Details of individual comments are available on request from the Department of Health.

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A small editorial group was set up in late 2001 to consider the comments that had been received and to amend and correct the text. Once this work had been completed the Report was published in its final form.

The findings of the Report are summarised in the Executive Summary. The overall picture is worrying. Research to refine the preliminary estimates of effects provided here and to probe effects of climate change that we have not been able to consider is clearly needed: recommendations have been responded to by Government Departments. The case for studies of methods of mitigation of the predicted effects is strong. That efforts should be made to reduce the likely extent of climate change goes without saying – that such climate change will pose a challenge to health in the UK during the coming century is equally clear.

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Contents

Page No.

Executive Summary

1. The Department of Health asked the Expert Group on Climate Change and Health in the UK to advise on the likely effects of climate change on health in the United Kingdom (UK). This report presents the Group's findings. The available evidence has been examined and it has been concluded that climate change will have a significant effect on health in the UK. The various features of the changing climatic pattern of the UK will affect health in different ways and not all the effects are likely to be negative. The probable warming of our winters, for example, is likely to be associated with a decline in winter mortality. On the other hand, a rise in sea level and an increase in the frequency of severe winter storms will make flooding of low-lying coastal areas more likely. Our examination of the evidence has led to a number of conclusions and recommendations; these are summarised below. One significant conclusion is presented here. It is recognised that far too little is known of the likely effects of climate change on health in the UK and we recommend that an expanded research programme should be put in hand as a matter of urgency.

2. The current review of evidence has been based on data provided by the UK Climate Impacts Programme (UKCIP). These data have been invaluable and the staff of the UKCIP have played an important part in the work of the Group. We do not seek here to summarise the work of the UKCIP - this has been presented elsewhere. The climate scenarios produced by UKCIP for the UK in the 2020s, 2050s and 2080s have been used and the implications of the changes in the UK climate indicated in these scenarios have been considered. It is clear that climate in the UK is changing and will continue to change: UK winters will become less cold but wetter, summers will become warmer and probably drier in some places. Whilst the overall frequency of gales may not change greatly, the frequency of severe winter gales is likely to increase and this, in combination with an increase in sea level may cause severe flooding in low lying coastal areas. We note, with concern, the difficulties inherent in predicting changes in the UK climate and recognise the possibility of non-linearities in the pattern of climate change. For example, melting of the Antarctic ice cap or a significant change in the thermohaline circulation of the oceans could produce profound effects. We accept however, that such events though possible, are unlikely, and have excluded them from our analysis. It is understood that should conditions change and such events become probable, this analysis will need to be revised.

3. In considering ways of approaching our task three approaches were identified:
   - ☐ the use of spatial analogues;
   - ☐ the use of predictive modelling (involving both biological and empirical-statistical models); and
   - ☐ the use of expert judgement.

4. Spatial analogues seemed particularly appropriate when considering possible changes in the prevalence of vector-borne diseases. Modelling was used, for example, in dealing with the effects of climate change on levels of air pollutants and their effects on health. Expert judgement was applied throughout.

5. In looking at the relationship between temperature and health, we have considered the effects of both cold and hot weather. The UK has the highest cold weather excess mortality in Europe, with an estimated 60 000-80 000 cold-related deaths. The determinants of this excess

and the contributory role of temperature *per se* have not yet been fully quantified. Nevertheless, assuming that temperature plays an important role in mortality, we estimate that by the year 2050 excess cold weather deaths will have declined significantly, perhaps by 20 000 per year. This estimation assumes that other social and material conditions do not change. We also estimate that heat-related deaths occurring in the summer will increase from about 800 to around 2800 per year. A significant increase in hospital admissions is also likely. We caution against comparing the estimated reduction in cold related deaths with the increase in summer deaths, since the mechanism and time-frame by which temperature affects health differ between cold and warm weather.

6. Cases of food poisoning in the UK that are linked to warm weather have been increasing rapidly. This increase is likely to continue, and perhaps accelerate, as summer temperatures rise. An increase of about 10 000 cases each year by 2050 is estimated: clearly worrying even when seen against the background of the approximately 100 000 cases that currently occur each year. However such an increase is not inevitable, indeed, it may be largely preventable if effective measures are adopted. This is a theme that runs through this report: early and appropriate action may mitigate many of the effects on health of climate change.

7. Much has been written about the possible effects of climate change on the prevalence of vector-borne diseases in the UK. We have focused on malaria and tick-borne diseases including Lyme disease and encephalitis. By 2050 the climate of the UK may be such that indigenous malaria could become re-established, but this is unlikely to present a major problem. Local outbreaks of malaria caused by *Plasmodium vivax* may occur in the UK and precautions should be taken by those living in low lying salt-marsh districts to avoid mosquito bites. The picture in other countries is less encouraging and significant changes in the global distribution of malaria caused by *Plasmodium falciparum* are likely to affect travellers returning from abroad. This particularly dangerous form of malaria is unlikely to become established in the UK due to conditions being unsuitable for the breeding and survival of the particular species of mosquito that can act as its vector. While more contact with ticks is likely, predictions of a significant increase in tick-borne diseases in the UK are not well founded. The risk of tick-borne encephalitis, now significant in parts of Europe, is likely to decrease.

8. The UK has an excellent reputation for providing safe drinking water and good sanitation. This record and the measures upon which it is based are likely to prevent a significant increase in water-borne diseases as the UK climate changes. Cholera and typhoid, for example, are most unlikely to become problems in the UK. Outbreaks of disease caused by the protozoal organisms of the cryptosporidium group do, however, occur. Oocysts of these organisms can survive current methods of water treatment and this has been addressed in new regulations. Algal growths and algal blooms may increase and closer monitoring of water used for recreational purposes may be necessary. The overall impact of such changes is likely to be small. Whilst drought may well continue to be a major problem in many parts of the world its effect on health in the UK is expected to be small. The use of alternative sources of water for drinking during periods of drought may present problems and increased monitoring and treatment of supplies may be needed.

9. The likely increase in occurrence of severe winter gales is a cause for concern. Deaths during severe gales are commonplace, as are severe injuries. These reflect people being simply blown over, being struck by flying debris or being crushed by falling trees or collapsing buildings. The likely loss of electrical power supplies during severe storms adds very significantly to these problems. Recommendations are therefore made for improved inspection of buildings,

particularly hospitals, and a re-examination of building standards. Better forecasting of gales and better design and more frequent exercising of disaster plans may well help to mitigate the worst effects.

10. Attention is drawn to the considerable amount of original material in this report that deals with windstorms and the risk of coastal and riverine flooding. There seems little doubt that the risk of severe flooding of coastal areas is likely to increase as a result of rising sea levels and increased storm surges. Flooding that spreads inland from coastal areas may be catastrophic though we recognise there is a lack of development in the field of predicting both the probability of, and the risks likely to be attendant upon, such events. This should be addressed as a matter of urgency. Dealing with severe floods that leave perhaps tens of thousands of people temporarily homeless will always be difficult. Good forecasting and planning are of critical importance.

11. In general, levels of air pollution in the UK are falling and will continue to fall for some time. This decline, coupled with climate change, is likely to lead to a decline in air pollution-related deaths and illnesses. It is likely, however, that a small increase in levels of tropospheric ozone will occur and that associated deaths and episodes of illness will increase. Estimates of the effects are summarised in the table shown below.

Summary of effects on health of changes in levels of air pollutants likely to be associated with climate change

Pollutant	Year 2020	Year 2050	Year 2080
Particles	Large decrease	Large decrease	Large decrease
Ozone (no threshold)	Large increase (by about 10%)	Large increase (by about 20%)	Large increase (by about 40%)
Ozone (threshold)	Small increase	Small increase	Small increase
Nitrogen dioxide	Small decrease	Small decrease	Small decrease
Sulphur dioxide	Large decrease	Large decrease	Large decrease

12. At the same time as the UK climate is changing, emissions of chemicals are reducing levels of ozone in the stratosphere and penetration of ultraviolet (UV) radiation from the sun to the earth's surface is increasing. Warmer summers may well lead to increased outdoor activity and certainly to an increased risk of exposure to UV radiation. An increase in skin cancer and eye damage will follow unless steps are taken to limit exposure. Our estimates of the extent of the likely increase in these conditions are predicated upon the achievement of commitments made in the Montreal Convention and the subsequent Copenhagen Amendments to reduce the production of chemicals that damage the ozone layer. However, if current world levels of emissions remain at today's levels, the UK could expect 30 000 extra cases of skin cancer each year by 2050. If, on the other hand, the commitments of the Copenhagen Amendments are met then this could be reduced to 5000 extra cases per year. We estimate that 2000 excess cases of cataract may also occur each year by 2050. Measures to prevent a large part of such increases are possible through the use of sun screening creams, broad brimmed hats and the limitation of exposure.

13. Many countries, including the UK, are making efforts to reduce emissions of greenhouse gases and so limit the extent of climate change. Some of the UKCIP climate scenarios for later this century take these into account. Measures to reduce emissions may also have secondary and

beneficial effects on health. Reduced traffic speeds have been shown to reduce road accidents. A decreased dependence on motor transport could encourage walking and the use of bicycles which would also improve health. Efforts to improve insulation of houses may contribute to a decline in cases of cold-related deaths and illness. However, such benefits will need to be considered in light of possible deteriorations in indoor air quality resulting from decreased ventilation.

14. In conclusion, we have considered the likely effects of climate change on health in the UK. We acknowledge that there are considerable uncertainties relating to these predictions. For the purposes of this summary we focus on the Medium-High scenario for the 2050s (see Sections 1.2.1 and 1.2.3). More detailed analyses are provided in the following chapters. Briefly, our conclusions can be summarised as follows:

    - cold-related deaths are likely to decline substantially, by perhaps 20 000 cases pa;
    - heat-related deaths are likely to increase, by about 2000 cases pa;
    - cases of food poisoning are likely to increase significantly, by perhaps 10 000 cases pa;
    - vector-borne diseases may present local problems but the increase in their overall impact is likely to be small;
    - water-borne diseases may increase but, again, the overall impact is likely to be small;
    - the risk of major disasters caused by severe winter gales and coastal flooding is likely to increase significantly;
    - in general, the effects of air pollutants on health are likely to decline but the effects of ozone during the summer are likely to increase: several thousand extra deaths and a similar number of hospital admissions may occur each year;
    - cases of skin cancer are likely to increase by perhaps 5000 cases per year and cataracts by 2000 cases per year;
    - measures taken to reduce the rate of climate change by reducing greenhouse gas emissions could produce secondary beneficial effects on health.

15. When the preparation of this report began we were asked to advise on the implications for the NHS of the effects of climate change on health in the UK. Given the uncertainties surrounding our estimates of likely effects on health, such advice is particularly difficult. However, in general terms and given adequate planning and resources, the NHS should cope well with the impact of climate change on health in the UK. An exception to this perhaps optimistic conclusion is provided by the possibility of major coastal flooding on a scale not seen in the UK since 1953. Should such an event occur, and climate change may well increase the risk of such an event occurring, local NHS resources would be likely to be overwhelmed.

16. We wish to emphasise that many of the possible effects of climate change on health in the UK discussed in this report may be reduced by research and planning. A list of recommendations is provided that, if adopted, would prevent a significant part of the effects described in this report.

1 INTRODUCTION

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In recent years there has been a marked increase in research activity directed at better understanding of the links between climate variability, climate change and health. Climate change could potentially affect a range of geophysical, ecological and socio-economic systems which influence human health. Effects may be mediated through a short and direct chain of causation such as increased mortality from heatwaves, but other effects, particularly those mediated through changes in ecosystems or socio-economic circumstances, may be complex and require multidisciplinary research in order to advance understanding. It is also important to acknowledge that climate change is not occurring in isolation but in the context of other large-scale societal and environmental changes such as changes in land use, biodiversity, urbanisation and economic growth or decline. These may also affect patterns of health and disease, both directly and via their influence on climate change and society's responses.

The growing awareness of the prospect of climate change has stimulated several assessments of its likely impacts on human population health. In particular, the United Nation's Intergovernmental Panel on Climate Change (IPCC) has comprehensively reviewed the scientific literature on this topic in the Third Assessment Report (IPCC, 2001 WGII Chapter 9)[1]. A comprehensive assessment of the health impacts of climate change has been undertaken by a Task Group convened by the WHO, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP)[2]. The potential impact of climate change on human health has been identified as one of the priorities for action at the recent European Third Ministerial Conference on Environment and Health (London, June 1999)[3]. The primary recommendation in relation to climate change submitted jointly by the European Science Foundation, WHO and the EC was "to improve the epidemiological and mechanistic science base and develop predictive methods for the assessment of future health risks of human-induced climate change and increased exposure to UV radiation".

Countries that are signatories to the United Nations Framework Convention on Climate Change (UNFCCC), including the United Kingdom, are obliged to undertake national assessments of the impacts of climate change. Few countries have conducted reviews of the potential health impacts of climate change[4]. The Canadian Global Change Programme (CGCP), set up in 1992, also had a wider remit to identify and prioritise research themes in health sciences related to global change[5]. Within Europe, national impact assessments, which cover various sectors (e.g. agriculture, industry) have been published for most countries. The US Government has recently completed "The US National Assessment Potential Consequences of Climate Variability and Change"[6].

On the formal research front, very few resources have been allocated to climate/health research. This is beginning to change in the UK, as evidenced by the joint funding support by the Medical Research Council (MRC) and the Natural Environment Research Council (NERC) for competitive research proposals on environment and health, including climate variability, climate change and health. The then Department of the Environment, Transport and the Regions (DETR) has also funded, during 1998-2001, multidisciplinary research linking projected global climate change scenarios from the Hadley Centre to modelled health outcomes. Government agencies and research institutions in the US have taken a more proactive approach to research funding than those in Europe.

The modest targets for greenhouse gas emissions agreed in Kyoto under the UN Convention on Climate Change are likely to have little effect on the projected rises in temperature within the next 50 years. As we are already therefore committed to climate change, societies will need to adapt in order to minimise the adverse effects on health and social well-being. A shortcoming of many climate change impact assessments has been the superficial treatment of the adaptive capacities and options of diverse populations. The WHO-European Centre on Environment and Health working group on the early implications of climate change for human health has identified the need to strengthen surveillance in Europe for climate-sensitive diseases as a priority[3]. This will facilitate obtaining better data about changes in disease as they occur and to improve our understanding of climate/disease relationships and adaptation to climate change.

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1.1 The Relationship of the Health Effects Report with the UK Climate Impacts Programme

Dr M McKenzie-Hedger and Ms M Gawith
UK Climate Impacts Programme

This study on the Health Effects of Climate Change in the UK, which is led by the Department of Health, will also have the status of a sectoral study within the UK Climate Impacts Programme (UKCIP). Through this Programme it has already been possible to make links to other work on the impacts of climate change in the UK and it is hoped this process can be further developed. Cross-sectoral, integrated research is necessary for two reasons: the impacts of climate change will trigger a cascade of effects across sectoral, regional and national boundaries; and the ability of one sector to adapt to climate change impacts may be constrained by the competing demands of another. Experience in operating the UKCIP has found that health issues attract considerable attention across a range of stakeholders.

UKCIP is part of the ongoing research strategy on climate change of the Department for the Environment, Food and Rural Affairs (DEFRA) which has the lead within Government on the broad climate change issue. UKCIP's establishment specifically followed the second report in 1996 of the UK Climate Change Impacts Review Group which was a sectoral assessment by experts based on the HadCM1 climate model. DEFRA decided that a stakeholder-led integrated assessment would be the most appropriate next stage. A detailed scoping study by a team of experts identified the structure[1] and approach with first priority studies - UKCIP was funded by DEFRA from 1997. UKCIP is charged with coordinating and integrating stakeholder-led assessments on the impacts of climate change in the UK at a regional and national level. The bottom-up, stakeholder-led structure of UKCIP has attracted considerable international interest as an innovative methodology. Links have been established with other national coordinated programmes, including the USA, Canada and the Caribbean region.

At the heart of UKCIP is a core Programme Office. The Programme is advised by a Steering Committee comprising representatives of key Government Departments, public agencies, the private sector and Non-Government Organisations. A Science Panel oversees the integrity of the work and a User Panel enables stakeholders to interact directly. There are also now a number of steering committees for projects operating within the Programme.

The Programme currently has no direct funds of its own to undertake research, so works largely in a 'bottom-up' mode, supporting organisations - the "stakeholders" - to initiate studies which assess their own vulnerability to climate change and work out their adaptation responses. The conceptual framework is of modular studies, which can be used to prepare an integrated national assessment. Integration will be achieved principally through:

- the common use of core data sets and scenarios;
- development of networks of funders and researchers;
- developing and applying specific methodologies.

Underpinning products for the programme in the form of Technical Reports are separately funded by DEFRA:

- Report on climate change scenarios[2] (see the presentation of the UKCIP98 scenarios in Sections 1.2.1 and 1.2.3 which are then used in several chapters). A new set of scenarios is being prepared for Spring 2002.
- An analysis of socio-economic scenarios[3] - a study intended to provide baseline socio-economic scenarios for the UK was completed in 2001 and may be of use in next stages of health research.

- Risk, uncertainty and decision-making - this work has been undertaken by consultants with the assistance of the Environment Agency (EA) and is intended to provide guidance to policy-makers on how they can plan for climate change without complete information. The report will be published in 2002.
- Costing the impacts of climate change - the purpose of this study is to develop appropriate methodologies that non-economists can use to perform ‘desk-top’ climate change costing analyses at a local/regional scale, disaggregated by sector. Technical and summary reports will be published in 2002.

Studies within the Programme fall into two major groups, sub-UK (or regional) studies and sectoral studies. The sub-UK studies have all briefly covered health issues. This report is expected to provide inputs for developing methods and approaches at a sub-UK level in future UKCIP studies. So far the following studies are underway or completed:

Sub-UK/regional studies

- Scotland - report launched in December 1999, funded by the Scottish Executive[4];
- A scoping study for Wales was completed in February 2000, funded by the National Assembly for Wales[5];
- A scoping study for the North West England was completed in December 1998, funded by a regional consortium of local government, the regional Government Office, NGOs, and the EA[6];
- A scoping study for South East England was completed in November 1999, funded by an intra-regional consortium of local government, the regional Government Office, NGOs, the EA and Country Life magazine[7]. A regional co-ordinator has now been appointed to take forward climate impacts work in the region;
- A major conference for South West England took place in October 1999 and a scoping study is now planned;
- A regional scoping study was completed for the East Midlands of England in mid-2000[8], with an initial assessment underway in the West Midlands;
- A conference on climate impacts on the North East of England was held in May 2001;
- A scoping study is underway in Yorkshire and Humberside commenced in Autumn 2001; and
- A London scoping study is at inception.

In view of the great interest in the health issue from the perspective of public awareness, most studies examined the impacts on health for their areas. The methods used involved interpretation of existing climate change/health studies by the teams of consultants (which did not include health experts). All regions:

- Anticipated reductions in winter deaths;
- Did not view health as a critical climate impacts issue for their region;
- Saw health as integral to other issues (water quality; housing quality; provision of and access to health care services; changes in exposure owing to lifestyle changes); and
- Called for further research into the subject.

The Wales scoping study concluded that human health will be affected, but that impacts will be minor compared with other factors affecting future health, and reduced winter mortality would not be offset by a rise in summer mortality due to asthma, water-borne and insect-borne diseases and skin cancer. A sectoral evaluation of the severity of climate change impacts in Wales consequently ranked health as 1 on a scale of 1-5 (5 = high impact) owing to projected reductions in overall mortality.

Delegates at the Climatic Challenge Conference in the south west of England concluded that the region could be particularly vulnerable to certain health impacts, particularly:

- ❏ Extreme high temperatures, owing to its elderly population and high number of visitors during the height of summer when heatwaves are most likely to occur and:
- ❏ Lyme disease which could become more common in the region as lifestyle changes may increase exposure to carriers of the disease.

It was thought that the public health and socio-economic infrastructure within south west England would probably be able to cope with adverse effects on health but that further research into the issue was needed.

Health was identified as a sector likely to benefit from climate change in the north west England scoping study.[7]

Sectoral studies

In addition to this health study, a small number of detailed sectoral studies have been completed. UKCIP is supporting these studies, *inter alia*, through the acquisition of datasets and dissemination of results. The following studies may produce outputs and develop methods which may be of use in taking forward research on health impacts.

- ❏ Biodiversity - two studies have been completed: The DEFRA-funded Biodiversity Review[9] was a scoping study which used a literature review and expert judgement to determine the implications of climate change for nature conservation policy in the UK. Another quantitative modelling exercise, the MONARCH project (Modelling Natural Resource Response to Climate Change), was led by specialised agencies and NGOs and published in 2001[10]. A second phase is now underway. Possible links could be developed with studies on vector borne diseases.
- ❏ Built environment - a major initiative was launched in Autumn 2001with the Engineering and Physical Sciences Research Council (EPSRC) and UKCIP to fund research into the impacts of climate change on the built environment over the next three years.
- ❏ Other sectoral studies currently underway are: a scoping study on the impacts of climate change on gardens, led by the Royal Horticultural Society and National Trust; an assessment of impacts on the marine environment, to be completed in 2005; and a study on climate change impacts on water demand (CC:DEW).
- ❏ One of the priority studies identified from the original scoping study for UKCIP was the need for integrated assessments of impacts of climate change on the water sector. To develop methodologies a major study (REGIS) was funded by DEFRA and UKWIR (the research arm of the privatised water industry) for two years looking at four sectors (water, land use, biodiversity and coasts) in two regions (East Anglia and North West England), which was completed in summer 2001. Data gathering on extreme events and floods for this project informed the work in Sections 4.5 and 4.6 of this report.
- ❏ The results of the first three years of the Programme are presented in a report published in June 2000[11]. This report also gives consideration to the next stages of UKCIP.

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1.2 What is Happening to Global Climate and Why?

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Summary

❏ The climate of the UK is now warmer than it has been in at least 350 years. The average temperature during the 1990s was 0.5°C higher than that during the period 1961-1990.

❏ Current understanding would suggest that the rate of future warming in the UK is likely to accelerate. Average temperatures by the 2050s are likely to be between 0.8° and 2.3°C warmer than the 1961-1990 average.

❏ This continued warming is likely to lead to a number of changes to UK climate. Among these will be more frequent and more intense summer heatwaves, less severely cold winter weather and an increased risk of winter river floods.

The changing global climate

Evidence for the warming of our planet over the last 200 years is now overwhelming[1]. This is seen not only in climate observations, but also in physical and biological indicators of environmental change, such as retreating glaciers and longer growing seasons. It is also becoming increasingly clear that human activities have contributed to this warming[2]. It is likely that the climate during the next hundred years will be the warmest that human society has experienced. The rate of climate change is unprecedented in human history and may bring significant risks for human health.

On longer, geological time-scales the climate of our planet has obviously changed by very substantial amounts. The evidence for this comes from ice cores, deep-sea sediments and continental records. Over Antarctica, for example, estimates suggest that regional temperatures have fluctuated by 10°C or more over glacial and inter-glacial cycles. These cycle lengths are typically between 20,000 and 100,000 years. Globally, these temperature fluctuations have been perhaps half this amount. Changes in the past have also been quite rapid, at least on some occasions. It is thought possible, for example, that about 12,000 years ago temperatures around the North Atlantic Basin may have fluctuated by between 5° and 10°C over a period of only a few decades, although it is not clear that planetary temperature has fluctuated as rapidly as this. While these historical fluctuations in regional and global climate have been large, and possibly rapid, they occurred either before humans had evolved to their present status, or else before the beginnings of civilised human societies. It is hardly valid therefore to draw inferences from these past climate changes about the likely significance of future climate change; they hardly provide a useful analogue for the present and future impacts of climate change on twenty-first century society.

For the last millennium, recent work[3] has established the first reconstructions of northern hemisphere surface air temperature, based on a combination of tree-ring, ice core, coral and historical documentary evidence (Figure 1.1). While the uncertainty of this series increases further back in time, the data indicate relatively cool centuries between 1600 and 1900, they highlight the effect of large volcanic eruptions in cooling the planet in certain years (e.g. 1601), and clearly suggest that the observed twentieth century warming has been most unusual. The year 1998 was probably the warmest of the last millennium.

Figure 1.1

Record of Northern Hemisphere mean summer surface air temperature (1000AD to 1998AD) reconstructed using pales-data and expressed as deviations from the 1961–1990 average of 20.5˚C (observed data shown in red)

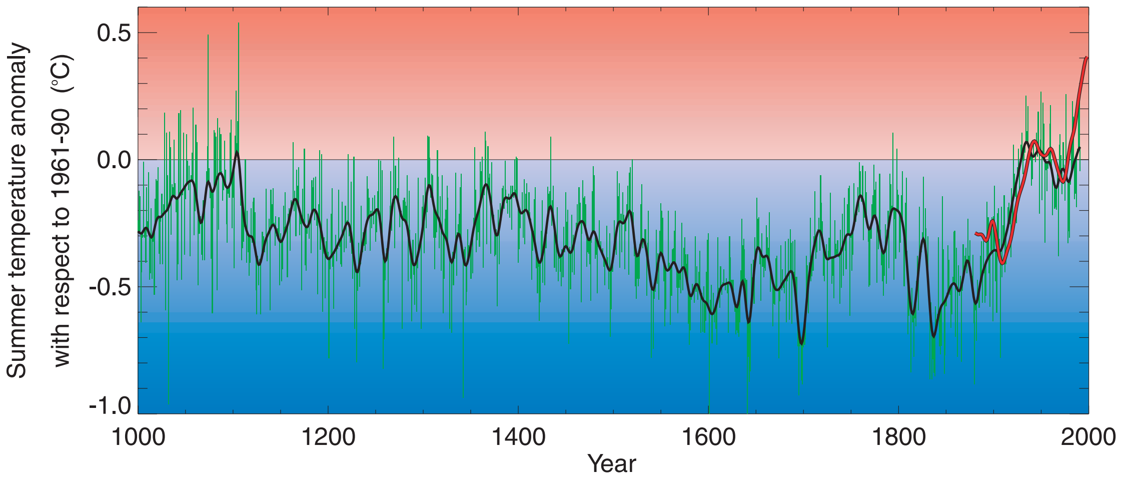
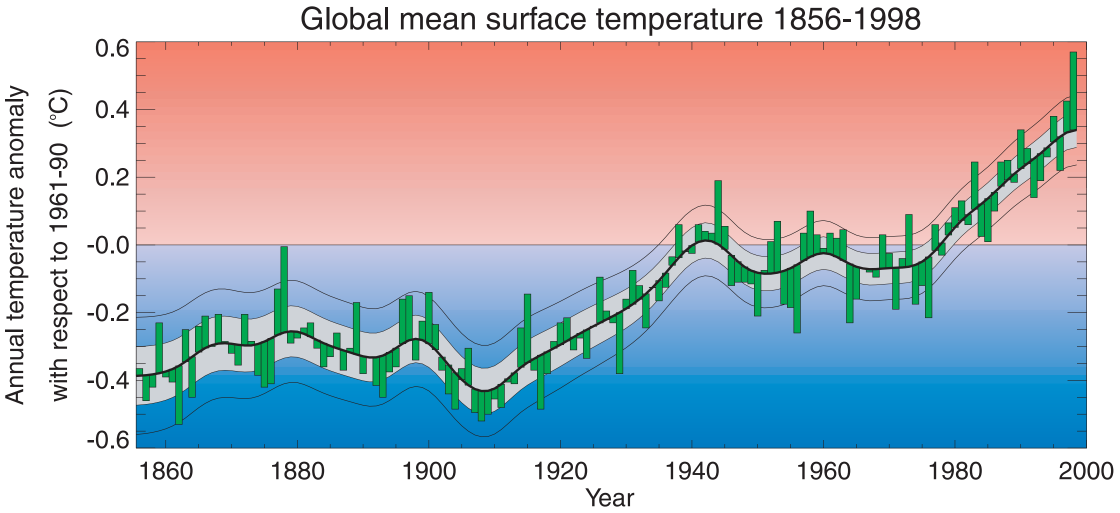


Figure 1.2

Record of annual global mean surface air temperature (1856–1998) expressed as deviations from the 1961–1990 average of about 14˚C. The smooth curves show the trend line (bold) and associated error margins (shading and thin line)



Instrumental climate data allow us to monitor more accurately the changing global mean air temperature since 1856. These data show a global warming at the surface of between 0.4°and 0.8°C, with the six warmest years all occurring in the last decade (Figure 1.2). For the majority of land areas the recent warming has been greater at night than during the day, partly reflecting increased cloudiness over land. The warming has been greater over land than sea. Data series are much shorter for upper air temperatures, but radiosonde measurements taken since the 1960s suggest that the lower stratosphere has been *cooling* at a rate of about 0.5°C/decade.

The human influence on climate

Why should the surface of the planet have warmed in such a way, while the lower stratosphere has cooled? Global climate can vary naturally, due both to what is called 'internal variability' within the climate system and to changes in external forcing unrelated to human activities - for example, changes in the sun's radiation or volcanic activity. Recent climate model experiments show that these natural causes of global temperature variability cannot, on their own, explain the observed surface warming and stratospheric cooling[4]. When these experiments are repeated with rising historic concentrations of greenhouse gases and shifting distributions of sulphate aerosols, much better agreement between observed and modelled global patterns of surface and stratospheric temperature change is achieved. Although the precise contribution of human activities to global warming cannot yet be stated with confidence, it is clear that the planet would not be warming as rapidly if humans were not currently emitting several billion tonnes of carbon into the atmosphere each year. The IPCC concluded in their Third Assessment Report in 2001 that "*...most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations*".

Possible future climates and sea-level rise

Given that humans are likely to be implicated in the cause of global warming, and recognising that the potential consequences of a rapidly warming climate for natural and human systems are great, it becomes important to estimate the possible range of future climates we will experience over future decades and centuries. Fundamental to this exercise are estimates of future greenhouse gas emissions, whether from energy, industrial or land-use sources. Of particular importance are estimates of future carbon dioxide emissions, the greenhouse gas that alone causes about 60 per cent of the human-induced greenhouse effect. Recent calculations[5] suggest that, given the range of possible future emissions, the current 1999 CO_2 concentration of about 370 parts per million volume (ppmv) will rise by 2100 to between 550 ppmv and 830 ppmv. These concentrations compare with concentrations before the industrial age of only about 280 ppmv.

What effect will this increase in carbon dioxide and other greenhouse gas concentrations have on global climate? This depends largely on how sensitive the Earth's climate is to rising greenhouse gas concentrations*. By combining a range of choices for climate sensitivity with the range of possible future emissions, a range of future changes in global temperature and sea level can be calculated. The annual global-mean surface air temperature over the period 1961-1990 was about 14°C and this has already risen to 14.3°C during the 1990s. Models predict that the planetary temperature will reach between 15.3° and 18.6°C by 2100, representing rates of change of between 0.1° and 0.4°C per decade. This compares with a global warming rate of 0.15°C per decade since the 1970s and of about 0.05°C per decade since the late nineteenth century. By comparison, the

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*** The climate sensitivity is defined as the change in global mean temperature that would ultimately be reached following a doubling of carbon dioxide concentration in the atmosphere (e.g. from 275 ppmv to 550 ppmv). The Intergovernmental Panel on Climate Change (IPCC) have always reported the likely range for this quantity to be between 1.5° and 4.5°C, with a central estimate of 2.5°C.**

planetary surface air temperature is estimated to have reached only between 15.0°C and 15.5°C during the last interglacial, warm, period 125 000 years ago.

One of the most striking consequences of a warming climate will be the rise in global mean sea level. Observed sea-level has risen by between 10 and 25 cm over the last century, reaching its highest level during the 1997/1998 El Niño event, and recent calculations suggest a future rise of between 22 cm and 124 cm by 2100 compared with average 1961-1990 conditions. The largest contribution to this sea-level rise comes from the expansion of warmer ocean waters, while melting land glaciers contribute up to 20 per cent.

Mitigating climate change and adapting to its effects

How much of this anticipated climate change can be averted by reducing greenhouse gas emissions? The short answer is 'some, but not much'. For example, under the terms of the Kyoto Protocol, signed in 1997 but not yet ratified, greenhouse gas emissions from industrialised countries have to fall to 5.2 per cent below their 1990 levels by 2010[6]. This target, if achieved in isolation, would reduce future global warming by at most 0.2°C[7]. Of course, post-Kyoto targets will be needed to achieve a greater reduction in the global warming rate. For example, Figure 1.3 shows the effect on global temperature of stabilising CO_2 concentrations in the atmosphere at either 750 ppmv or 550 ppmv, relative to an unmitigated emissions scenario that is similar to the UKCIP Medium-High scenario (see below). Even under the 550 ppmv scenario global temperature continues to rise through the twenty-second century before eventually stabilising at just more than 2°C warmer than present day.

Given this prospect of future climate change it is important that our climate change management strategy includes efforts both to mitigate climate change (pursuing options for emissions reductions) and to adapt to some of the more inevitable consequences (designing our resource and management systems to cope with changing climate and emerging climate change impacts). To pursue both these objectives, and especially the latter, it is important that we understand some of the possible health impacts of climate change in order to be better prepared to take any early actions that will be needed to safeguard public health.

1.2.1 What are climate change scenarios?

Climate change scenarios present coherent, systematic and internally-consistent descriptions of changing climates. These scenarios are typically used as inputs into climate change vulnerability, impact or adaptation assessments, but are used in many different ways by many different individuals or organisations. Some studies may require only semi-quantitative descriptions of future climates, perhaps as part of a scoping study. Others may need quantification of a range of future climates, perhaps with explicit probabilities attached, as part of a risk assessment exercise. Others may require information for very specific geographical areas. There is also a range of time horizons that may be considered relevant, depending on the type of decision to be made. Water companies may be concerned with operating conditions over the near-term (10-20 years), while coastal engineers or those making decisions about investments in forestry, may need to consider longer-term horizons.

Climate change scenarios are most commonly constructed using results from global climate model (GCM) experiments. These model experiments provide fairly detailed descriptions of future climate change that can be used to inform vulnerability and adaptation assessments. GCM-based scenarios, however, are uncertain descriptions of future climate for a number of reasons[8].

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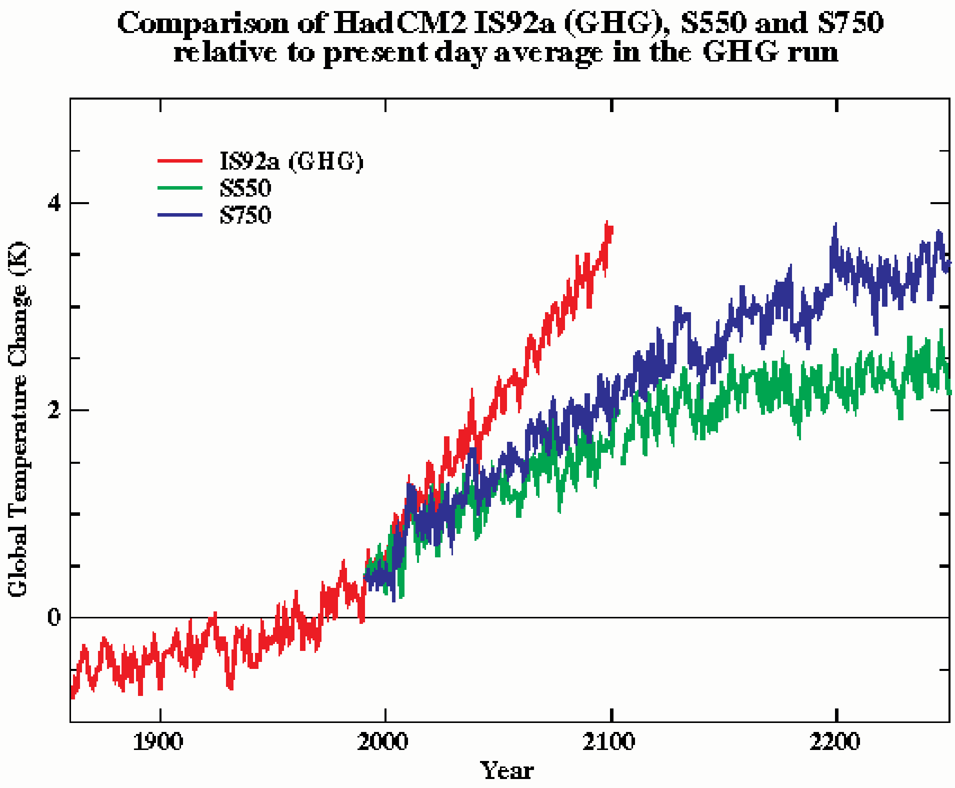
Figure 1.3

Effect on global temperature of stabilising CO_2 concentrations in the atmosphere at 750 ppmv or 500 ppmv, relative to an unmitigated emissions scenario that is similar to the UKCIP Medium-High scenario



A fundamental source of uncertainty in describing future climate originates from the unknown world future. How will global greenhouse gas emissions change in the future? Will we continue to be dominated by a carbon-intense energy system? What environmental regulation may be introduced to control such emissions? Different answers to these questions can lead to a wide range of possible emissions scenarios. Since any climate change GCM experiment has to choose an emissions scenario, different choices can lead to quite different predicted climate outcomes. The main modelling uncertainties in climate change prediction stem from different values of the climate sensitivity of the climate models and from the contrasting behaviour of different climate models in their simulation of regional climate change. These latter differences are largely a function of the different schemes employed to represent important processes in the atmosphere and ocean (known as parameterisations) and the relatively coarse resolutions of the models. In the Hadley Centre GCM, for example, the UK land area is represented by just four gridboxes, making it impossible to differentiate between the climate change predicted for, say, the Lake District and Merseyside or for the Wash and the Thames Estuary.

For these two reasons - unknown future emissions and uncertainties in climate modelling - together with the current unpredictability of natural climate variations, it is preferable to talk about future climate change scenarios rather than future climate predictions. The climate scenarios used in this report are based on those published in 1998 for the UK Climate Impacts Programme - the so-called UKCIP98 scenarios[9]. These scenarios rely largely on two sets of GCM experiments completed by the Hadley Centre during 1995 and 1996. These experiments were undertaken using a coupled ocean-atmosphere GCM called HadCM2[10]. This model has been extensively analysed and validated and represents one of the leading global climate models in the world. These UKCIP98 scenarios have been widely used in UK climate impacts assessments over the last 3 years and it is therefore appropriate to base this current report on these same scenarios. A new set of national UK climate-change scenarios are to be launched by the government during April 2002 - the UKCIP02 scenarios - and these will be based on new, higher resolution modelling work completed by the Hadley Centre and reflect new developments in the science of climate change as reported in the Third Assessment Report of the IPCC. Obviously, these new scenarios have not been used in any impacts assessments to date, although in qualitative terms the changes in climate for the UK in the UKCIP02 scenarios are broadly similar to those reported in UKCIP98.

Although GCMs provide the most credible basis for constructing climate change scenarios, it is important to make some comments about the use of spatial analogue climates. Spatial analogue climates have generally been used in one of two ways in climate scenario and impact studies: i) as a means of generating a climate scenario for a region, and ii) as a means of considering the sort of impacts climate change may induce in a region. We will comment briefly on each of these in turn.

When using spatial analogues to construct climate scenarios, the contemporary climate of a geographically distant location is used as an analogue for the future climate of the target location. The analogue region is usually identified simply on the basis of the assumed future change in annual mean temperature at the target location. Thus the climate of southwest England by 2050 may be said to resemble the present climate of the Bordeaux region in France following a 2°C warming, simply because Bordeaux is presently about 2°C warmer than southwest England. This approach to climate scenario construction is seriously flawed since climate cannot be transposed in space simply on the basis of an annual mean temperature. For example, the seasonal and multivariate character of climate at a location is intimately bound up with the local topography and land surface characteristics and cannot be captured by annual mean temperature.

The second use of spatial analogues to identify possible impacts has more legitimacy. Here, multivariate future climate scenarios for the target location are derived using GCM results for a given time period. The question is then asked, 'Where, at the present time, are there climates similar to those the target location will experience in the future?'. Lessons may then be learned from these derived analogue regions about the range of climate-dependent ecosystems, diseases, etc. that the target location may experience in the future. As long as this search for analogue climates uses multivariate techniques for climate matching - for example, by matching the annual range of temperature, precipitation seasonality, humidity regimes - rather than just the annual mean temperature, then this use of analogue regions may have some value. It should be noted, however, that their approach says nothing about the rates of change, nor the ability of species to migrate. This latter approach to analogue climates is further discussed in Sections 3.2 and 4.3 with regard to particular health applications.

Given these difficulties in making firm predictions about future climate, how should we proceed? Should we try to make the 'best' judgement or most likely estimate of future greenhouse gas emissions, employing the 'best' model available and then create the 'best' estimate of future climate change? This is the sort of approach that leads to a 'best guess' or 'business-as-usual' climate scenario. Alternatively do we consider a wide range of emissions scenarios and climate modelling uncertainties to try and capture a wide range of possible climate outcomes for a region like the UK? In this case it is necessary to judge where the important extremes in the range of possibilities lie, but still keep the number of resulting climate scenarios to a manageable number. The approach adopted in the UKCIP98 scenarios was to present four alternative scenarios of climate change for the UK spanning a 'reasonable' range of possible future climates. Some of the key assumptions behind the UKCIP98 climate scenarios are listed in Box 1.1. The future changes in climate described here are based on these UKCIP98 scenarios, paying particular attention to the period of the 2050s for all four scenarios and for all three time periods - 2020s, 2050s and 2080s - to the Medium-High scenario. We also include a number of additional analyses that did not appear in the original UKCIP98 scenario report. Section 1.2.2 below is concerned with recent observed trends in UK climate; the ranges of future global and UK climate changes are described in Sections 1.2.3 and 1.2.4. Finally, Section 1.2.5 discusses the main sources of uncertainty in climate predictions.

Box 1.1: The UKCIP98 Climate Scenario Assumptions

❏ Since no single climate-change scenario can adequately capture the range of possible climate futures, four alternative climate scenarios for the UK are presented – **Low, Medium-Low, Medium-High** and **High.**

❏ This range of scenarios derives from different values for the climate sensitivity, from different future levels of anthropogenic forcing of the climate system, and from different global climate models. The range adopted is consistent with the IPCC Second Assessment Report.

❏ The scenarios result from future changes in greenhouse gases alone. Changes in natural forcing factors such as volcanoes or solar variability are not considered; neither are changes in the concentration or distribution of sulphate aerosols created by human emissions of sulphur dioxide. The effects of sulphate aerosols on climate are highly uncertain, in addition to which their effects are likely to be transitory and of diminishing magnitude, especially over the UK.

❏ Three future time periods are considered: the 2020s, the 2050s and the 2080s.

❏ The **Medium-High** scenario is used widely, but not exclusively, in this report, since more climate model simulations and analyses have been completed under its assumptions than for the other scenarios. The **Medium-High** scenario assumes a future increase of 1% per annum in greenhouse gas concentrations. This is regarded as a convenient assumption regarding the outcome of future anthropogenic emissions rather than as a 'best-guess' outcome. Where possible, the alternative UKCIP scenarios – **Low, Medium-Low** and **High** – are also used for the 2050s period.

❏ It is assumed that Global Climate Model results have meaning at the scale of individual gridboxes (typically 300-400 km), but we generally do not attempt to interpret these results on smaller scales.

1.2.2 Observed trends in UK climate

Following the transition from a glacial to an inter-glacial world – a transition that took perhaps from about 15,000 to 10,000 years ago to be fully complete – the average temperature of the UK, when estimated for periods of 50 years or more, has fluctuated by no more than about ±1°C. For example, the period from 1650 to 1700 – the so-called 'Little Ice Age' – was no more than 1°C cooler than the twentieth century average. Associated with these small fluctuations in temperature have been fluctuations in rainfall amount and seasonality, although these changes are harder to reconstruct in quantitative terms from proxy evidence, like peat bogs and tree rings, than are those for temperature.

For the last three and a half centuries in the UK we can be rather more certain about the extent of climate variability and change. The UK possesses some of the longest instrumental climate time series in the world, the longest being the Central England Temperature series[11] which extends back to 1659 and is homogenous since 1772. This presents a unique opportunity to examine climate variability in the UK on long time scales based on observational data. It would be advantageous if these long time series could be treated as describing purely natural climate variability, thus enabling better identification of the level of human-induced climate change that is truly significant. This may not be a correct interpretation, however, since, at least during the 20th century, human forcing of the climate system has been occurring through increased atmospheric concentrations of greenhouse gases. A more probable interpretation of these long instrumental data series, therefore, is that they illustrate a mixture of natural climate variability and human-induced climate change, with the contribution of the latter increasing over time.

It is nevertheless very instructive, before future climate change scenarios are examined, to look back and appreciate the level of climate variability that the UK has been subject to in recent generations. This will give us a background for examining year-to-year, decade-to-decade and even century-to-century variations in relevant climate indices. It is within this history of past climate that the British environment, economy and society, including our health management system, has evolved and to which it has in some measure adapted. Just as future climate change can only be sensibly interpreted against a background of observed climate variability, so too the impacts of future climate change for the UK can only be properly evaluated in the context of environmental and societal adaptation to past climate variability.

Changing temperatures

The annual values of the Central England Temperature (CET) series are plotted in Figure 1.4, together with a version smoothed with a 100-year filter to emphasise the century time-scale trends. From the CET data, three observations are emphasised. First, there has been a warming of UK climate* since the seventeenth century. A linear trend fitted through the time series suggests a warming of about 0.8°C over three hundred years and of about 0.6°C during the twentieth century. Second, this warming has been greater in winter (1.1°C) than in summer (0.2°C). Third, the cluster of warm years at the end of the record means that the last decade, 1990 to 1999, has been the warmest in the entire series, with four of the five warmest years since 1659 occurring in this short period.

The CET series can also be used to examine changes in daily temperature extremes, although only since 1772[12]. Figure 1.5 shows the frequencies of 'hot' and 'cold' days in central England over this period. There has been a marked reduction in the frequency of cold days since the eighteenth century particularly during March and November. The annual total has fallen from between 15 and 20 per year prior to the twentieth century to around 10 per year over most of the twentieth century. There has been a less perceptible rise in the frequency of hot days, although several recent years (1976, 1983, 1995 and 1997) have recorded among the highest annual frequencies of such days. As with annual temperature, the last decade has seen the highest frequency of such days in the entire series averaging about 7.5 hot days per year, nearly twice the long-term average. The warm year of 1995 recorded 26 hot days in Central England, the highest total in 225 years of measurements.

Changing precipitation

There are no comparable long-term trends in annual precipitation, whether over England and Wales or over Scotland. Variations over thirty-year time scales have, nevertheless, on occasions exceeded ±10 per cent on an annual basis, or over ±20 per cent on a seasonal basis. These are quite large fluctuations in multi-year precipitation and taking such estimates to be the background level of natural precipitation variability on these time scales has important implications for how water and other moisture sensitive resources are best managed in the UK. There have been systematic changes in the seasonality of precipitation, however, with winters becoming wetter and summers becoming drier (Figure 1.6). This increasingly Mediterranean-like precipitation pattern has been evident both in Scotland (not shown) and in England and Wales.

*** Although the Central England Temperature record is based on measurements in a triangular area bounded by London, Manchester and Worcester, the year-to-year values are highly correlated with temperature variations over most of the UK.**

Also noticeable over recent decades has been an increase in the proportion of winter precipitation falling in the heaviest intensity events (rain and snow storms), a trend that has been noted across most of the UK[13]. The shift towards higher intensity precipitation in winter has been mirrored by a shift towards less intense precipitation in summer (Figure 1.7). There have been no coherent national trends in the precipitation intensity distributions of spring and autumn.

Figure 1.4

Central England temperature annual anomalies (degrees Celsius) for the period 1659–1999 expressed with respect to the 1961–1990 mean (shown by horizontal line). The smooth curve emphasises century time-scale variability

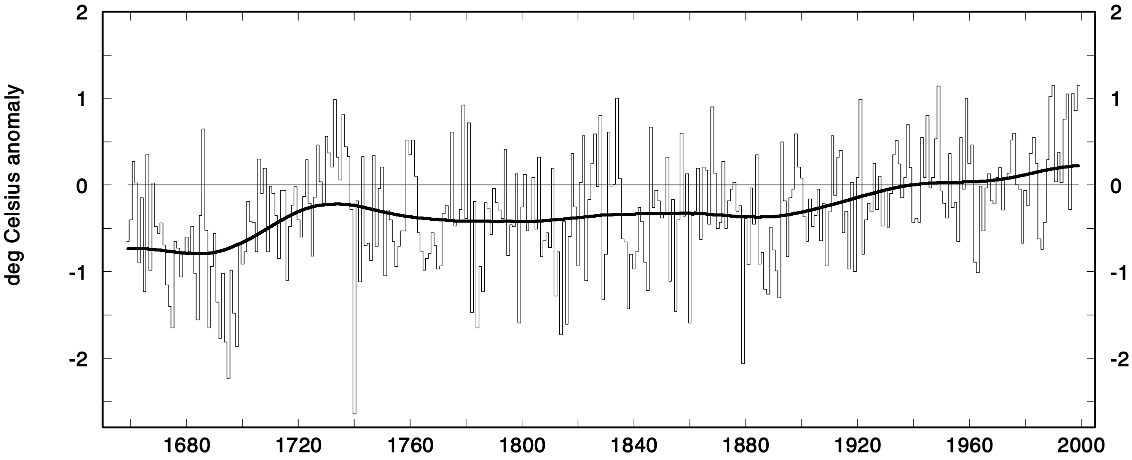


Figure 1.5

Occurrence of 'hot' and 'cold' days derived from daily mean temperature in the CET series from 1772–1999. 'Hot' days are with T_{mean} greater than 20°C and 'cold' days are with T_{mean} below 0°C

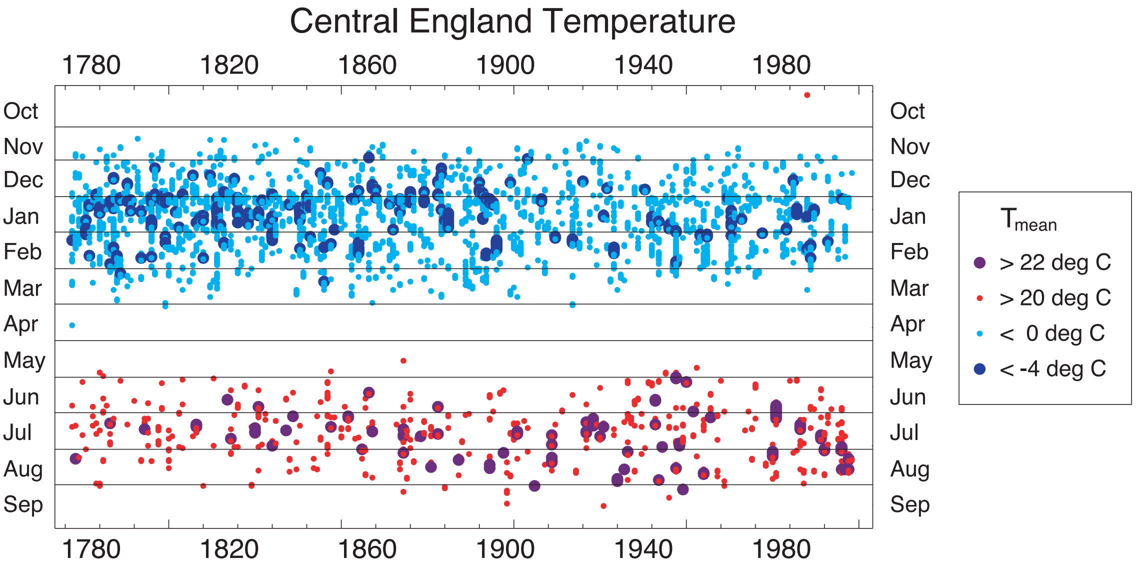


Figure 1.6

The difference between winter and summer precipitation over England and Wales for 1766–1998. The series is with respect to the 1961–1990 mean (shown by horizontal line). The smooth curve emphasises thirty year time-scale variability

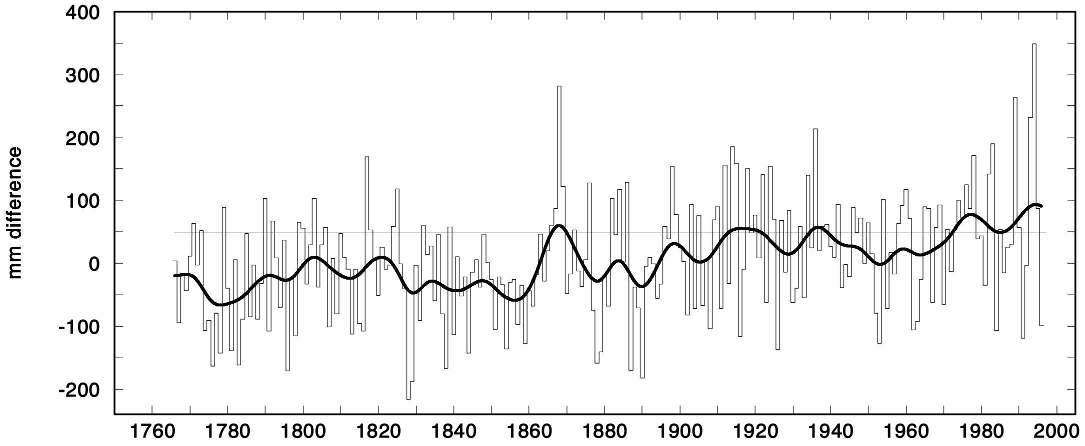
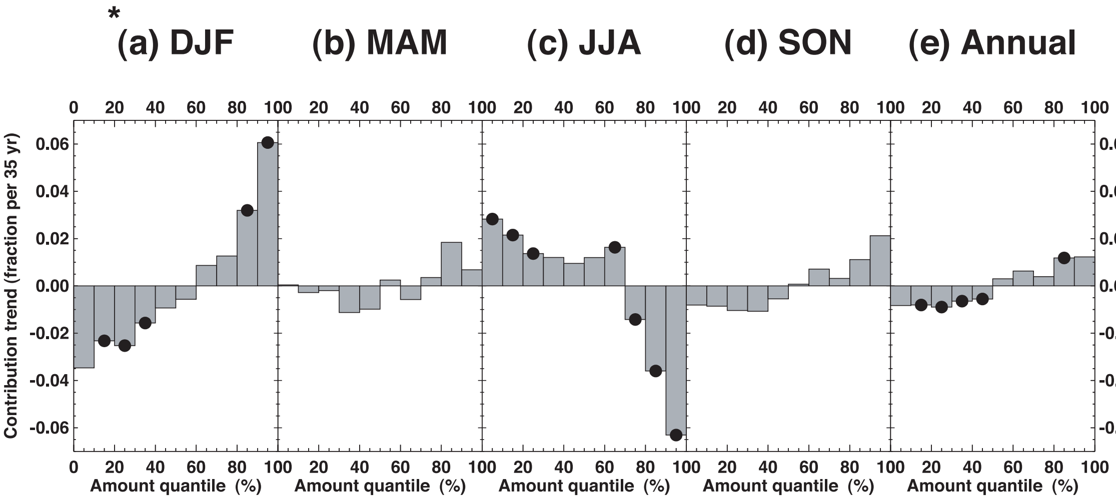


Figure 1.7

1961–1995 trends (fraction per 35 years) in the contribution of precipitation events falling in each of the 10 amount quantiles to the total winter, spring, summer and autumn and annual precipitation, after averaging the contribution time series across all UK stations. Statistically significant trends at 90% are marked with black dots[13]



* months

Changing storminess

The available data on gale frequency over the UK only extend back to 1881 and this series shows no long-term trend over the 120-year period[14]. Gale activity is highly variable from year-to-year. For example, a minimum of two gales occurred in 1985 and a maximum of 29 gales occurred in 1887. The 1961-1990 average is for just over 12 'severe gales' to occur in the UK per year, mostly in the period November to March. The middle decades of this century were rather less prone to severe gales than the early and later decades and the highest decadal frequency of 'severe gales' (15.4 per year) since the series began in 1881 was recorded during 1988 to 1997.

Changing sea level

A final indicator of trends in UK climate relates to sea-level. Climate warming is anticipated to lead to a rise in global mean sea level, primarily because of thermal expansion of ocean water and, secondly, because of land glacier melt. Long-term series of tide-gauge data for a number of locations around the UK coastline have been analysed[15]. All of these series indicate a rise in mean sea level, ranging from 0.7mm/year at Aberdeen to 2.2mm/year at Sheerness. These raw estimates of sea-level change need adjusting, however, to allow for natural rates of coastline emergence and submergence resulting from long-term geological readjustments to the last glaciation. The adjusted net rates of sea-level rise resulting only from changes in ocean volume range from 0.3mm/year at Newlyn to 1.8mm/year at North Shields. These data provide convincing evidence of a rising ocean around the UK coastline.

1.2.3 Future changes in global climate

Starting our description of future climate change at the global scale allows us to explore the relative importance of the two most important factors that affect our estimation of future climate change over the UK, namely, how will greenhouse gas emissions change in the future and how will climate respond to this change. The first factor depends upon what assumptions are made about population, consumption and energy technology, while the second factor depends *inter alia* upon the value of the climate sensitivity (Section 1.2). The UKCIP98 scenarios selected four global warming outcomes (Table 1.1) by combining two different greenhouse gas emissions futures with three different values for the climate sensitivity. The spatial and temporal changes in UK climate were subsequently related to these four different rates of global warming. None of the UKCIP analyses considered the modest direct cooling effect of sulphate aerosols. The four UKCIP98 scenarios were:

- Low: IS92d emissions scenario with a low (1.5˚C) climate sensitivity;
- Medium-Low: the HadCM2 GGd experiment (~IS92d emissions and ~2.5˚C sensitivity);
- Medium-High: the HadCM2 GGa experiment (~IS92a emissions and ~2.5˚C sensitivity); and
- High: IS92a emissions scenario with a high (4.5˚C) climate sensitivity.

Table 1.1 Global climate change estimates for three future time-slices for the four UKCIP98 scenarios.

	1980s	**1990s**	**2020s**			**2050s**			**2080s**		
	ΔT	*ΔT*	ΔT	ΔSL	CO$_2$	ΔT	ΔSL	CO$_2$	ΔT	ΔSL	CO$_2$
	degC	*degC*	degC	cms	ppmv	degC	cms	ppmv	degC	cms	ppmv
Low	*0.13*	*0.29*	0.57	7	415	0.89	12	467	1.13	18	515
Medium-Low	*0.13*	*0.29*	0.98	8	398	1.52	18	443	1.94	29	498
Medium-High	*0.13*	*0.29*	1.24	12	447	2.11	25	554	3.11	41	697
High	*0.13*	*0.29*	1.38	38	434	2.44	67	528	3.47	99	637

Note: Changes in global temperature and sea-level are calculated with respect to the 1961-90 mean. The time-slices are thirty-year means centred on the decades shown. No sulphate aerosol effects have been considered. The data for the 1980s and 1990s are observed global-mean temperature changes, again calculated with respect to the 1961-90 mean.

ΔSL: change in sea level

ΔT: change in temperature

These four scenarios predict global warming by the period 2010-2040 (i.e., the 2020s) by between 0.6° and 1.4°C, a decadal rate of warming of between 0.11° and 0.28°C/decade. The observed rate of global warming for the last two decades has been about 0.14°C/decade*. By the period 2071-2100 (i.e., the 2080s), the UKCIP98 scenarios predict a warming range of 1.1°C to 3.5°C. The global mean sea-level changes and carbon dioxide concentrations associated with the four UKCIP98 scenarios (Table 1.1) similarly reflect a range of values that may be used in climate change impacts assessments. Pre-industrial carbon dioxide concentrations (~ 275 ppmv) double by the 2050s under the Medium-High scenario and the average 1961-90 concentration (~ 334 ppmv) doubles by the 2080s under this scenario. Changes are more modest for the Low and Medium-Low scenarios, so that even by the 2080s concentrations remain below double the pre-industrial level (515 and 498 ppmv respectively). Global mean sea-level rises throughout each scenario, but the rate of rise varies from about 2 cm per decade for the Low scenario to about 9 cm per decade for the High scenario.

1.2.4 Future changes in UK climate

This Section presents a summary of climate changes for the UK for the four UKCIP98 scenarios defined in Section 1.2.3. The change patterns for the Low scenario are derived from the HadCM2 GGd experiment and for the High scenario from the HadCM2 GGa experiment. In each of these cases, the GCM patterns are scaled by the respective global warming curves to yield magnitudes of change for the UK consistent with these low (1.1°C warming by the 2080s) and high (3.5°C) rates of global warming. The patterns of change for the Medium-Low (1.9°C warming by the 2080s) and Medium-High (3.1°C) scenarios are extracted directly from the respective HadCM2 experiments, GGd and GGa. Climate changes are presented for one of three future thirty-year periods centred on the 2020s, the 2050s and the 2080s. The climate changes for each of these

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*** This observed rate of warming is quite consistent with UKCIP98 scenarios, although being calculated over only 30 years of data one should be cautious about over-interpreting the significance of this consistency.**

periods are calculated as the change in thirty-year mean climates with respect to the 1961-1990 average. The 2020s are therefore representative of the period 2010-2039, the 2050s of 2040-2069 and the 2080s of 2070-2099. The changes shown here are those anticipated to result from greenhouse gas forcing of the climate system under the assumptions discussed in Section 1.2.1. Natural climate variability (i.e., the noise of the system) will in reality modify these magnitudes and patterns of change, whether this variability is internally generated or whether it results from external factors such as solar variability or volcanic eruptions (Section 1.2.5).

Changes in temperature

Figure 1.8 shows the changes in annual-mean temperature for the four UKCIP98 scenarios. For all scenarios and for all seasons (not shown) there is a northwest to southeast gradient in the magnitude of the climate warming over the UK, the southeast consistently warming by several tenths of a degree Celsius more than the northwest. Warming rates vary from about 0.1°C per decade for the Low scenario to about 0.3°C for the High scenario. Although in general warming is greater in winter than in summer, this is not always the case. In the Medium-Low scenario for example, summers over southeast England by the 2080s are 2.4°C warmer than the 1961-1990 average, while winters warm by only 2.0°C. The year-to-year variability of seasonal and annual-mean temperature also changes. Winter seasonal mean temperatures become less variable (because of fewer very cold winters), while summer seasonal mean temperatures become more variable (because of more frequent very hot summers).

The consequences of rising mean temperature and changing interannual temperature variability are changing probabilities of very hot years (and seasons). Table 1.2 shows the changing probabilities that the annual mean temperature anomaly experienced in central England in 1997 will be exceeded in the future*. Under all four scenarios, such an annual anomaly becomes much more frequent, occurring once per decade by the 2020s under the Low scenario and nearly seven times per decade under the High scenario. By the 2080s, virtually every year is warmer than 1997 in the Medium-High and High scenarios, and between 55 and 90 per cent of years are warmer than 1997 in the Low and Medium-Low scenarios.

*** 1997 was the third warmest year ever recorded in the UK, nearly 1.1°C warmer than the average 1961-1990 temperature.**

Figure 1.8

Change in mean annual temperature (with respect to the 1961–1990 mean) for thirty-year periods centred on the 2020s, 2050s and 2080s and for the four UKCIP98 scenarios. Top row: Low scenario, changes are scaled from the HadCM2 G Gd ensemble-mean. Second row: Medium-Low scenario, changes are from the HadCM2 G Gd ensemble mean. Bottom row: High scenario, changes are scaled from the HadCM2 G Ga ensemble mean. Background fields are interpolated from the full HadCM2 grid, while the highlighted numbers show the change for each HadCM2 land gridbox over the UK

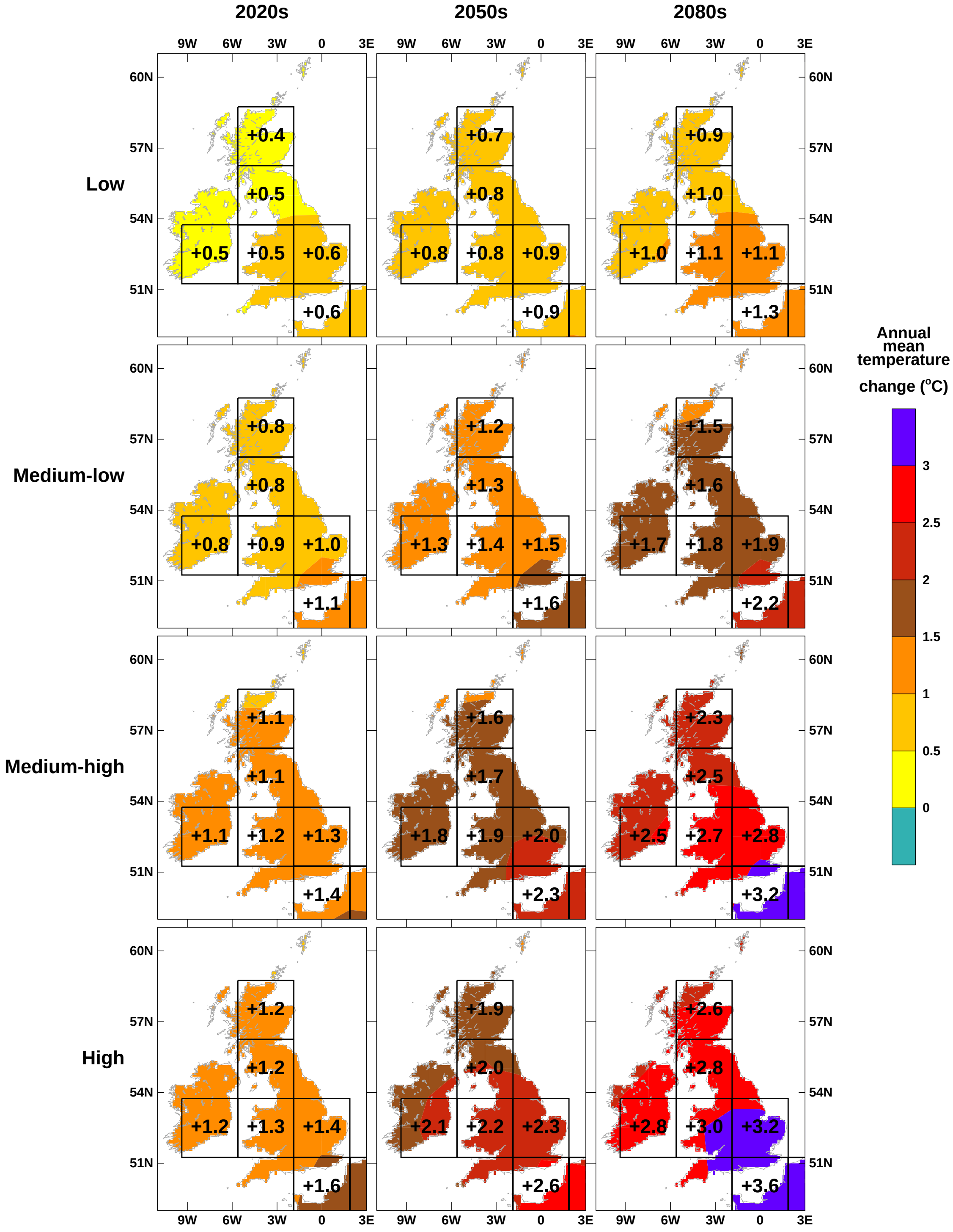

Figure 1.9

Cumulative probability distributions of model-simulated daily minimum (winter) and daily maximum (summer) temperature for Scotland (top row) and southeast England (bottom row). The blue curve shows the pre-industrial distribution, the green curve the 1961–1990 distribution and the red curve the 2080s distribution under the Medium-High scenario

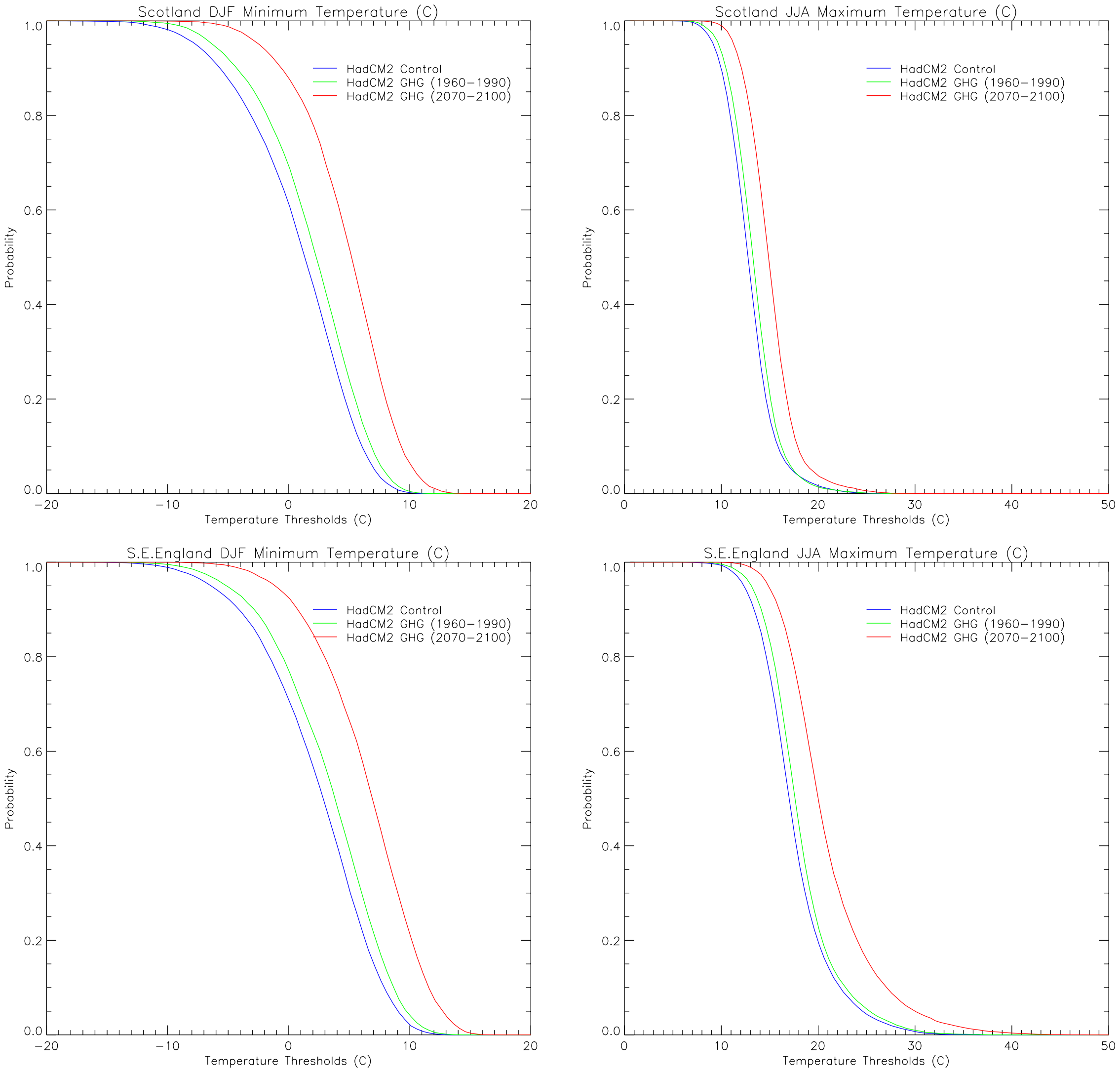

Table 1.2 Percentage of years in southern UK exceeding an annual-mean temperature anomaly of +1.06°C above the 1961-1990 mean (i.e., the observed 1997 annual anomaly for central England) under the four UKCIP98 scenarios

	1961-1990	**2020s**	**2050s**	**2080s**
Low	6	13	26	56
Medium-Low	6	47	74	88
Medium-High	6	59	85	99
High	6	67	89	100

The 1961-90 values are based on model simulations and not on observations

The distribution of daily temperature extremes also changes in the future. Figure 1.9 shows, for the Medium-High scenario by the 2080s, the new distributions of daily minimum (winter; Figure 1.9 left) and maximum (summer; Figure 1.9 right) temperatures for two regions in the UK. The shapes of the distributions do not change greatly, but they are all displaced by approximately the mean seasonal warming expected by the 2080s. Thus for southeast England in winter, the mildest nights are currently about 12-13°C, but by the 2080s some winter nights reach 15°C. Similarly in summer over Scotland, the hottest days currently reach between 23-24°C, but by the 2080s some daily maxima reach 27°C. Some further specific examples of changing probabilities of model-simulated daily temperature extremes are shown in Table 1.3*.

Table 1.3 Probability of daily temperature extremes for Scotland and SE England derived from the HadCM2 model for the UKCIP Medium-High scenario

	Winter nights below freezing		**Summer days above 25°C**	
	Scotland	**SE England**	**Scotland**	**SE England**
Present: 1961 -1990	0.28	0.20	0.00	0.06
Future: 2080s	0.11	0.07	0.01	0.18

These probabilities are for climate model gridbox regions (~10 000km^2) and therefore the absolute probabilities will differ from those measured at individual stations

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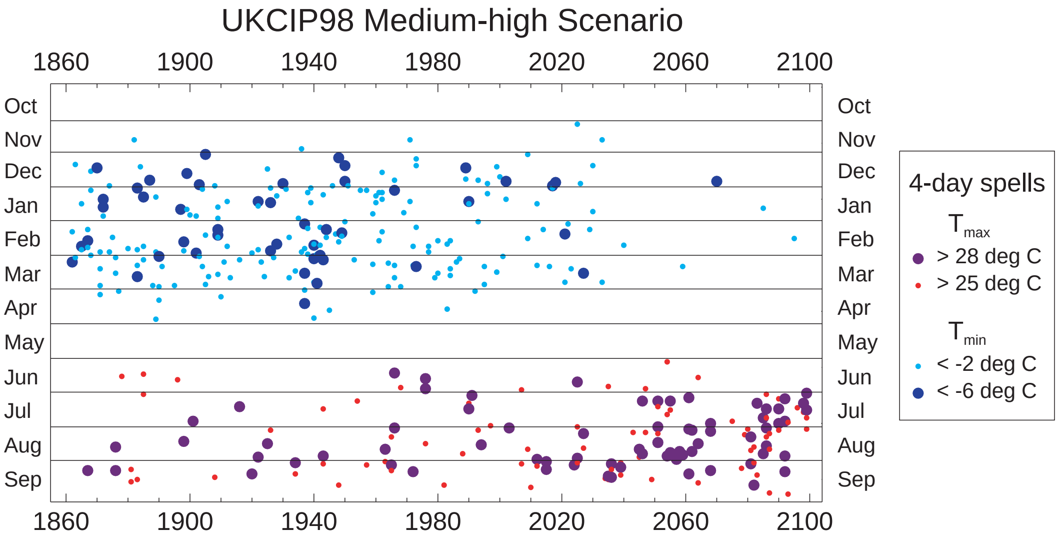
*** It should be noted that all these quoted temperatures refer to model-simulations; although the relative changes may be credible, the absolute numbers cited will differ from site observations.**

Changes in these distributions of daily temperature extremes will lead to changed probabilities of 'hot' and 'cold' spells of different duration. Figure 1.10 shows one example for the southern UK for the Medium-High scenario. This Figure plots the occurrence of hot and cold spells of four or more consecutive days with daily maximum temperature above one of two thresholds (25°C or 28°C) and with daily minimum temperature below one of two thresholds (-2°C and -6°C). The effect of climate warming is quite dramatic. During the twentieth century there were on average 1-2 cold spells (-2°C threshold) per winter. After the year 2040, only four such cold spells are recorded. Conversely for hot spells, less than one hot spell (25°C threshold) per summer was recorded during the twentieth century, but after 2040 more than two such hot spells are recorded on average each summer. The increase in hot spell frequency where daily maximum temperatures are sustained above 28°C is even more noticeable (Figure 1.10). Further work is possible to examine the changing frequencies of days with high temperature and high humidities.

Figure 1.10

Frequency of 'hot' and 'cold' spells in southern UK from 1860 to 2099 as simulated by the HadCM2 model for the Medium-High scenario. Hot spells are four or more consecutive days with T_{max} greater than 25°C or 28°C. Cold spells are four or more consecutive days with T_{min} less than -2°C or -6°C



Changes in precipitation

Figures 1.11 and 1.12 show the per cent changes in total precipitation for winter and summer for the four scenarios and the future time periods. The patterns of precipitation change are less consistent between seasons and scenarios than the equivalent temperature changes. Annual (not shown) and winter precipitation increases for all regions, periods and scenarios, although the annual increases by the 2080s for the Low and Medium-Low scenarios are very modest at only a few per cent. Winter precipitation increases are largest and reach 20 per cent or more for the 2080s in the High scenario. Increases in winter precipitation of this magnitude are certainly significant. For the summer season, there is a general tendency for drying in the south of the UK and wetting in the north. These changes are modest, however, and probably only significant in the southeast of the UK and for the 2080s period in the Medium-High and High scenarios. The other two seasons (spring and autumn) are not shown here, but autumn displays patterns of change broadly similar to winter, while precipitation changes in spring are generally very small (not significant).

Despite these contrasting changes in mean seasonal precipitation, all seasons experience an increase in the year-to-year relative variability of seasonal precipitation throughout the UK. This means that seasonal precipitation totals will differ from the average level by greater amounts more often in the future than at present. Two examples of what this may mean for future precipitation anomalies are shown in Table 1.4. The probability of summers experiencing rainfall deficits of 50 per cent or more increases very substantially. By the 2080s such dry summers occur once per decade compared to once per century under modelled present-day climate. In contrast, the probability of successive dry years - defined as a two-year precipitation deficit of 10 per cent or more - changes little in the future. By the 2080s, such successive dry years actually becomes less likely because the increased summer precipitation deficits are more than compensated by increased precipitation in other seasons. The statistics in Table 1.4 relate to precipitation only and make no allowance for increased moisture deficits induced by higher evaporation losses. The warming UK climate is likely to lead to higher evapotranspiration rates. For the Medium-High scenario for example, summer potential evapotranspiration increases by up to 10 per cent or more over southern UK. Summer droughts, when defined in terms of precipitation minus evaporation, are likely to become much more frequent in the future, especially over the southern UK.

Figure 1.11

Change in winter precipitation (with respect to the 1961–1990 mean) for thirty-year periods centred on the 2020s, 2050s and 2080s and for the four UKCIP98 scenarios. Top row: Low scenario, changes are scaled from the HadCM2 G Gd ensemble-mean. Second row: Medium-Low scenario, changes are from the HadCM2 G Gd ensemble mean. Bottom row: High scenario, changes are scaled from the HadCM2 G Ga ensemble mean. Background fields are interpolated from the full HadCM2 grid, while the highlighted numbers show the change for each HadCM2 land gridbox over the UK

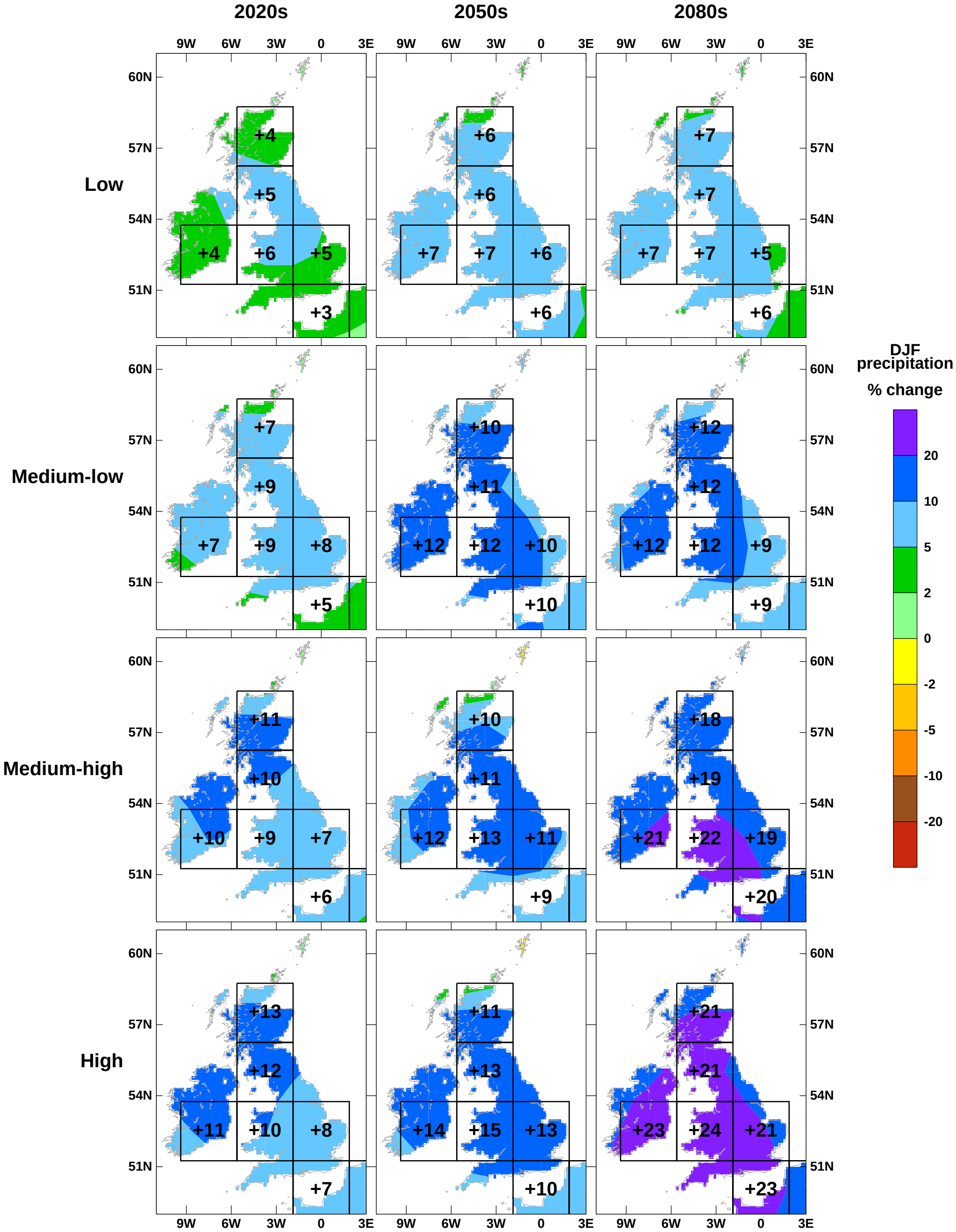


Figure 1.12

Change in summer precipitation (with respect to the 1961–1990 mean) for thirty-year periods centred on the 2020s, 2050s and 2080s and for the four UKCIP98 scenarios, changes are scaled from the HadCM2 G Gd ensemble mean. Bottom row: High scenario, changes are scaled from the HadCM2 G Ga ensemble mean. Background fields are interpolated from the full HadCM2 grid, while the highlighted numbers show the change for each HadCM2 land gridbox over the UK

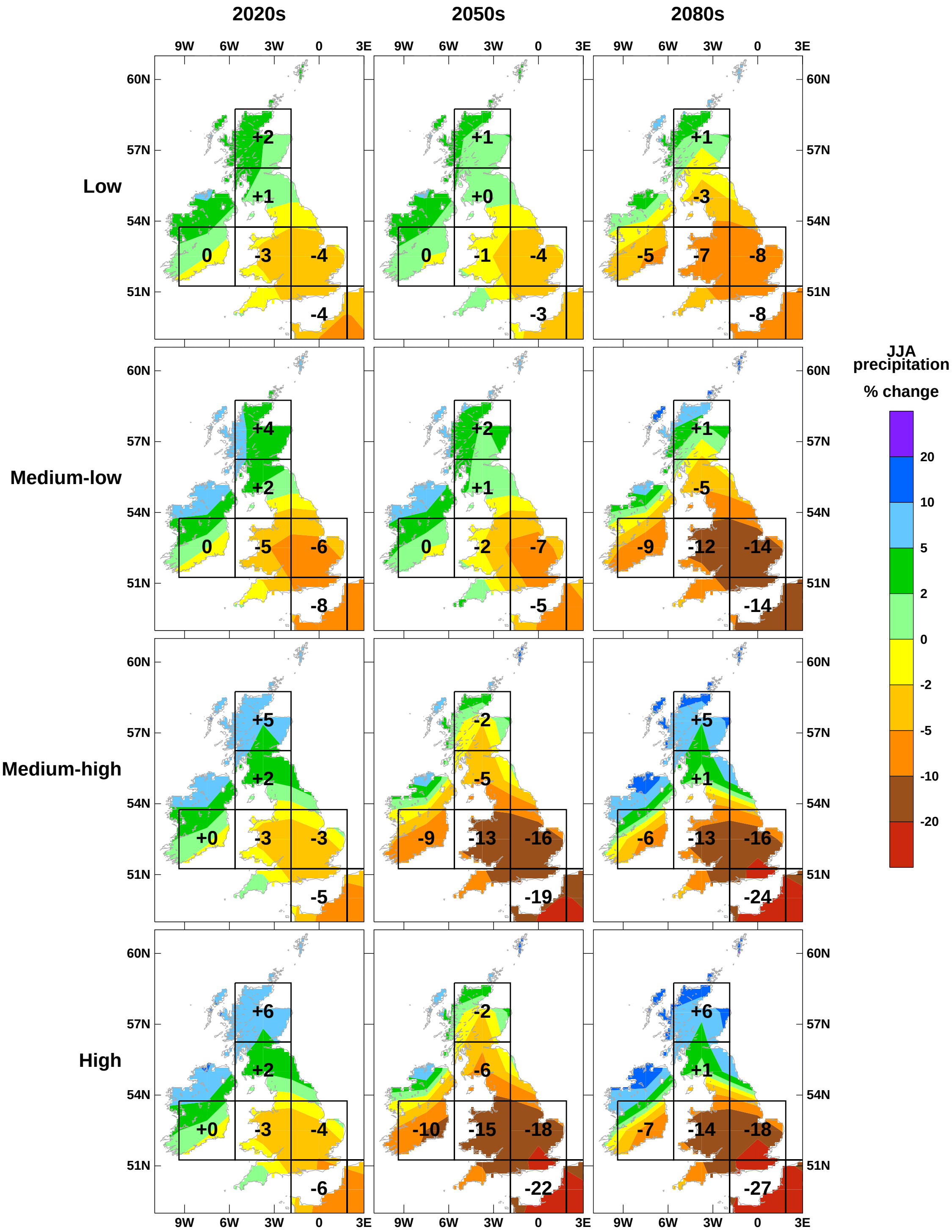


Table 1.4 Percentage of years experiencing various seasonal precipitation anomalies across southern UK for present climate (1961-1990) and for three future thirty-year periods for the Medium-High scenario

	1961-1990	2020s	2050s	2080s
Summer precipitation below 50% of average	1	7	12	19
A 2-year precipitation total below 90% of average	12	11	14	6

The 1961-1990 values are based on model simulations and not on observations

It was noted in Section 1.2.2 above that the intensity of daily winter precipitation in the UK has been observed to be increasing over recent years. Increases in the intensity of daily precipitation over the UK are also a feature of the UKCIP98 climate scenarios, in both winter and summer seasons. Interestingly, the increase in the intensity of daily summer precipitation occurs despite the overall reduction in seasonal totals, at least over the southern UK. This future increase in precipitation intensity, particularly in the winter half-year, is likely to increase the risk of riverine flooding in various UK catchments. Analysis of the daily precipitation regimes over the UK in the Hadley Centre Regional Climate Model (RCM)* confirms these increases in precipitation intensities[16]. In the RCM, the most intense daily precipitation events - those events that occur just 1 per cent of the time - increase in frequency by the 2080-2099 period under the Medium-High scenario by about 50 per cent in summer and by up to 150 per cent in winter.

Changes in storminess

Storminess is measured here in terms of gale frequencies over the UK, these gale frequencies being derived from large-scale surface atmospheric pressure fields. Changes in the frequencies of three different categories of gales are shown in Table 1.5 for the Medium-High scenario. For the winter season, there is a suggestion that overall gale frequencies may decline in the future, although very severe winter gales may increase. Note that the changing sign of the changes in severe gale frequencies between the three periods indicates that a clear anthropogenic signal in severe gale frequencies is not easily detectable from the noise of natural climate variability. Summer gales are much less frequent (less than two per year) than winter gales and consequently any changes in summer gale frequencies are likely to be small.

*** The RCM operates at a spatial scale of 50km, compared with the GCM (from which the UKCIP98 scenarios were derived) resolution of about 300km**

Table 1.5 Changes in seasonal gale frequencies over the British Isles for the 2020s, 2050s and 2080s for the Medium-High scenario shown as per cent changes from the 1961-1990 mean

	1961-1990 Gales/year	2020s %change	2050s %change	2080s %change
Winter gales	10.9	-1	-9	-5
Winter severe gales	8.5	-1	-10	-5
Winter very severe gales	1.4	+8	-10	+11
Summer gales	1.8	+3	0	+14
Summer severe gales	1.1	0	-2	+15
Summer very severe gales	0.1	+25	-16	+9

The 1961-1990 frequencies are calculated from climate model outputs and not from observations

Related to this analysis of gale frequencies are changes in airflow characteristics over the UK. Three aspects of airflow are analysed: flow strength, vorticity (i.e., anticyclonic or cyclonic flow) and flow direction. This analysis suggests a tendency for autumns to experience windier conditions, with a reduction in northerly and easterly flow and an increase in southwesterly and westerly flow. Summers become slightly more anticyclonic in character with more westerly and northwesterly flow, while winter and spring become slightly less anticyclonic. These changes in airflow characteristics may be important for certain aspects of the UK environment, for example air pollution levels in cities or episodes of acid deposition.

Possible changes in the frequency of lightning may also be suggested under the Medium-High UKCIP98 scenario. Lightning frequencies are related to convective thunderstorm activity. Although lightning frequency is not modelled explicitly in HadCM2, on the basis of sensitivity experiments performed in other climate modelling centres[17] and the changes in convective precipitation estimated by the HadCM2 model, by the 2080s, lightning frequency over the UK for the Medium-High scenario may increase by about 20 per cent. This conclusion is consistent with the picture of increasing precipitation intensities that emerged earlier.

Changes in sea-level

Changes in mean sea level around the UK coast will be very similar to the global mean shown in Table 1.1. Although there will be regional differences in the rate of sea-level rise due to climate change, for the UK region the HadCM2 experiments generate results that for the 2050s are generally within 2 or 3 cm of the global mean. For the 2050s, for example, sea level rise around the UK coast is about 10 per cent higher than the global mean. This occurs due to regional changes in ocean currents and atmospheric pressure that lead to greater rates of thermal expansion and water accumulation in the northeast Atlantic compared to the global average. What is more important when evaluating these sea-level changes, however, is to consider natural vertical land movements and changing storm-surge regimes.

Vertical land movement (a naturally rising or falling coastline) occurs as a result of isostatic adjustments. The UK is tilting as a result of such adjustment, so that much of southern UK is presently sinking and much of northern UK is rising. We show some representative rates for the UK coastline in Table 1.6, alongside the climate-induced changes in sea level for the 2050s. The two most extreme regions for vertical land movements are East Anglia, sinking by 9 cm by the 2050s, and western Scotland, rising by 11 cm. Under the lower-estimate scenarios of climate-induced sea-level rise these natural land movements can be very significant in exacerbating or reducing the estimated climate-induced change in mean sea level around the UK coast.

Table 1.6 Representative changes in sea level (cms) around the UK coast by the 2050s due (i) to global climate change only ('Climate') and (ii) to the combined effect of climate and natural land movements ('Net')

	Low		Medium-Low		Medium-High		High	
	Climate	**Net**	**Climate**	**Net**	**Climate**	**Net**	**Climate**	**Net**
West Scotland	13	2	20	9	28	17	74	63
East Scotland	13	8	20	15	28	23	74	69
Wales	13	18	20	25	28	33	74	79
English Channel	13	19	20	26	28	34	74	83
East Anglia	13	22	20	29	28	37	74	83

The global-mean climate-induced sea-level changes shown in Table 1.1 are used here, but adjusted by 10 per cent to account for slightly higher rates of increase around the UK coastline. Changes are with respect to average 1961-1990 levels

A second factor to consider in relation to sea-level rise and coastal flooding risk is the changing nature of storm surges. A rise in mean sea-level will result in a lower surge height being necessary to cause a given flood event, leading to an increase in the frequency of coastal flooding. If surge statistics remain the same in the future this changed flooding risk may be calculated quite simply. However, surge statistics may change for a number of reasons. The tracks and intensity of mid-latitude cyclones may change in the future and the formation and evolution of storm surges may also change, particularly in shallow waters. Recent model analysis[18] has explored these issues for the UK coastline and we cite one example for Immingham, on the North Sea coast.

Under current climate and meteorology, a storm surge height of 1.9 m at Immingham is estimated from models to occur on average once every 500 years. A rise of 50 cm in mean sea level (expected by about 2090 in the Medium-High scenario), and a simple calculation assuming other factors remain unchanged, suggests a new return period of about 30 years for the 1.9 m surge. Allowing for changes in storm activity and surge propagation further reduces the 1.9 m surge return period to about 12 years, a 50-fold increase in flooding risk by 2090. This same analysis can also be expressed in terms of the increased height of the 1-in-500 year surge - an increase of 80 cm from 1.9 m to 2.7 m (50 cm due to the background rise in mean sea level and 30 cm due to changed storm surge statistics). Such potential changes in risk of coastal flooding raises concerns about the adequacy of our coastal protection infrastructure and our ability to provide early flood warnings.

1.2.5 Consideration of uncertainties

The future climates of the UK illustrated in this section are modelled scenarios. They are plausible and self-consistent descriptions of future UK climate, but they originate from different assumptions about future emissions of greenhouse gases. Furthermore, the transformation of these emissions into future climate change estimates is itself beset with uncertainty due to the role of other climate agents and poorly-represented processes in the climate models.

The existence of uncertainties does not imply the absence of knowledge. There are some aspects of future climate change we may have greater confidence in than others. Although formal levels of confidence cannot be applied, we judge that we are more confident about future increases in carbon dioxide concentrations and in mean sea level than we are about increases in storminess or about more frequent summer droughts. On the other hand the likelihood of rapid, non-linear changes in regional climate is simply unquantifiable at the present time.

It is worth briefly rehearsing five of the main sources of uncertainty about future climate prediction since all of these qualify the descriptions of future UK climate summarised here. These five main sources of uncertainty are:

- unknown future greenhouse gas emissions;
- natural climate variability;
- different responses between different global climate models;
- poorly resolved regional and local climate changes; and
- the possibility of abrupt, non-linear changes in the climate system.

Uncertain future greenhouse gas emissions

The UKCIP98 scenarios assume two different future growth rates for greenhouse gas emissions: 1% per annum growth in net atmospheric greenhouse gas concentrations for the High and Medium-High scenarios and 0.5% per annum growth for the Medium-Low and Low scenarios. The 1% per annum growth rate approximates the IS92a emissions scenario, which has been widely used as a standard emissions profile, while the 0.5% per annum growth rate approximates an emissions profile more like IS92d. The current (1990s) growth rate in net greenhouse gas concentration is approximately 0.8% per annum. These IS92 emissions scenarios presume that no intervention occurs and are based on different assumptions about future population and economic growth and about different energy futures. It is possible of course that future concentration growth rates may fall outside this range. The new set of emissions scenarios being prepared for the IPCC Third Assessment Report (the SRES scenarios) also assume non-intervention, and the range of their greenhouse gas concentration growth rates is from about 0.4% per annum growth to about 1.1%.

Whether or not one sees these different emissions profiles as equally likely, it is clear that the UKCIP98 Medium-High and Medium-Low scenarios span a reasonable, but not comprehensive, range of the possible future climate outcomes that are due to different anthropogenic forcing rates. It is important, nevertheless, to consider at the very least each of these two emissions futures in an impact assessment. We have no objective way of assessing which of these two futures, or indeed any other future one may define, is the more likely[19].

The effects of natural climate variability

Other factors that are also not 'predictable' will almost certainly affect climate, in particular cooling due to volcanic dust and both warming and cooling due to the changing energy output of the sun. However, the effect on climate of even a major volcanic eruption, such as Mt Pinatubo in 1991, disappears after a few years and so, barring an unusual succession of major energetic eruptions, modifications due to volcanoes of the climate change scenarios shown here are likely to be small. Although the direct output of the sun affects climate, this effect has been small over the past 100 years and there are no indications that these quite modest effects will change in the future. There are theories that the sun can affect climate in indirect ways, such as its ability to modify cosmic rays and, potentially, cloud cover, but these theories remain speculative.

The natural internal variability of the climate system may also modify the climate change scenarios described here. For example, natural internal climate variability may cause the 30-year average climates described here to vary in temperature by up to ±0.6°C in winter and up to about ±0.4°C in summer and in precipitation by up to about ±10% in both summer and winter. This latter result means that it is possible that for some of our scenarios and for the earlier time periods, natural precipitation variability may even switch the sign of average seasonal precipitation changes, more so in summer than in winter.

Uncertainties arising from climate modelling

The UKCIP98 climate scenarios are based on results from the HadCM2 climate model experiments, results from other GCM experiments were not used. There are several climate laboratories around the world, however, that perform similar climate experiments to the Hadley Centre. Different global climate models yield different estimates of regional climate changes, sometimes quite large differences, and it is difficult to know which are inherently more believable. For example, a number of other leading global climate models show more rapid annual warming over the UK compared to the UKCIP98 scenarios, in some cases by almost 0.1°C per decade. For precipitation, all leading models show an increase in annual and winter precipitation over northern UK, but differ in their response in the south of the country and in summer. Some models show more extreme summer drying than the UKCIP98 scenarios and some models show less drying. Quantifying such differences between models is important if the full range of uncertainty is to be sampled[20].

Obtaining regional scenario information

The climate scenario information for the UK has been depicted at the spatial scale that is resolved by the HadCM2 climate model, namely 2.5° latitude by 3.75° longitude. This model resolves only four discrete regions within the UK, roughly describable as 'Scotland', the 'Scottish/English borders', 'Wales' and 'England'. The coarse resolution of global climate models such as HadCM2 is necessary in order for them to run on even the largest supercomputers but it has a number of implications for the climate change scenarios derived from them. First, the coarse GCM grid greatly simplifies the coastline and topography of a country like the UK. For example, the Shetland Islands do not exist in HadCM2 and the 'Scotland' gridbox has a uniform elevation of 221 metres. These simplifications of geography may alter the larger-scale circulation in the model and make the modelled response to anthropogenic forcing, even at the GCM resolution, different from reality. Second, within each gridbox there is a great deal of heterogeneity in the land cover characteristics that interact with the atmosphere. This heterogeneity cannot be captured by a GCM and, again, means that the large-scale modelled response to external forcing is greatly simplified. Third, and largely because of the first two limitations, within a single GCM gridbox there may in reality be quite different climate responses to anthropogenic forcing. Thus warming over the east of Scotland may be different to warming over the west. The UKCIP98 scenarios cited here cannot discriminate between such local differences.

This coarse spatial resolution of GCM-based scenarios is therefore a limitation in their application to a range of impact assessments. These assessments may either be quite localised - around a single river catchment or urban area - or may operate on a national scale, but with a spatial resolution of kilometres or tens of kilometres rather than hundreds of kilometres, for example a national land use classification assessment. Just how much of a limitation this is requires some consideration of the problem of 'downscaling' climate change information. A downscaling analysis for the UK is beyond the scope of this Report, but it should be noted that more detailed regional climate change scenarios may modify some of the climate descriptions presented here. For this reason, Regional Climate Models have been developed with a higher resolution (typically 50km), but extending over a domain smaller than global (e.g. Europe). They are driven by boundary conditions taken from a GCM and hence are subject to uncertainties present in the GCM, but they do provide a much more realistic and detailed representation of current climate and hence give more detailed regional climate predictions than do GCMs. The new set of national UK scenarios - the UKCIP02 climate-change scenarios - use results from RCM experiments.

Rapid or non-linear climate change

The UKCIP98 climate scenarios have been derived from climate models that include the best possible representation, consistent with current understanding and computing limitations, of processes in the atmosphere, ocean and land that will determine climate change. However, we do not understand the climate system well enough to be able to rule out other outcomes. It has been suggested, for example, that relatively rapid climate change could occur if the climate system shows a non-linear response to increased greenhouse gas concentrations.

One example of this would be a change in the thermohaline circulation (THC) of the world's oceans. The THC consists of strong ocean currents that transport large amounts of heat around the world. It has been suggested for some time that a collapse of the THC in the north Atlantic could cause cooling over northwest Europe. The THC brings warm sub-tropical water into the North Atlantic and this water loses its heat to the atmosphere, hence keeping northwest Europe, and particularly the British Isles, warmer than it would otherwise be. A recent model experiment in which the THC was artificially switched off left the British Isles some 3°C cooler than at present. It is thought that under certain climate regimes the THC could flip from an 'on' state to the colder 'off' state. The last time this is believed to have happened in a major way was in the Younger Dryas era, about 11 000 years ago, when Europe experienced a substantial cooling for a few centuries, interrupting the general warming coming out of the last ice age. There is also some suggestion that weaker variations in the THC have occurred more recently, resulting in less dramatic, but still significant, climate variability on a number of different time scales.

The Hadley Centre model, in common with some others, shows a slow weakening of the THC as greenhouse gas concentrations increase[21]. It is important to realise, however, that the slow cooling due to this effect will only partially offset the general warming from the increases in greenhouse gases. The north Atlantic will still warm, but parts will warm at a slower rate than if the THC had remained constant. A sudden, more dramatic collapse of the THC has not been seen in any experiment using the most comprehensive climate models. Nevertheless, we must take the possibility seriously because of the potential major impact of such an event. Large unforced variations in the THC have been seen in some climate models, albeit less dramatic than those that occurred during the Younger Dryas, but which still lead to significant climate impacts on the UK. There are also some model studies that suggest that THC variability becomes larger as a result of global warming. The likelihood of a major collapse of the THC, and hence a much reduced warming over the UK or even a cooling, does not appear to be high. At present, however, we have little no way of assigning even a nominal probability to such an event occurring. For the purposes of this report this possibility has been ignored.

Another potential non-linearity in the climate system stems from the response of the natural carbon cycle to human-induced climate change; this factor is not included in the UKCIP climate scenarios. The Hadley Centre has recently developed a climate model which for the first time includes an interactive carbon cycle. This shows that human-induced climate change could result in the dying back of some natural forested areas, with a consequent release of additional carbon dioxide into the atmosphere. Higher temperatures may also cause soils to give up some of their stored carbon. Both these factors lead to a substantially higher model-simulated atmospheric carbon dioxide concentration in the future, and hence to a more rapid climate change. This result is preliminary, but at least indicates the potential for amplification of climate change via a positive carbon cycle feedback.

A third area for concern lies in the behaviour of the west Antarctic ice sheet (WAIS). It is possible that a much more rapid rise in sea level than suggested in our scenarios could occur should the WAIS disintegrate. The WAIS is grounded below sea level and is therefore potentially unstable. If it were to disintegrate completely, global sea-level would rise by about five metres, possibly over as short a period as 200 years. This would present major disruption to our coastal regions. Predictions about the contribution of the WAIS to sea-level rise are difficult and uncertain for at least two reasons. The first is the complexity of processes determining the stability of the WAIS and the second is the uncertain relationship between changes in accumulation and discharge of ice due to global warming and the effects of natural millennial-scale trends in climate. The most likely scenario[22] appears to be one in which the WAIS contributes relatively little to sea-level rise in the twentieth century, but over following centuries higher discharge rates from the ice sheet increase its contribution to sea-level rise to between 50 and 100 cm per century. Furthermore, by the end of the next century, temperatures may have risen sufficiently for melting of the Greenland ice sheet to double the rate of global sea-level rise indicated in Section 1.2.3[23].

1.2.6 Research needs

- There remains a fundamental need to improve our ability to model global climate using global climate models.
- A robust range of future climate scenarios should be developed that are derived from regional climate models and which better represent changes in daily weather extremes.
- A better understanding of the processes and thresholds that may lead to abrupt, non-linear changes in the climate system is needed.

1.2.7 Further reading and sources of information

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Web sites

The Climate Impacts LINK Project: http://www.cru.uea.ac.uk/link/

The Hadley Centre for Climate Prediction and Research: http://www.met-office.gov.uk/sec5/sec5pg1.html

The UK Climate Impacts Programme: http://www.ecu.ox.ac.uk/ukcip.html

The British Atmospheric Data Centre (BADC): http://tornado.badc.rl.ac.uk/

The Inter-governmental Panel on Climate Change (IPCC): http://www.ipcc.ch/

The IPCC Data Distribution Centre (DDC): http://ipcc-ddc.cru.uea.ac.uk/

The IPCC Special Report on Emissions Scenarios (SRES): http://sres.ciesin.org/index.html

The LARS Weather Generator: http://www.lars.bbsrc.ac.uk/model/larswg.html

The Tyndall Centre for Climate Change Research: http: //www.tyndall.ac.uk/

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2 PUBLIC PERCEPTION OF THE HEALTH IMPACTS OF CLIMATE CHANGE

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2.1 Introduction

This section covers the health effects of climate change as people perceive them. It summarises what is known about how well the links between climate change and health are understood and about public attitudes to climate change as a factor in health. It attempts to set out some of the questions the different constituencies of the public might have on the subject.

A knowledge of the public perception of the health impacts of climate change is important for a number of immediately practical reasons:

- ❑ as a measure of the effectiveness of official communication about the topic;
- ❑ as a guide to the questions that Government and scientists will have to answer in dealing with public concern;
- ❑ as a factor to be considered in setting priorities for research;
- ❑ as an indication of the potential for change in behaviour to address the problem of climate change; and
- ❑ as a measure of the likely strength of public pressure for political action on climate change.

There is also the prospect that a study of public understanding will reveal lay knowledge that will contribute to the understanding of the problem and of potential solutions.

There is now a considerable body of information on the broad topic of public understanding of environmental change, derived from surveys, work in groups and media analysis. Much of this work has been undertaken to obtain a more rounded understanding of public attitudes towards the environment for the purposes of developing and implementing environmental policy and environmental information programmes. The aim has been to describe the shades of opinion across society, the relationships between expert and lay knowledge of the environment, and to examine how public appreciation of problems and the desirability of finding solutions could be a basis for action.

There are broadly two approaches, with a distinction between survey work focused on cognitive issues of individual understanding[1] and work in groups exploring cultural and moral dimensions, aimed at a knowledge of contextual understandings of climate change[2].

Studies made of public perceptions of environmental problems therefore include investigations of the way in which the issues are understood by different sections of society and their evaluation of and attitude towards them[1]. The relative importance of environmental issues to other public concerns has been investigated, as has the degree of public support for action at political, community and personal levels through risk analysis techniques[3].

There are a number of international comparisons which seek to explore differences between different societies either through large scale surveys[4] or in-depth work with small groups[5].

Since we now live in highly pluralist societies a single unique 'public attitude' or 'opinion' on any specific environmental issue is unlikely, although some societies display a more developed consensus than others. In general, the different constituencies of the public (referred to frequently in the literature simply as 'publics') must be expected each to present a spectrum of opinion. Similarly it can be expected that there will be considerable differences between the most commonly held views of the different publics. There is, therefore, an issue about the general relevance of work done on public perception, even where the results are taken from a sample chosen to represent a cross section of the wider public in a particular society.

There is also a question about the degree to which perception should be translated into a propensity for action. Where surveys suggest support for particular official positions or policy initiatives, does this continue to apply even where the consequences might be problematic at an individual level?[4,6,7]

Despite these methodological issues, several broad common themes have emerged from the work on public perception of the environment. This section aims to describe some of these themes as they apply to the specific issue of health and climate change.

However, within the study of public understanding of the environment, the problem of health impacts of climate change is highly specific and there is little work available. The principle route into the topic is therefore through a combination of work on the broader issues of climate change and health and the environment.

2.2 Public Understanding of Climate Change

There is a large amount of published work on public understanding of climate change. Much of it derives from interest in the cognitive or psychological processes by which people make sense of the risk associated with climate change[8]. There is also work on the understandings people acquire from the representations of the climate change as shown, for example in the media[9]. There are a few studies of the way in which the understanding reached is embedded in (and affected by) the broader notions of citizenship and individual and institutional responsibility in different societies[2]. The following is an attempt to summarise the broad themes that emerge from this work.

There is considerable consensus amongst investigators that the problem of global warming is now understood by lay publics as a reality and as an issue of concern within society. It tends to dominate discussions of global environmental problems. However, most studies suggest that global warming is no longer peoples' main social or environmental concern; crime and unemployment commonly rank above the environment[4] and of environmental concerns, air pollution and toxic waste are generally perceived as more pressing than climate change[10].

Studies also show that people have a strong tendency to use 'global warming' as a catch-all phrase, so that the problems of stratospheric ozone depletion and air pollution in general often become included within it[11]. There is also evidence that there is a tendency to confuse climate and weather[12]. Some investigators believe this to be driven, at least in part, by the media treatment of recent episodes of severe weather. It is widely recognised that there are cycles of media attention and that these have a powerful role in influencing the type and framing of issues within the public arena for debate[13]. Environmental issues, including global environmental change, are subject to these cycles of attention[14] and where periods of higher media attention to environmental issues coincide with particular catastrophic events or risk issues, these are often conflated in both the framing strategies of the media and in lay discussions[2].

Apart from increased incidence of severe weather, people may attribute changed agricultural yield, species extinction and health effects to climate change; the health impact is seen largely in terms of an increase in skin cancer[1]. When environmental issues are framed as health concerns any gender variation in the perception of risk tends to disappear[15].

People's perception of the responsibility for action seems diffuse. There is wide understanding that pollution from energy conversion and industry is the prime cause of climate change, but few people make the link between their own energy consumption and greenhouse gas emissions. This is a common finding in studies of public understanding of climate change: the failure to link global impacts to the personal action of individuals[11].

Studies of public reaction to environmental risk issues suggest a considerable mistrust of governments companies or experts. However, there seems to be a strong belief that governments should take the lead in resolving environmental problems[16]. This is linked to feelings of lack of personal efficacy identified above, as well as the social desire for institutional accountability.

There appears to be a moderate degree of trust in the ability of experts to address climate change effectively, more so than in their ability to address other key concerns such as crime or traffic accidents. However, there is less confidence in expert ability to address climate change than environmental pollution in general or health risks such as AIDS or heart disease[16].

Studies of perception between different societies suggest that the patterns described above are broadly repeated, though with differing emphasis. A comparative study of public understanding in the UK and the Netherlands, for example, found that the mistrust of claims of safety was particularly pronounced in the UK. The citizens of the Netherlands had a firmer 'social contract' with their government and institutions, and seemed more willing to accept change[2].

2.3 Public Perspectives on Environment and Health

At a local scale, people routinely include issues of health in their evaluations of their environment. In particular, the main issue associated with traffic pollution is that it is a threat to health[17].

Perceived risk to health seems to be a major factor in determining whether or not individuals will take environmental action[18]. Studies of claims made by campaigning groups and the media suggest that such groups tend to focus on the health aspects of environmental issues, probably because these make a powerful and direct appeal to the individual, motivating people politically but without making an overtly party political point[19].

Experience in the United Kingdom suggests that the most effective campaigns for both non-government organisations (NGOs) and government are those where health effects can most directly be linked to environmental pollution in public perception. The unleaded petrol campaign in the UK was driven by the health impacts of exposure to lead. In Germany the leading issue was that unleaded petrol was essential for the introduction of new vehicle technology (catalytic converters) to reduce other pollutants from petrol driven vehicles. This was translated into action in the two countries in different ways.

In Germany there was political and individual support for the Federal German Government campaign in Europe for stringent emission standards, but little interest in unleaded petrol as an issue in its own right. In the UK the Government ran an aggressive campaign to promote unleaded petrol with vigorous NGO and public support, but failed to elicit much enthusiasm from the public for the campaign on vehicle emission standards.

2.4 Health and the Global Environment

The main focus of public concern at a global level seems to be the belief that the stratospheric ozone layer will be affected by global warming, with the threat of increasing levels of skin cancer[1]. This is interesting in itself as it suggests that the link between the ozone layer and health has been established, even in countries like the UK with generally low levels of sun. There seems therefore to be no intrinsic reason why an issue of global concern cannot be linked to local health impacts.

Despite the considerable volume of published and well publicised work on health impacts of climate change, there are few studies which have explored the detailed public understanding, beyond the general appreciation that there may be health effects mostly linked to skin cancer. However, it is likely that the issue will enter the public domain more forcefully following the publication of this report. As the debate moves from scientific and policy circles to the public arena an explosion of contested understandings and competing claims can be expected. There will then be a vigorous public debate with the potential for a more informed discussion of public health in a changing climate. There will also be an opportunity to study public understanding of the specific health issues likely to arise as climate changes.

2.5 Conclusions

Despite considerable public awareness of climate change there is little evidence to indicate whether there is good understanding of it health impacts. Such evidence as there is tends to the conclusion that public understanding conflates climate change with the depletion of the stratospheric ozone layer and thus skin cancer.

There is, however, the prospect that the connection between climate change and health, once established by the public, will invigorate the debate on the scale and nature of action to be taken.

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3 METHODS TO ASSESS THE EFFECTS OF CLIMATE CHANGE ON HEALTH

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Summary

- ❑ A variety of methods are required to assess the potential impacts of climate change on human health, including: spatial analogue studies, predictive modelling (biological models or empirical-statistical models) and expert judgement.
- ❑ Climate impact and adaptation assessments should incorporate the following steps: selecting the most appropriate climate and socio-economic scenarios; validation and calibration of models; description of sources of uncertainty; sensitivity analyses; and the evaluation of adaptation strategies and autonomous adjustments.
- ❑ It is difficult to detect any impacts of climate change on health outcomes in the UK at present. Monitoring of health indicators, including enhanced surveillance of diseases sensitive to climate, needs to be developed in order to detect and respond to impacts.

3.1 Introduction

The assessment of health outcomes in relation to climate change is a complex task due to three distinctive features:

- ❑ the large spatial scale (i.e. national, regional or global);
- ❑ the long temporal scale (20-100 years);
- ❑ the level of complexity in the systems being studied. This type of health risk assessment must accommodate the multiple uncertainties from environmental and social changes that affect health.

The assessment of the health impacts of climate change refers predominantly to processes that are likely to occur over future decades. We are committed to making forecasts by estimating how *future* environmental scenarios will affect health[1]. We must rely on current knowledge and theory - even though we cannot be sure of the extent of their applicability to future, and uncertain, climate, environmental and social conditions. Because of the multifactorial nature of disease, assessing the role of climate as a single factor involved in disease occurrence requires careful analysis. On the global scale, factors such as population density, availability of food, sanitation, and the quality and accessibility of health care, as well as the level of economic development, must all be considered. For the UK, the increasing number of elderly people and other changes in vulnerable populations need to be addressed. Understanding the capacity of a population to adapt to new climate conditions is also essential in order to achieve a more realistic assessment of the potential health impacts of climate change[2,3].

The IPCC* has developed guidelines for climate impact assessments in order to ensure standardisation across sectors and disciplines[2-7]. Figure 3.1 illustrates the various steps that are required in impact and adaptation assessment following the current paradigm of a "top-down" scenario based approach. The assessment of adaptation (i.e. responses to the impacts of climate change) is often neglected in such assessments.

There is an acknowledged need to develop improved methods for estimating the health impacts of climate change[7]. The scenario-based modelling approach is clearly limited by the lack of data, the lack of models and the complexity of human disease (see below). Therefore, assessments have also addressed current vulnerability to climate variability. For example, the US national assessment[8], addressed the following questions:

❑ What are the current environmental stresses and issues for the United States that will form a backdrop for potential additional impacts of climate change?

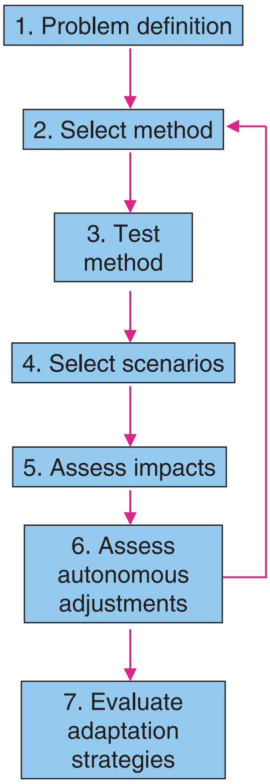
❑ How might climate variability and change exacerbate or ameliorate existing problems?

❑ What are the priority research and information needs that should be addressed so policy makers can be better prepared to reach wise decisions related to climate variability and change?

❑ What research is the most important to complete over the short term? Over the long term?

❑ What coping options exist that can build resilience into current environmental stresses, and also possibly lessen the impacts of climate change?

Figure 3.1
Steps in climate impact and adaptation assessment[2]



*** Inter-governmental Panel on Climate Change**

The UK Climate Impacts Programme (UKCIP) is developing a stakeholder-led approach to climate impact assessments in the UK by bringing organisations in the public and private sectors together to undertake sectoral- and regional-based impact assessments within an integrated national framework (Section 1.1). UKCIP is based on two main premises. First, that climate impacts research driven by stakeholders will provide information which meets their needs for planning how to adapt to climate change. Second, that by providing an integrative framework within which studies are undertaken, individual sectors will obtain a more realistic assessment of climate change impacts[9]. The conceptual framework is one of modular studies that can be used to prepare an integrated national assessment. Integration is achieved principally through the use of common datasets and scenarios; development of networks of funders and researchers and development and application of specific methodologies.

The integrated approach to climate impacts assessment is important, as climate impacts are likely to transcend 'sectoral' or regional boundaries, with impacts in one sector affecting the capacity of another sector, or region, to respond[10]. This is particularly true of health issues, which are inherently complex and affected by broader social and environmental changes. The magnitude of health impacts experienced will depend, for instance, on impacts on water resources management, transport, and coastal and flood plain infrastructure, as well as the responses to these impacts. UKCIP experience is also revealing that many stakeholders are using the health issue to stimulate awareness of climate change and to promote research into its wider impacts, an approach which is facilitated by the integrated framework of the UKCIP. By integrating results of modular studies UKCIP seeks to provide information that will enable appropriate adaptation strategies to be developed to take account of impacts and interactions across sectors and regions. The assessments will also be used to strategically inform Government policy on the need to mitigate and adapt to climate change.

3.2 Methods available for estimating the effects of climate change on health

There are several methods available to assess future risks to population health from climate change (Table 3.1):

- ❏ using (partial) analogue studies that foreshadow future (projected) aspects of climate change;
- ❏ using early evidence of changes in health status due to observed climate change, especially in climate-sensitive, early-responding, health phenomena;
- ❏ using existing empirical knowledge and theory to conduct predictive modelling (or other integrated assessment) of likely future health outcomes.

Table 3.1 Methods used to forecast future health impacts of climate change[11]

Methodology	Measurement	Function
Analogue studies	Qualitative or quantitative	Describe basic climate/health relationship, e.g. correlation of interannual variation in malaria incidence with minimum November temperature
		Analogue of a warming trend, e.g. association of changes in malaria incidence in highland areas with a trend in temperature
		Impacts of extreme event, e.g. assessment of mortality associated with a heatwave
		Geographical analogue, e.g. comparison of vector activity in two locations, the second location having a climate today that is similar to that forecast for the first location
Early effects	Empirical	Analysis of relationships between trends in climate and indicators of altered health risk (e.g. mosquito range) or health status (e.g. heat-attributable mortality)
Predictive models	Empirical-statistical models	Extrapolation of climate/disease relationship in time (e.g. monthly temperature and food-poisoning in a population) to estimate change in temperature-related cases under future climate change
		Extrapolation of mapped climate/disease (or vector) relationship in time and space to estimate change of distribution of disease (or vector) with future change in climate
	Process-based / biological models	Models derived from accepted theory. Can be applied universally, e.g. vector-borne disease risk forecasting with model based on vectorial capacity
	Integrated assessment models	Comprehensive linkage of models: 'vertical' linkage in the causal chain and 'horizontal' linkage for feedbacks and adaptation/adjustments, and the influences of other factors (population growth, urbanisation, and trade). e.g. modelling the impact of climate change on agricultural yield, and hence on food supplies and the risk of hunger

When selecting the methods, several factors needed to be considered such as the scale of the 'exposure' unit and of the 'effects'. One of the major problems of estimating future impacts is the mis-match between the spatial and temporal scale of environmental factors that affect health (e.g. local concentrations of air pollutants, focal vector distributions) and scenarios of future climate change (global climate model grid boxes). It is important to distinguish between long-term climate change and short-term meteorological change, including daily, monthly, or interannual variability and extreme events. Many health outcomes are sensitive to short-term meteorological extremes such as heavy rainfall or high temperatures but are not likely to be significantly affected by long-term, incremental, climate change, unless these same meteorological extremes also change in frequency or character.

3.2.1 Analogue studies

Knowledge of the relationship between climate and health outcomes is a prerequisite to any formal attempt to forecast how future climate change is likely to affect human health. We can assume that some aspects of the future will be similar to the present or past and, by analogy, current or past impacts of climate on health will be relevant in the future. However, some major impacts or climate-change induced 'surprises' cannot be foreseen, such as emerging diseases or rapid climate change (Section 1.2.5).

There are two approaches to the use of analogues. The first uses situations that simulate anticipated aspects of future climate change that can be considered as a type of climate change 'scenario'. The second approach looks at impacts associated with an 'analogue' situation.

There are three basic types of analogue studies[2]:

- ☐ historical trends (e.g. local warming trend, decreases in precipitation);
- ☐ historical events (e.g. extreme weather events, floods, drought); and
- ☐ cross-sectional spatial analogues (e.g. one current location, X, is compared with another current location, Y, the present climate conditions of which are deemed analogous to the future conditions of X).

Recent trends in the UK climate may provide an opportunity to look for associated changes in the incidence of climate-sensitive diseases. It is important that several levels of evidence are addressed before a causal relationship between observed climate change and changes in health outcome is inferred. However, because health outcomes over a long period of time are likely to be significantly affected by non-climate factors (e.g. changes in reporting) it is difficult to attribute unequivocally any changes in health outcomes to observed climate change.

Studies of the impacts of extreme weather events on health have focused primarily on the mortality associated with weather-related disasters. Extreme events in the UK can be linked with loss of life and long-term psycho-social impacts (Sections 4.5 and 4.6). The study of the consequences of heatwaves for health is of relevance because they are likely to increase in frequency under conditions of climate warming (Section 4.1).

Assessments of the health impacts of climate variability can provide useful information about climate-health relationships. Climate variability occurs on a variety of timescales, from days (synoptic) to months (seasonal) to interannual (sometimes driven in the UK by the North Atlantic Oscillation) to decadal. Many studies have now shown correlations between outbreaks of diseases such as malaria or dengue and El Niño and La Niña years[12]. However, the use of a cyclical event such as El Niño as an analogue for future, long-term climate change is not straightforward and, further, UK climate is not significantly affected by El Niño.

The use of spatial analogues is discussed in more detail in Section 1.2.1. Such analogues can sometimes be used to explore the effect of a change in climate on vector species. An example of a spatial analogue is used in Section 4.3 to investigate the impact of climate change on vector-borne diseases.

3.2.2. Has climate change already had an impact on health in the UK?

The UK has experienced an increase in average annual and seasonal temperatures this century (Section 1.2.2). There is good evidence that this warming has affected natural ecosystems by influencing patterns of plant growth and distribution[13] and changes in the distribution and behaviour of animal species[14]. Changes in the northern limit of the pathogen-transmitting European tick, *Ixodes ricinus,* over the last two decades have recently been attributed to observed warming in Sweden[15].

With respect to health outcomes attributable to observed climate change, the debate has primarily focused on malaria in the highlands of Africa, as well as recent well-publicised vector-borne disease outbreaks in the US. There is a particular problem with detecting the influence of long-term climate change in health outcome data[15a]. This is for two main reasons. First, there is large interannual variability in most health outcomes. Second, the past 10-20 years have seen changes in factors that are not climate related that would affect health outcomes in the UK, including: improved reporting of disease incidence, improved detection, changes in health care, changes in treatment, and changes in exposures not related to climate. For example, improvements in case detection and reporting are primarily responsible for the observed increases in the number of cases of Lyme disease in the UK (Section 4.3).

The time frame of the emergence of the health impacts of climate change depends on several factors[11].

❑ The delay that exists between environmental event and onset of ill-health, which ranges from almost zero (storm-induced injury for example), to weeks or months (vector-borne infections), to years and to decades (UV-related skin cancers).

❑ Factors influencing 'detectability', given that a change really does occur. The extent and quality of information and variability in the background or pre-existing level of disease must be considered. The detection and attribution of health impacts of climate change will depend on:

  - sensitivity of the response to climate change;
  - threshold effects; and
  - sensitivity of response to non-climate (e.g. confounding) factors.

There is a need for monitoring systems to be created in order to detect the early impacts of climate change on health.[16,17,18] It is likely that the first detectable changes will be changes in the geographic range (latitude and altitude) of certain vector-borne infectious diseases and/or in the seasonality of these diseases. For example, summer-time food-borne infections (e.g. salmonellosis) may show longer-lasting annual peaks. If extreme weather events (e.g. heatwaves, floods) become more, or less, severe, then it would be possible to detect changes in the magnitude of health impacts associated with such events. There has been no research to date that demonstrates an impact of climate change on health in the UK.

3.2.3 Predictive modelling of global climate change and health

Modelling is often used by epidemiologists in the analysis of empirical data, for example, to gain insights into the underlying dynamics of observed infectious disease epidemics such as HIV. Dose-response relationships derived from epidemiological studies have been used to estimate the attributable burden of disease. The estimation of the future health impacts of projected scenarios of climate change poses some particular challenges, both because of the complexity of the task and the difficulties in validating the model against relevant historical data-sets and calibrating it against external observations. There are several well-recognised limitations and drawbacks of predictive models[2] which include:

- ☐ the high level of aggregation (spatial and temporal);
- ☐ the limited possibilities for data-based validation;
- ☐ the limitations of pre-existing knowledge; and
- ☐ the necessary simplifications in the specification of the model.

There are three main approaches to the predictive modelling of climate change and health: empirical-statistical models, process-based or biological models, and integrated models (Table 3.1). The choice of model depends on several factors, such as the purpose of the study and the type of data available. The process-based approach is ideal but such models are difficult to develop. The statistical approach is considered second best but is easier to do in the absence of full information. Integrated assessment models use any or all of these methods to forecast the potential impact of global climate change and other major environmental changes (e.g. population growth, urbanisation) and policy responses upon human health.

Empirical-statistical models

These models are based on statistical models fitted to explain the observed short-term (daily to annual) relationships between meteorological variables and health (or health-related) outcomes. They may range from applying simple indices of risk to using complex multivariate models which combine important environmental factors that affect the risk to health. Thus, these models extrapolate from a climate-related (usually temperature-related) dose-response relationship derived by observations or experiment. Where these models are based on good empirical observations they can be useful in assessing the health impact of climate change. Examples of such models are used in Sections 4.1 and 4.2.

A major consideration when using health models is whether confounding has been adequately addressed. Methods of regression analysis are used for studying the effects of environmental exposures (e.g. air pollutants, temperature) on daily counts of mortality where any seasonal effects are treated as confounders and are removed. A further consideration is their limited ability to predict the effect of climatic events that are outside the range of present-day climate variability[2]. An important criticism of these types of model is that they do not supply information on the mechanisms of the climate-health interaction.

The complex spatial dimension of environmental exposures can now also be addressed using Geographic Information Systems (GIS) and other technologies. Empirical-statistical models are used to map changes in vector species or even disease distribution. Environmental data can be used to identify factors that are predictive for vector distributions, principally meteorological variables and vegetation indices from satellite data. Such analyses have been conducted for ticks, tsetse flies, and mosquitoes[19,20]. Spatial analysis of vector habitats, in combination with demographic and other data, can establish the geographic patterns for risk of human infection. Such combinations of spatial data can become very complex, and new spatial-statistical tools are being developed as spatial analytic techniques evolve. Models incorporating a range of meteorological variables have been developed to describe a specific 'bioclimate envelope' for a particular vector or pest species (this method is applied in Section 4.3 to estimate the impact of climate change on malaria and tick-borne encephalitis distribution). However, there is sometimes a lack of suitable historical health/vector data over sufficient geographical distribution that can be used to validate these models.

Process-based or biological models

Process-based or biological models are based on established relationships between environmental variables and disease-relevant biological factors. Such models incorporate mechanistic insights into the underlying processes and are assumed to apply universally. Much climate/health research has been focused on the process-based modelling that has been done in relation to future climatic influences on the global distribution of malaria and dengue[21,22].

Classical epidemiological models of infectious disease use the basic reproduction rate, R_o, defined as the number of new cases of a disease that will arise from one current case when introduced into a non-immune host population during a single transmission cycle[23]. With respect to vector-borne diseases, the basic biological relations between temperature and the extrinsic incubation period of the infectious agent have been determined by field studies and laboratory research. The process-based model, by incorporating these equations and thus summarising the relevant processes, can then be used to simulate health outcomes in response to specified climate scenario inputs. One of the major criticisms for these models is the lack of full information, as only part of the R_o relationship is modelled[21]. Further, the global vector-borne disease models show the spatial distribution of *relative* risk into the future, compared to the present day risk, but without addressing any disease control measures. Thus large changes in risk are indicated at the fringes of transmission where the absolute present risk changes from a very low baseline. This can be misleading as it does not relate to the absolute level of disease risk.

The validation of the global models using historical data is an important part of the modelling process. Therefore there is need to develop regional and local models that can be validated as well and which would incorporate important local factors that affect disease transmission.

Integrated assessment modelling

Integrated assessment modelling is the combination of several models that describe quantitatively the cause-effect relationship (vertical integration), and cross-linkages such as feedbacks and adaptation or adjustments (horizontal integration). Typical integrated assessments models (IAM) include the output of a global climate model (GCM), linked to first- and second-order impacts models, as well as the driving greenhouse gas emissions scenarios which are generated by energy-economic models. IAMs are considered to be the most comprehensive treatment of the interactions between scenarios of climate change and society. IAMs address impacts across different sectors and across different regions. They are a very useful tool of decision-making, in particular, for questions relating to mitigation policies and what amount of climate change can be 'tolerated'.

The major advantages of using more fully integrated assessment models are:

- the linkage of a rich variety of modules which permits exploration of relationships and development of new concepts;
- the inclusion of interactions and feedback mechanisms; and
- the enhanced communication between scientists of many disciplines, and between scientists and decision-makers[24].

The major disadvantage is that, as yet, health impacts have not been incorporated into such models, although a malaria/dengue model is included as one of the impacts in the TARGETS model[25].

3.3 Use of scenarios

The climate change scenarios used for this assessment have been described in Sections 1.2.1-1.2.5 One of the major difficulties in using scenarios for health impact assessment is spatial scale, as GCM scenarios are provided at a coarse geographical and temporal resolution. Downscaling is the method by which the output of a GCM is made more specific, using additional local or regional topographic and meteorological information. It has not been possible to employ any downscaling in this assessment due to limited resources.

It is important to specify the baseline when undertaking an impacts assessment. Often it is implied that the current situation is the baseline. For some health conditions it is difficult to get accurate incidence or prevalence data and, therefore, assumptions about the use of baseline information must be made clear. The baseline should not only include climate but also social, environmental and health conditions and how they change over time. Some global and regional socio-economic scenarios have been developed which include projections of population growth and economic development over the next 100 years. National socio-economic scenarios have also been developed for the UK[26].

Climate change scenarios are typically presented for 3 time slices (the 2020s, 2050s and 2080s), which may not be appropriate for planning in many sectors. Health service managers typically plan only 5-10 years in advance and this should be considered when designing health impact and adaptation assessments.

3.4 Uncertainty analysis

A number of factors contributes to uncertainty in forecasting future impacts (Figure 3.2). It is therefore recommended that this uncertainty is disaggregated in this assessment. The IPCC has developed formal methods to look at uncertainty, such as assigning levels of confidence to particular statements.

Sources of uncertainty include:

❑ future climate change itself (Section 1.2.5);

❑ climate-biological relationships upon which health depends, e.g. vector-ecology;

❑ climate-human health relationships;

❑ problems with predictability due to stochastic behaviour in the system;

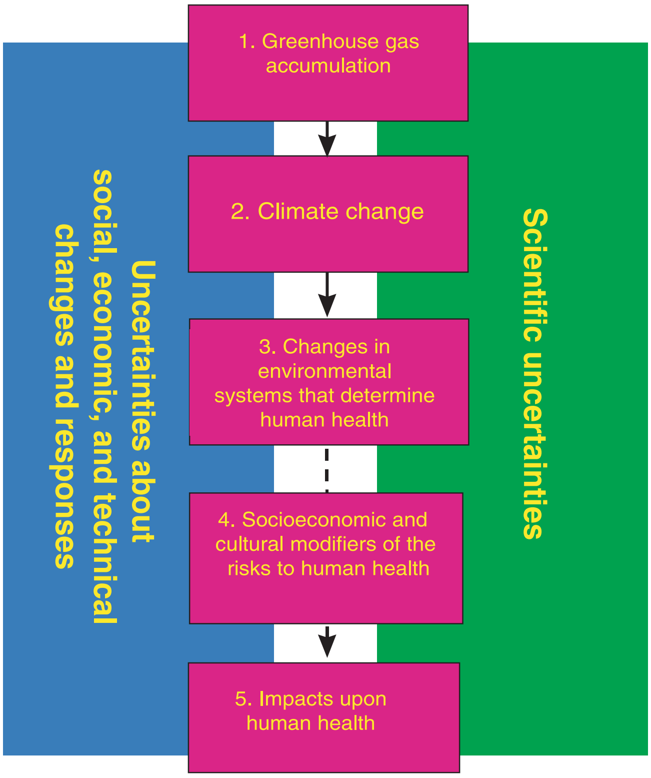
❑ uncertainties due to simplifications in models; and

❑ future socio-economic change and adaptation, including human behaviour.

Confidence intervals are used in classical empirical epidemiology but it may not be possible to provide these for the results of scenario-based health risk assessment. However, it is important to specify the likely range of uncertainty and the magnitude and direction of error.

Figure 3.2

Sources of uncertainty in climate health impact and adaptation assessment[11]



3.5 Adaptation

It is likely that decision makers will respond to the impacts of climate change. Such responses may lead to adaptation by a range of mechanisms. An important part of the assessment is the description of vulnerability, specifically the identification of vulnerable groups in order to target adaptation strategies.

Active adaptation i.e. that which is not spontaneous, requires decision-making. New policies should be focused on those individuals or groups within a given population that are particularly vulnerable if they are to be effective. Adaptation strategies for specific health outcomes are discussed in the respective chapters. Adaptation strategies should be evaluated to confirm that they reduce health impacts and are cost-effective.

Autonomous adjustments are defined as those which are undertaken spontaneously by individuals or enterprises in response to incremental change. With respect to health, these would include physiological responses in the human population (e.g. acclimatisation), as well as changes in behaviour in response to heatwaves (e.g. drinking more fluids). Other autonomous adjustments could occur in the UK infrastructure, such as changes in housing design in order to reduce indoor temperatures.

3.6 Monitoring and surveillance

Monitoring of the potential impacts of climate change on health is needed in order to[16,17]:

- ❑ inform policy makers about the magnitude of the actual or potential impacts of climate change;
- ❑ provide data for empirical studies of climate-health relationships;
- ❑ model validation/calibration; and
- ❑ evaluate adaptation strategies.

Most current surveillance systems that monitor infection have been designed to detect particular causes, such as in foodborne disease, and individual risk factors, such as overseas travel. The monitoring of the effects of climate change requires a more comprehensive approach to infection aetiology and should examine the possible influence of climate both on the environmental sources of pathogens and on human behaviour. Table 3.2 indicates some of the requirements for such a monitoring scheme.

Another challenge for climate-health research is the size of data sets required. While trends in any one country will be a starting point, improved co-ordination of data on infection across regions, and even countries, will be needed[27]. A range of sources of data and types of study design can be used to improve understanding of the potential health impacts of climate change. Increasingly, the linkage of monitoring systems for climate, the oceans and the land surface will provide better information about the diverse impacts of climate change on the earth's geophysical and ecological systems.

Monitoring and surveillance activities clearly have a close relationship to research in that data from such activities can be analysed to develop or test hypotheses about climate-health relationships. Data from monitoring and surveillance systems can help to improve predictive models, and models in turn may suggest vulnerable regions or populations that may be particularly appropriate to monitor.

Table 3.2 Summary of global health impact monitoring requirements[15]

Health impact	Location	Data requirements
Vector-borne diseases, e.g. malaria, dengue	Margins of distribution both latitude and altitude, e.g. highlands of East Africa for malaria Areas with sporadic or seasonal epidemics	Mortality data Primary care data Communicable disease surveillance centres Vector data from local field surveys Land use/vegetation data (remote sensing) Need for current datasets to be standardised
Water-borne diseases, e.g. cholera, *Cryptosporidium*	Current areas of endemicity and sporadic disease	Mortality data Communicable disease surveillance data
Disease related to marine ecosystems, e.g. cholera	Oceans Coastal populations	Disease surveillance, e.g. cholera cases Sampling of phytoplankton for pathogens, biotoxins, etc. Remote sensing for algal blooms, etc.
Heat-related mortality	Urban populations in developing and developed countries	Daily mortality and morbidity (chronic cardiorespiratory) data
Extreme-weather events e.g. floods, storms	All regions	Mortality data Disease surveillance, e.g. gastro-intestinal diseases Data on impacts of disasters
Sea-level rise	Vulnerable populations, e.g. on low lying islands	Ground water quality Diarrhoeal disease surveillance
Malnutrition/food supply	Critical regions	Population nutritional status Land use data Socio-economic data

3.7 Discussion and conclusions

The anticipation of health impacts of global climate change has prompted a rapid evolution of concepts and methods for characterising and estimating those impacts. Some of the scientific tasks can be accomplished by the empirical study of analogous situations. Some may be amenable to study by following early changes in indices related to health, as climate and other environmental change continues. However, much of the task must be addressed through scenario-based risk assessment, using various types of predictive modelling. The quality of modelling also depends greatly on the quality of the data. Models should be validated before they are used in the assessment. One problem with validating health impacts models is that many climate-health relationships are population-specific. For example, temperature-mortality relationships may vary widely between cities in temperate countries. It would be difficult to find independent data with which to validate such models, as health outcomes are dependent on cultural values such as behaviour, diet etc.

The cost of impacts to health is another consideration. There are established ways of costing health outcomes and costs to health care provision that should be incorporated into future health impact and adaptation assessments[28,29].

The piecemeal epidemiological evidence available to date, and the certainty that aspects of the future will not be direct extensions of the past or present, ensures that our knowledge base is incomplete for predicting the range, timing and magnitude of future health impacts of global environmental changes. Uncertainties in modelling are therefore unavoidable, and explicit caveats must be stated. Further, the inevitable interaction between these global changes, both as processes and in their induction of health impacts, compounds the difficulty of predictive modelling. Increasing scientific effort is underway to develop integrated mathematical modelling that takes account of many of these aspects, including developing the capacity for down-scaling global models to regions and countries, taking account of local physical, ecological and demographic factors.

3.8 Research needs

- ☐ To develop methods for quantitative risk assessment that better address public health issues in the context of climate change.
- ☐ To develop methods of integrated modelling that adequately addresses health impacts at the appropriate temporal and spatial resolution.
- ☐ To develop datasets with health outcome or vector data over sufficient geographical distribution to create and validate predictive models.

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4 OVERVIEW OF CLIMATE CHANGE IMPACTS ON HUMAN HEALTH IN THE UK

4.1 Heat- and cold-related mortality and morbidity and climate change

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Summary

- ❏ High temperatures have significant adverse effects on mortality and morbidity. In the UK, heat-related deaths begin to occur when mean daily temperature rises above the minimum mortality band of 15.6-18.6°C.
- ❏ Under current climate conditions, an estimated 800 'heat-related' deaths occur in the UK per year (defined as excess deaths above this temperature threshold). It is estimated that these deaths are accompanied by approximately 80×10^3 days additional NHS hospitalisation.
- ❏ The impact of climate change on temperature-related mortality can be estimated from the observed temperature-mortality relationship, assuming that this relationship is causal and does not change in the future. The Medium-High climate change scenario would result in an estimated 2800 heat-related deaths per year in the UK in the 2050s (an increase of 250% when compared with 800 heat-related deaths per year under current climate conditions) and an estimated 280×10^3days per year of heat-related NHS hospitalisation in the 2050s (compared with 80×10^3 under current climate).
- ❏ These estimates are likely to be overestimates in the long-term since they ignore ameliorative effects of physiological acclimatisation and adaptive changes in lifestyle, which could be expected in time to reduce the impact of hot episodes.
- ❏ The increases would be more than matched by a fall in cold-related deaths (to 60 000 compared to 80 000 under the current climate) and hospitalisation (to 6100×10^3 days per year compared to 8200×10^3 under the current climate) due to progressively milder winters, as the climate changes. Nevertheless, as a discrete category of excess morbidity and mortality, these heat-related events should be countered independently, by advice on heat avoidance behaviour, improved indoor ventilation and air conditioning.

4.1.1 Introduction

Mortality and morbidity rise in hot weather, particularly in elderly people[1,2,3]. Heatwaves in the UK have been associated with significant short-term increases in mortality[4,5]. Fortunately, compared with most parts of Europe and the US, extreme high temperature episodes ('heatwaves') are relatively infrequent in the UK. However, it has been projected that the equivalent of the hot 1976 summer in the United Kingdom, very unlikely in today's global climate (i.e. occurring once every 310 years), would occur every 5-6 years under the anticipated warmer climate of 2050[6] (Section 1.2.4).

This section describes separately the changes in mortality and hospitalisation to be expected from effects of heat and of cold with the increases in temperature expected over the next century. Many more deaths occur in winter than in summer. Therefore any changes in future winter temperatures may be the predominant influence on year-round mortality rates. Behavioural and physiological adjustments are likely to modify this relationship even in the absence of specific policies. Some specific adaptation options are described below.

4.1.2 Factors in heat-related mortality

Hot weather increases daily mortality in Greater London. Very few deaths are certified as heat-related in the UK and the observed increases in deaths during heat episodes are mainly from cardiovascular, cerebrovascular and respiratory disease. Rooney *et al.*,[4] estimated excess mortality in England and Wales associated with the 1995 heatwave (30 July-3 August) at 619 deaths (8.9% increase). Heat-related mortality due to coronary thrombosis and cerebral thrombosis can be explained by loss of salt and water in sweat, with reduction in plasma volume and consequent thrombogenic increases in red cell and platelet counts, plasma cholesterol and blood viscosity.[7] Table 4.1 gives the breakdown of heat-related mortality by age, sex and attributed cause in England and Wales during the 1995 and 1976 heatwaves (Figure 4.1). These data indicate that the impact of heatwaves is greater in an urban area (Greater London) than in the population as whole.

Elderly people are particularly vulnerable to heat stress, particularly those in hospital or long-term care institutions. Vulnerability to heat in old age is linked to intrinsic changes in the regulatory system or to the presence of drugs that interfere with normal homeostasis (Table 4.2). In the USA, a case-control study of acute heat-related deaths in the 1995 major Chicago heatwave indicated that the people involved were already ill, confined to bed, unable to care for themselves, isolated, or without air conditioning[8]. Preliminary analyses of the impact of the 1995 heatwave in Greater London and England and Wales[9] suggest that excess mortality was proportionally higher in more deprived populations.

A proportion of the 'acute' effect of heat on mortality is probably due to the hastening of death in people who are already ill by a few days or weeks. A Belgian study[10] calculated that 15% of the excess mortality represented this effect, but such 'harvesting' is difficult to quantify. Air pollutants may also have significant effects on daily mortality. However, as high temperature episodes are often associated with high pollution episodes (particularly of tropospheric ozone, see also Section 4.7), it is difficult to separate the effects. Some studies suggest an interaction between air pollution and high temperature[10,11].

Figure 4.1

Daily mortality during the 1976 heatwave in Greater London (all cause mortality). Mortality (7-day moving average), temperature (mean daily temperature (°C) from Holborn weather station)

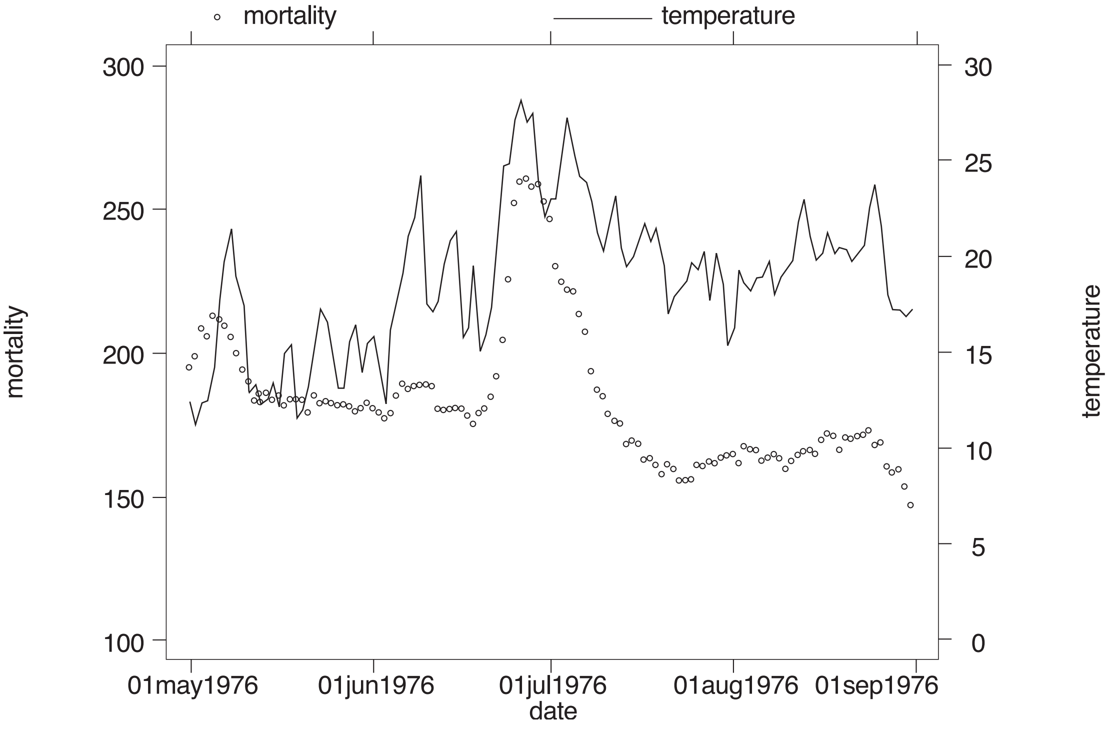

Table 4.1 Comparison of excess mortality during 1995 and 1976 heatwaves (excess calculated from 31-day moving average in same year)[4,5]

	England & Wales		Greater London	
	1976 Excess deaths %	1995 Excess deaths %	1976 Excess deaths %	1995 Excess deaths %
Age (years)				
0–15	5.9	4.5	13.5	13.1
16–64	7.2	8.2	12.0	15.6
65–74	7.2	8.4	10.2	13.2
75–84	11.5	8.5	19.5	14.9
85 and over	14.8	10.3	21.6	20.1
All ages	9.7	8.9 (8.6)*	15.4	16.1 (15.4)*
Sex				
Males	7.9	6.2	13.4	8.3
Females	11.6	11.3	17.4	23.3
Cause of death				
Neoplasms	6.3	5.3	9.4	12.0
Ischaemic heart disease	7.7	8.1	14.9	5.6
Cerebrovascular disease	12.7	11.3	22.0	38.9
Respiratory disease	15.8	12.4	22.7	15.7

* Values are age-adjusted to the age-at-death distribution of 1976

Table 4.2 Risk factors for heat stress[33]

Risk factor	Comments
Extreme old age	>80 years
Dependency	Bedridden>semi-dependent>mobile
Drugs	Especially phenothiazines, antidepressants, alcohol, diuretics
Cardiovascular	Congestive heart failure, ischaemic heart disease
Neurological	Cerebrovascular disease, autonomic impairment, head injury, cerebral tumour or abscess
Mental condition	Dementia, confusional states
Endocrine	Diabetes mellitus, hyperthyroidism, hyperpituitarism
Skin disorders that impair sweating	
Infections	Respiratory, gastrointestinal and septicaemia

4.1.3 Factors in cold-related mortality

In the United Kingdom excess winter death has been estimated to represent 20 000-50 000 more deaths per year than would be expected from mortality rates in the rest of the year[12]. However, such calculations were based on mortality in the four months December-March, as an excess over the daily mortality in the rest of the year. Since mortality actually rises in the autumn long before December, these estimates underestimate total 'excess' mortality in cold weather. This seasonal excess is now declining (even after allowance for diminution of influenza epidemics)[13,14] but is still one of the highest in Europe[15].

Increased mortality from coronary thrombosis in the cold is associated with haemoconcentration (thickening of the blood), which occurs as fluid is lost from the circulation after vasoconstriction in the cold[13,16,17], and with increased blood pressure and with raised fibrinogen levels due to respiratory infections in winter[18,19]. Arterial thrombosis due to these changes causes just over half of the excess winter deaths, and respiratory disease approximately a further 20%. There is evidence that housing factors and the substantial numbers of elderly living in fuel poverty may influence the risk of excess winter deaths[20,21]. Inadequate indoor heating and outdoor clothing are likely to be important factors, therefore, in the observed associations with social deprivation. Recent studies of Europe and Russia show that mortality increases to a greater extent for a given fall in temperature in regions such as the UK and Greece that have relatively warm winters, than in colder countries where priority is given to keeping warm regardless of other factors. This was associated with cooler homes and wearing of less effective clothing outdoors in countries with mild winters[15,22,23].

4.1.4 Previous modelling of future impacts of climate change on temperature-related mortality

Studies that have estimated the direct health effects associated with climate change have been concentrated in the United States and Europe. All are based on extrapolations of statistical models of the short-term association between daily or weekly mortality and temperature. An air mass-based synoptic approach has been applied to mortality studies in the US, Canada and the UK[24,25]. Kalkstein and Green[24] estimate that, in the USA, increases in heat-related deaths will be greater than decreases in cold-related deaths by a factor of three. Other studies, based on the linear extrapolation of the temperature-mortality relationship, indicate that reductions in winter mortality in some regions may be greater than increases in summer mortality in temperate countries[26,27]. A UK study has estimated that approximately 9000 fewer winter-time deaths (representing a 2-3% reduction) would occur annually by the year 2050 in the UK with 2-2.5°C increases in winter temperature[28]. Few studies have estimated the impact of increased frequency of temperature extremes, but Gawith *et al.*,[29] have estimated potential changes in the frequency and intensity of heatwaves in one city (Oxford) in the UK.

4.1.5 Method of current assessment of the impact of climate change on mortality in the UK

In our work for this report we have calculated the mortality changes that would occur by a range of possible scenarios of climate warming if the current temperature-mortality relationship, with linear extrapolation at its warm end, does not change. Data on daily deaths from all causes in the UK were obtained from death registration data for 1976-1996, and mortality rates calculated using annual mid-year population estimates. Morbidity data on in-patient hospital days were calculated from NHS admissions data for England (1995-1996) and Wales (1996-1997) and from the average length of stay in hospital for all except psychiatric patients.

Central England Temperature (CET) is a weighted mean temperature for England and Wales derived from measurements at four dispersed meteorological stations (Squires Gate, Lancashire; Manchester Airport; Malvern, Worcestershire; Rothamsted, Herts). Temperatures for Scotland were the mean of Aberdeen and Glasgow stations; those for Northern Ireland were the mean of Belfast and Armagh. Occasional missing values were replaced by interpolation. Data were not lagged, since unlagged data gave the steepest mortality/temperature relationship for heat-related mortality.

The 3°C temperature band in which mortality was lowest was calculated and mortality in this band used as the baseline. Heat-related deaths are defined as all deaths on days with mean temperature above 18.6°C. Cold-related deaths are defined as all deaths on days with mean temperature below 15.6°C. The estimates of heat and cold-mortality are based on analyses without correction for season, and they assume that the excesses of deaths on hot and cold days are due to temperature and not to non-thermal factors such as changes in exposure to infection or in diet. Estimates of temperature impacts on mortality would be somewhat lower if adjustments for season were made. Time-series analysis of short-term changes in temperature and mortality strongly indicates temperature as the most important explanatory variable for increased mortality in winter[15]. The impacts for three climate scenarios for seasonal temperature increases by the 2020s, 2050s and 2080s were assessed (Sections 1.2.1-1.2.5). All estimates of future mortality were based on the current UK populations. The climate scenarios for increases in temperature were calculated from a baseline of the observed climatology of 1961-1990. Databases are not available for daily mortality in the earlier part of that period, when mortality data are in fact greatly distorted by influenza epidemics. Regression analysis showed no significant change between the midpoints of the two periods, 1976 and 1986, after allowance for effects of influenza. Data were grouped in 1°C steps for graphs.

4.1.6 Results

Figure 4.2 illustrates the relationship between temperature and all-cause mortality for the United Kingdom and its component parts. Mortality in the UK was minimal with temperature in the range 15.6 to 18.6°C, and rose approximately linearly with rise or fall in temperature from this minimum mortality band. Total annual heat-related mortality above the band of minimum mortality was 14 per 10^6, or 798 deaths in the whole population of the UK, on 13 days per year at temperatures above the minimum mortality band (Table 4.3). Total annual cold related mortality for the same period was 1409 per 10^6, or 80×10^3 deaths for the whole population, on 312 days per year colder than the minimum mortality band. The pattern was broadly similar in other parts to the UK (Figure 4.2), except that temperatures above 22°C were absent in Scotland.

The estimates of the impact on mortality of each scenario of climate change, assuming no change in the relationship between temperature and mortality, are presented in Table 4.3. The estimated increase in annual heat-related mortality for the 2050s with the Medium-High scenario of temperature increase is 49 per million, or 1995 additional deaths for the UK population, a 253% increase. The estimated decrease in annual cold-related mortality for the 2050s (with the temperature increase) is much larger in absolute terms, 356 per million, or 20 292 less deaths for the UK, though in percentage terms a reduction of only 25%.

The ratio of annual patient days in hospital to annual deaths in England and Wales was calculated as 102 days in hospital per death (Table 4.3). Under the Medium-High scenario of temperature increase this indicates an annual increase in patient days due to heat of 204 × 10^3, and a decrease in patient days due to cold of 2070 × 10^3 by the 2050s for the UK population.

Figure 4.2

Temperature and 'all-cause' mortality for the United Kingdom and its component parts

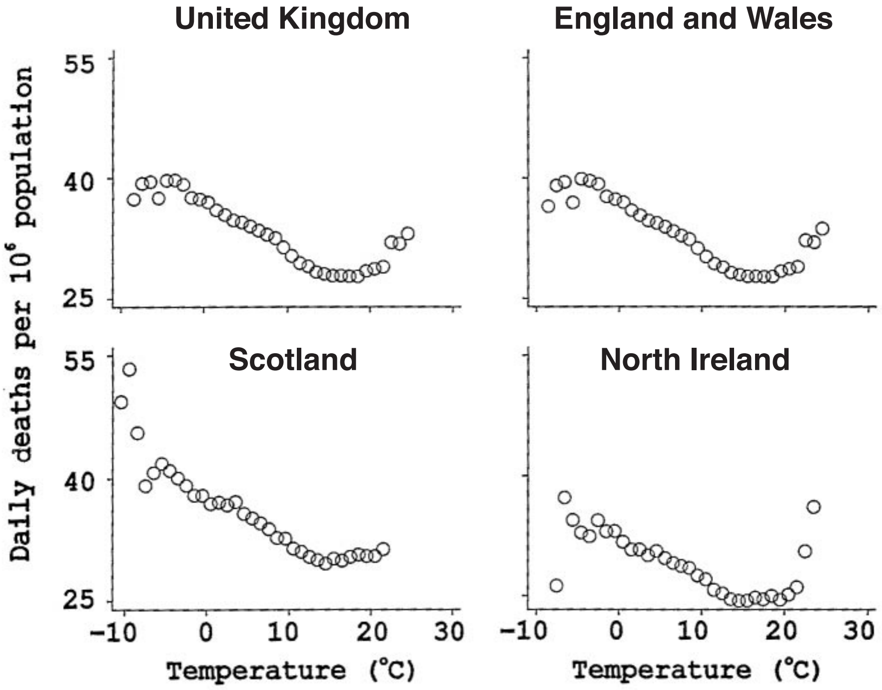

Table 4.3 Effects of climate change on mortality and morbidity

		2020s	**2050s**				**2080s**
Outcome	**Baseline (1990s)**	**Medium High**	**Low**	**Medium Low**	**Medium High**	**High**	**Medium High**
Expected rise in summer (JJA) temperature (°C)	0	+1.30	+0.83	+1.40	+2.00	+2.30	+2.47
Days per year >18.6°C	13	25	20	28	35	38	41
Heat-related deaths per year, per 10^6 population	14	32	24	34	49	57	63
Total heat-related deaths per year (UK)*	**798**	1824	1368	1938	**2793**	3249	3519
Patient-days per year in hospital due to heat (10^6)	**0.081**	0.186	0.140	0.198	**0.285**	0.331	0.359
Expected rise in winter temperature (°C)	0	+1.23	+0.83	+1.43	+1.90	+2.20	+2.83
Days per year <15.6°C	312	285	294	280	270	264	249
Cold related deaths per year per 10^6 population	1409	1172	1247	1136	1053	1002	899
Total cold-related deaths per year (UK)*	**80313**	66804	71079	64752	**60021**	57114	51243
Patient-days per year in hospital due to cold (10^6)	**8.192**	6.814	7.250	6.605	**6.122**	5.826	5.227

* Estimates are calculated on 1996 population estimates, i.e. assume no population change

Note: Heat-related deaths are defined as all excess deaths on days with mean temperature above 18.6°C. Cold-related deaths are defined as all excess deaths on days with mean temperature below 15.6°C. The calculation is undertaken for the whole year and thus the estimates of cold-related deaths are higher than those produced by considering only the four coldest months of the year

Bold entries denote heat- and cold-related deaths and NHS hospitalisation per year, at baseline and with Medium-High estimates for 2050s

The adverse effects of heat will be concentrated into a small number of days, 35 days per year on the Medium-High estimate of summer temperatures by the 2050s. This represents an average of 8143 patients in NHS hospitals with heat-related illness on each of these hot days. Again, heat-related illness here implies admissions that are attributable to high temperatures and does not imply a diagnosis of hyperthermia, heat stroke, heat exhaustion, etc. This assessment is not able to forecast whether the 'hot' days would occur in a cluster, although this has important implications for health-care facilities that may come under stress during heat episodes due to increases in admissions.

The fact that variability as well as the mean level of summer temperatures is expected to increase (Section 1.2.4) will tend to increase heat-related mortality above these estimates, but a number of other factors, probably larger in their effects, will tend to reduce the changes in both heat and cold related mortality; as will 'harvesting', the tendency for the excess mortality to affect the most vulnerable people, who are thereby removed from the pool of people at risk subsequently.

Some of the winter mortality may be due to non-climate seasonal factors, such as seasonal changes in diet. More important, physiological adaptation to heat, and spontaneous adjustments of the population to the changed climate by improvements in housing, clothing and behaviour, can in time be expected to reduce the changes in mortality due to climate change.

4.1.7 Discussion and conclusions

Our main estimates are based on the Medium-High scenarios of average temperature increase. The projected temperature changes under the High or Low scenario would change the estimates substantially. However the main uncertainty in these estimates of the impact of climate change on heat related mortality is the extent to which, even without specific adaptation strategies, physiological adaptation and factors such as behavioural changes and increased use of equipment such as of air conditioning in hot weather, will reduce them[30]. Estimates given are, therefore, worst-case assessments for the Medium-High scenario. Physiological acclimatisation to hot environments can occur over a few days, and this can explain why the impact of the first heatwave on mortality is often greater than that of subsequent heatwaves in a single summer[31,32]. The rate at which infrastructural changes will take place without specific help and advice is likely to be much slower. Neither the size nor the time course of these modifying factors can be predicted with any confidence. However, in practical terms it is clear that preventive measures will be needed to counter substantial initial adverse effects of heat, and probably also to counter lasting adverse effects of hotter summers that may affect the population. Systematic monitoring and review of actual changes in temperature and mortality will clearly be important.

Policy options to reduce the impact of thermal stress include:

- ❏ advice on how to stay cool including the use of portable fans;
- ❏ improved ventilation of homes, public buildings, hospitals and other residential institutions and workplaces;
- ❏ installation of air conditioning; and
- ❏ changes in working hours to cooler times of day.

Heat-watch warning systems have been implemented in some cities where heatwave mortality is high, and might be of value in southern England. With the exception of air conditioning, such measures are generally simple and inexpensive, but need to be in place before hot weather comes. A fan in place before a heatwave is worth many installed as the heatwave passes its peak. Raising awareness of heat-related illness among those who care for the elderly would also be an important preventative measure. The elderly are particularly vulnerable to hyperthermia, particularly those in hospital or long-term care institutions[33]. The need for a pre-emptive campaign to reduce heat stress is not negated by the fact that we predict that global warming will produce larger decreases in cold-related mortality and morbidity. Heat- and cold-related mortality may in any case affect a different subset of the population.

4.1.8 Research needs

- ❏ Assessment should be made of the speed of spontaneous adaptation by populations to warmer climate, and monitoring of actual changes in UK mortality and morbidity as temperature rises should be undertaken.
- ❏ Better assessment of the populations most at risk in heatwaves is required, and of future changes in the frequency and character of extreme temperature events.

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4.2 Food poisoning and climate change

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Summary

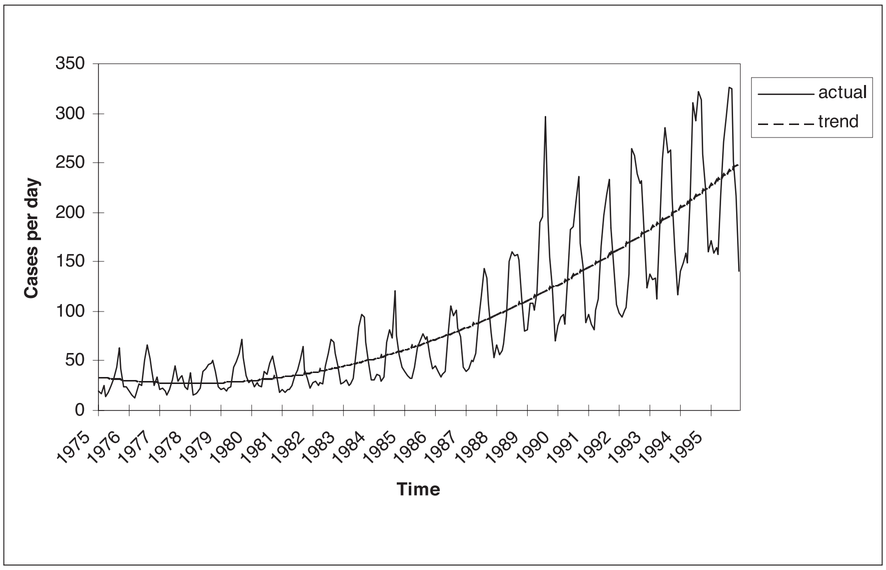
- Food poisoning is associated with warm weather. The predicted increase in UK temperatures is likely to be accompanied by an increase in cases of food poisoning.
- Using the climate scenarios discussed in Sections 1.2.1–1.2.5 it is estimated that between 4000 and 14 000 extra cases of food poisoning might occur each year in the UK as a result of climate change. Our best estimate is about 10 000 extra cases each year.
- This significant effect might be largely prevented by improvements in food storage, preparation and hygiene close to the point of consumption.

4.2.1 Food poisoning and climate change in the UK

Food poisoning is an important cause of morbidity in the general population and can lead to death in vulnerable individuals such as elderly or sick people. The costs of treatment and the loss of working time also make it an important economic problem[1]. Furthermore, it is a problem that has been increasing rapidly[2] and by 1998 there were 94 000 notified cases per year in England and Wales. Since many cases are not notified this is likely to be a large underestimate of real incidence. There remains considerable controversy about the causes of the rising trend in food poisoning. It could be related to changes in methods of food production such as the shift towards intensive rearing of poultry and other animals. It could lie in changing patterns of retailing or catering or in changing behaviour by consumers[2,3]. Superimposed on this rising trend is a pattern of seasonal changes with a high incidence in the summer and fewer cases during the winter (Figure 4.3). Hot summers may produce particularly large increases in food poisoning. For example, the Chief Medical Officer[4] suggested that the exceptionally large number of cases of food poisoning in England and Wales in 1989 may have been partly the result of the unusually long, hot summer of that year.

Figure 4.3

Notified cases of food poisoning per day in England & Wales 1975–1995: monthly data



Roberts[5] reviews the potential sources of infection in food, noting that foods of animal origin are the primary source of many foodborne infections. The factors which may cause problems include methods of animal husbandry, including building design and use of animal foodstuffs, transportation of live animals, and slaughter and processing practices. Organisms present in live animals may be transferred through food processing and preparation and appear in the final product. A large number of animals may reach the slaughterhouse excreting micro-organisms, and in the case of poultry, for example, continuous line processing may propagate the spread of infection from carcass to carcass. Ready-to-eat foods will often receive heat treatment in processing, but are unlikely to be sterile, whilst the safety of chilled foods is particularly dependent on correct storage temperature and attention to shelf life. Food preparation may also play an important role, with preparation too far in advance of consumption being recorded in 57% of outbreaks of food poisoning in England and Wales in 1970-1982[6]. Storage at ambient temperature was a factor in 38% of outbreaks, inadequate cooling in 32%. Food handlers may also spread infection by carrying organisms on their hands, particularly those constantly handling raw foods of animal origin.

Weather conditions could influence food poisoning risk in a number of different ways. One of the most direct is that high temperatures favour the multiplication of pathogenic micro-organisms in food. For example, multiplication of the salmonellas that are an important source of food poisoning in the UK is strongly temperature dependent with growth occurring above about 7°C and reaching an optimum at 37°C[7]. High temperatures may also have an influence on human health risks by affecting infection rates in food animals, for example by the multiplication of bacteria in animal feed. Other indirect influences on human risks could include a weather-influenced shift towards dietary items or forms of food preparation (e.g. barbecues) that are associated with increased risk. It is noteworthy that the peak of food poisoning notifications is typically in late summer, coinciding with or shortly following the period when the maximum temperatures are reached. However, an important exception to the relationship between ambient temperatures and multiplication of bacteria in food is campylobacter, which is now the commonest bacterial cause of food poisoning in the UK. Unlike salmonella, this generally requires temperatures above 30°C for growth to take place[8]. Nevertheless, it does show a clear pattern of a seasonal peak in early summer; but what (if any) the influences of weather conditions might be on this pattern remains to be elucidated.

The recognition of the seasonality of food poisoning incidence and of the various ways in which weather conditions might affect the microbiological safety of food have led to the suggestion that climate change could increase food poisoning risk[9]. There are two published studies[10,11] that have attempted to estimate quantitatively the potential effects of climate change on food poisoning notifications in England and Wales. This has been done by using evidence from the recent past as a guide to what might happen in the future if climate change leads to significantly warmer conditions. Irrespective of long-term trends in climate there is considerable natural variability in temperature and, in recent years, there have been several spells of high temperatures that provide analogues for the conditions that might become more common as a result of the enhanced greenhouse effect. Regression analysis has been used to develop statistical models of the relationship between the monthly incidence of food poisoning and temperatures in England and Wales in recent years (adjusted for longer-term trends and seasonal factors) and these have then been used to provide estimates of the possible impact of future warmer summers. In spite of differences in the data and statistical methods that were used these produced very similar findings; only the results of the later study[11] are reviewed here.

Figure 4.4 shows a tendency for the food poisoning notification rates to be higher in the months with warmer temperatures. However, Figure 4.5 shows an even stronger positive association between the food poisoning rates (de-trended) and the temperature one month earlier. A regression analysis showed that mean temperature (of the same month) and the mean temperature one month earlier explained 72% of the variance in the de-trended food poisoning notifications, rising to 75% when the dependent variable was transformed into logarithms. Longer lags for temperature were not significant at the P=0.05 level. The association with the temperature of the same month underlines the need for improvements in food storage, preparation and hygiene close to the point of consumption. However, the stronger association with temperature in the previous month points to the importance of conditions earlier in the food production process, possibly including animal husbandry and slaughtering. After adjustment for seasonal factors the association with the temperature of the same month weakened to the point where it became marginally non-significant (p = 0.073). However, the association with the temperature of the previous month remained highly significant (p ≤0.001). The resulting regression model of the association between temperature and food poisoning notifications (adjusted for trend and seasonal factors) was then used to estimate the impact on food poisoning notifications of scenarios of +1, +2 and +3°C temperature increases. This produced estimates of increases in food poisoning notifications of 4.5%, 9.5% and 14.8% respectively. If applied to the total of 94 000 notified cases of food poisoning for 1998 these would represent absolute increases of ~4000, 9000 and ~14 000 cases. It should be emphasised that because of the under-recording of food poisoning the real number of additional cases might be considerably higher. These results suggest that higher temperatures as a result of climate change might exacerbate the food poisoning problem which is already a significant threat to public health. However, although unwelcome, it should be emphasised that the estimated changes are small relative to the large increases that have occurred over the last twenty years as a result of other factors.

Figure 4.4

Food poisoning notification rate (actual/trend) and mean temperature of same month

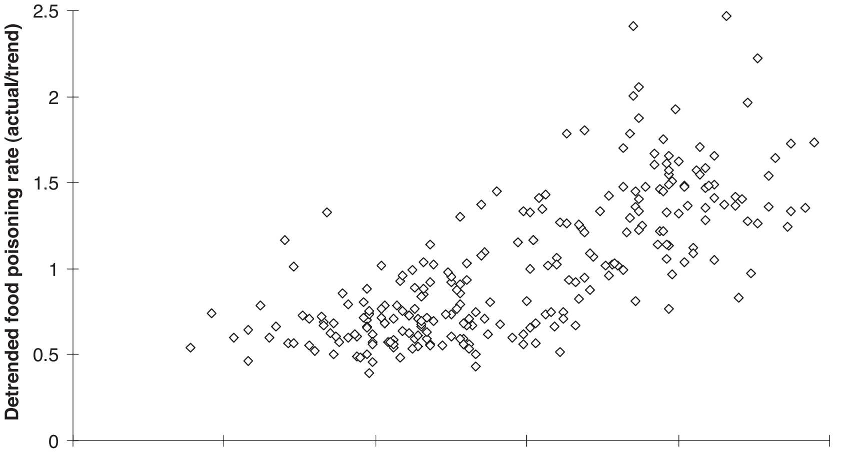
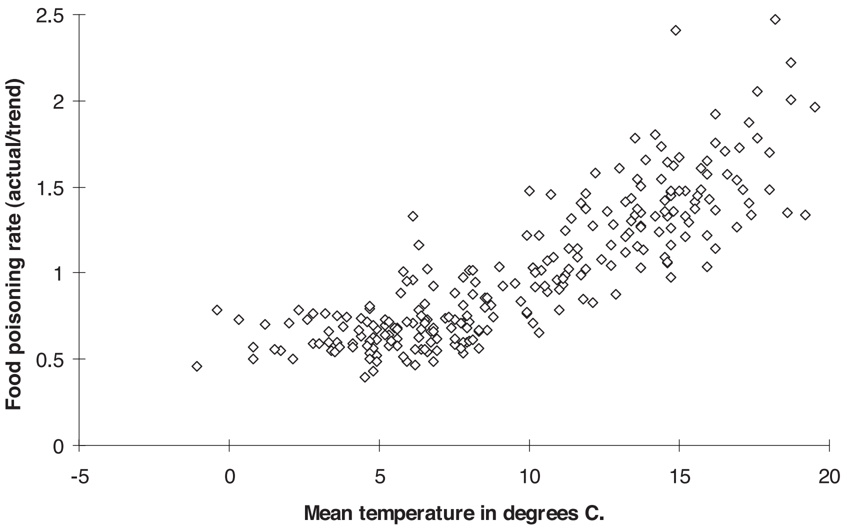


Figure 4.5

Food poisoning notification rate (actual/trend) and mean temperature of previous month



4.2.2 Research needs

A large amount is already known about the microbiological causes of food poisoning. Further research into improved means of food storage and preparation is needed as is research into how best to convey to people involved at all stages of food supply the importance of high standards of hygiene. This is more a matter for a public education campaign than for research.

4.2.3 References

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4.3 Vector-borne diseases and climate change

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Summary

- It is possible that indigenous malaria may be re-established in the UK by 2050. It is, however, unlikely to pose a major problem to health in the UK.
- Local outbreaks of malaria caused by *P. vivax* may occur and people who live in low-lying salt marsh areas should be advised to take precautions to avoid being bitten.
- Changes in the global distribution of malaria are likely and thus an increase in malaria caused by *P. falciparum* is probable in travellers returning to the UK from certain countries that are presently malaria-free. This particularly dangerous form of malaria is unlikely to become established in the UK in part due to conditions being unsuitable for the breeding and survival of the particular species of mosquito that acts as the vector.
- It is not possible to predict the effect of climate change on the abundance of ticks in the UK; warmer and drier weather is likely to have a number of effects on the biology of ticks and some of these will run counter to others.
- Human contact with ticks is likely to increase as a result of changing land use for agricultural and recreational purposes. There may be an increase or decrease in the proportion of ticks infected with the *Borrelia* genotypes which cause Lyme disease.
- Predictions of a significant increase in tick-borne diseases, such as Lyme disease are not well founded.
- None of the climate change scenarios considered in this report suggest that there will be an increase in the incidence of tick-borne encephalitis (TBE). Indeed, changes in the climate of Central Europe are likely to reduce the areas affected by TBE; thus the risk to UK holiday-makers may also decrease.

4.3.1 Introduction

Diseases caused by vector-borne pathogens are the result of complex interactions between three very different sorts of organism:

- ☐ the vertebrate host;
- ☐ the invertebrate (usually arthropod) vector; and
- ☐ the parasite (viruses, bacteria, etc.).

Each partner in the triangle is responsive to environmental changes in ways that make it very difficult to predict the altered outcome of these interactions. Rates of the biological processes (e.g. birth, death, development, biting by blood-sucking vectors, transmission between host and vector) vary independently and often in opposite directions in response to each climatic variable. Increased temperature, for example, generally accelerates development of both vectors and pathogens within those vectors, and causes vectors to bite more frequently (increasing transmission rates), but may cause higher vector mortality rates (which decreases transmission). Increased dryness may exacerbate vector mortality, and additionally decreases the availability of breeding sites for vectors such as mosquitoes. Although temperature and dryness may vary together, they will do so to different extents in different regions. In temperate regions with markedly seasonal climates, indices of mean annual climate changes alone are not sufficient for predictions of the risk of infection in the human population. For example, no matter how suitable most of the year may become in the United Kingdom for sub-tropical vectors, either a hot dry summer or an insufficiently warm winter may act as a bottle-neck, reducing vector survival.

We therefore urge caution in drawing conclusions about the future incidence of infection from existing relationships between single climatic variables and disease. In general, more than a single variable will determine transmission rates, and correlations observed today may fall apart, or at least change shape, if the underlying biological processes are disrupted by climate change beyond the normal fluctuations upon which those correlations are based.

4.3.2 Methodology

Baseline and modelled climatologies

The CRU 10 km British Isles climatology and 0.5° Global climatology (UKCIP Technical Report No. 1 1998, hereafter UKCIP98, Appendix 4) were used to interpret and model present-day distributions of vector-borne diseases. To these surfaces were added the HadCM2 model (difference) predictions for the 'Medium-Low' and 'Medium-High' scenarios. These differences were also scaled up or down by factors derived from UKCIP98 Appendix 6 to produce the equivalent 'High' and 'Low' global surfaces for the 2020, 2050 and 2080 periods. The same correction factors were applied to all climate variables (i.e. including vapour pressure and precipitation), following current accepted practice (M Hulme *pers. comm.*). Thus the future scenarios are a combination of the observed 1961-1990 climatology and the predicted GCM differences under the variety of scenarios considered: this, rather than using both modelled 1961-1990 climatology and difference information, also follows standard practice (M Hulme *pers. comm.*).

Before using any of the future scenario information the HadCM2 monthly imagery had to be re-sampled to the same image dimensions as the 0.5° global datasets. This was done using cubic spline interpolation, by columns and then by rows.

Modelling disease distributions

There are a number of options for modelling the impact of future climates on vector-borne and other transmissible diseases. This section discusses the alternatives investigated here.

a) The Biological approach

All biological processes are temperature sensitive, but the impact of this sensitivity on disease transmission is often difficult to predict. The temperature dependence of a number of important variables has been established experimentally, and may be included in predictive transmission models for a warmer world. Arising from this, developmental processes are often modelled by day-degree summation, where temperature differences from a developmental threshold are summed over time until a total is reached that represents the total developmental requirements, at which point development is judged to be complete. Such temperature summation may be used to model the incubation period of a parasite within vector insects, thus providing another input into general models for transmission.

> *The biological approach is used to predict the impact of the various GCM scenarios on the potential for transmission of vivax malaria in different parts of the UK.*

Whilst biological modelling of this sort is the ideal solution to the problem of predicting the impact of future climates on disease transmission, present models are unable to predict how mosquito abundance (an important component of such models) will change under different scenarios of climate change. Warming conditions from a cold temperature start are likely to increase vector numbers, but from a warm temperature start may well decrease numbers. Such population changes are ignored in all existing models of this sort, and model predictions are therefore of risk relative to the present day assuming constant vector numbers. In addition, the models tend to be driven only by temperature variables; the influence of all other variables is ignored. Increasing or decreasing moisture, in concert with temperature changes, is a critical factor that should also be considered.

Methods such as this, and the following ones, make predictions about the changing potential risk from biting vectors. Whether or not this potential risk is realised depends on the human response to varying biting frequencies; for example, while a low biting rate may be ignored, higher rates may elicit avoidance behaviour which reduces human-vector contact.

b) The Statistical approach

In this second approach, the present-day distributions of vectors or diseases of potential importance are statistically matched to current climatic variables, to provide a multi-variate description of present-day areas of disease risk. This understanding is then applied to future scenarios, and future distributions are predicted for them. The approach, therefore, is essentially a 'pattern-matching' exercise, from which conclusions may be drawn about the likely climatic sensitivity of vectors and/or diseases. Obtaining a good fit of the present-day distributions to present day climates is a necessary first step in this modelling exercise. Distributions are modelled here using maximum likelihood methods and discriminant analytical models with step-wise inclusion of temperature, vapour pressure and precipitation variables. Before analysis, all climate surfaces were temporally Fourier smoothed[1] and the means, maxima and minima of the smoothed variables were used in the analysis. The step-wise inclusion method identifies sequentially those variables most important in distinguishing presence and absence areas: we imagine that this reflects their biological importance (although this assumption urgently needs to be tested). For the present report, the top five selected variables only were used to make the predictive maps. Climate matching is well able to capture the rather subtle interactions between predictor variables (many of which co-vary) that are often important in shaping distributions.

> *The statistical or pattern-matching approach is illustrated for the cases of global malaria and tick-borne encephalitis (TBE) in Europe. The changing distributions of both diseases are modelled for a variety of future scenarios. Changing risks, both to the UK direct and to UK travellers to various regions, are predicted.*

The drawback of the pattern-matching approach is that it is essentially a statistical inference method, based on the past, that may not be a reliable guide to distributions in a climatically changed world where co-variation between climate variables may be different. It is also possible that the variable selection method will identify biologically spurious variables: it is therefore important to select the variables submitted to the analysis on the basis of prior biological understanding.

c) The Climate Envelope approach

This is a version of the above approach that matches current UK climates to other parts of the world and then examines what diseases are prevalent in them. Presumably there is some risk that the same diseases could affect the UK, depending also upon relative standards of living in the matched countries. The risks of future diseases may then be investigated by matching *future* UK climates to *present* global climates, to answer the question 'Where, at the present time, are climates similar to those that the UK will experience in 20, 50 or 80 years' time?' The diseases now prevalent in such areas may be those we need to guard against.

> *The climate envelope approach is applied to current and future UK climates. It is the only approach possible for situations where we lack any biological information for process-based modelling, or disease or vector distribution maps for the statistical approach.*

The interpretation of the results from the climate envelope approach involves substantial guesswork, not only because disease situations in other countries are even less adequately known than in the UK (with the notable exception of the USA), but also because the ways in which people live within their environments vary in so many ways. For example, if future UK climates match those of southern France today, what are the future risks in the UK of leishmaniasis, a protozoal disease mostly of dogs in the Mediterranean region, but occasionally transmitted by the sand-fly vectors to humans?

d) The Expert Opinion approach

When the above approaches cannot be applied, we must rely on expert opinion, often notable by its absence, its contradictions, or its inaccuracy. This in reality reflects the poor quantitative understanding we have of virtually all vector-borne and similar diseases - an ignorance that affects all prediction attempts in one way or another.

Currently the geographically variable importance of Lyme disease[2] reflects either biological reality, or inadequate diagnosis: increasing recognition in the UK has resulted in increased numbers of reported cases here[3] which probably has nothing to do with global warming. When future predictions are made of diseases such as this, already present in the UK, we fall back on a combination of biological insight to suggest how disease prevalence may change in vector populations, and guessed predictions of how altered British leisure activities in the future warmer world will affect human interactions with the infected vectors.

> *The expert opinion approach is used to make predictions about the future importance of Lyme disease, caused by bacteria transmitted by ticks. Lyme disease already occurs in the United Kingdom, throughout the rest of Europe and into the far East of the Russian Federation.*

A number of other potential future problems for the UK can be identified using expert opinion on the likely increase of insects and other creatures that are known to generate nuisance or public health problems at the present time. Such problems often come to the attention of experts only from articles in the local or national press, or from talking with colleagues whose advice has been sought by the affected regional health authorities. Neither is a particularly reliable or consistent measure of the real extent of such problems. Finally, expert opinion may be used to second-guess the future arrival in the UK of migrant pests such as locusts, or of imported pests such as the Asian tiger mosquito that has already spread rapidly in the USA.

> *Expert opinion is used in the Report to produce a list of potential problems in the UK from outbreaks of urticaceous caterpillars, stinging insects or nuisance flies in houses or around kitchens to more direct threats such as local outbreaks of blood-sucking black-flies (Simulium spp.).*

4.3.3 Malaria

Malaria is one of the world's most important infectious diseases killing between 1.5-2.7 million people every year[4]. The disease is transmitted by inoculation of the parasite during feeding by certain Anopheline mosquitoes, which breed in both fresh and brackish water. Despite attempts to control this disease there are between 300-500 million clinical cases each year and this number may be rising[4]. Of the four species of human malaria, *Plasmodium falciparum* is the most lethal and is widespread throughout the tropics. *P. vivax* is less harmful, but is still responsible for much illness and occurs widely in the tropics, although it is uncommon in much of Africa. The problem of malaria is particularly worrying because of the rapid spread of drug-resistant strains of the parasite and the possibility of untreatable forms of the disease.

Domestic malaria (predicted using the biological approach)

Malaria was a leading cause of death in many salt marsh communities in Britain between the 16th and 19th centuries[5] and there was even some indigenous malaria at the end of the 19th century. Those areas most badly affected included the Fens, Thames estuary, south-east Kent, the Somerset levels, the Severn Estuary, the Holderness of Yorkshire[5] and the coastal districts of the Firth of Forth[6]. Malaria declined progressively from the 1820s onwards due to a number of factors. Drainage schemes in the marshlands shrank mosquito-breeding sites. Housing improved and became less suitable for resting mosquitoes, which prefer damp and dark quarters. People began to sleep in separate rooms, often upstairs, making it more difficult for a mosquito to locate a human blood meal. Cattle numbers rose and were stabled away from homes, providing an alternative source of blood and reducing the chances of malaria transmission. At the same time improvements in medical practice occurred and quinine, an effective anti-malarial, became more affordable[7].

In 1917 and 1918 there were around 330 cases of locally-transmitted *vivax* malaria when infected servicemen returning from overseas were billeted near salt marshes on the Thames Estuary[8]. After that, effective control was achieved by making malaria a notifiable disease, with appropriate swift treatment and control action. All reported cases of indigenous malaria this century were *vivax* malaria, except for one unusual case of *falciparum* malaria in Liverpool.

Mosquito vectors and malaria transmission

It is highly unlikely that the most lethal form of malaria can be transmitted by British vectors, although the potential for *vivax* transmission remains. There are five species of Anophelines in Britain capable of transmitting both temperate and tropical strains of *vivax* malaria: *Anopheles atroparvus, An. messeae, An. plumbeus, An. claviger, and An. algeriensis*[7]. *An. atroparvus* can also transmit European strains of *P. falciparum*[9], but is completely refractory to strains of the same parasite from the tropics (quoted in Ref. 9). This mosquito is therefore the most important potential vector of malaria in the UK. Its distribution coincides fairly well with past patterns of malaria; it occupies houses and feeds readily on people.

Malaria and climate

P. vivax is better suited to the British climate than is *P. falciparum*. It requires lower temperatures (by 1-2°C) than *falciparum* to develop equally rapidly in mosquitoes, and thus does better at cooler temperatures. *Vivax* parasites, unlike *falciparum* parasites, also sequester in the liver of an infected person, and are later released to infect new generations of mosquitoes in the spring. As few parasites develop in mosquitoes below 15°C, the season for potential transmission is between June and September.

Temperature and rainfall both influence the level of malaria transmission[10]. Higher temperatures increase the rates of mosquito development, female mosquito feeding and maturation of the malaria parasites within the mosquito, but may decrease adult mosquito survival. Rainwater provides mosquito breeding sites and a humid environment, conducive for vector survival.

Impact of temperature changes

Here the risk of *vivax* malaria in the UK is modelled for *An. atroparvus* (see pp 121-122 for method). Maps of malaria suitability for a range of future climate scenarios (Figures 4.6 & 4.7)* show the number of months that *vivax* malaria, if it were introduced, could persist each year in different parts of the country. These maps are a rough guide of risk based on the effects of changing temperature on variables in the transmission process, but they do not take into account changes in precipitation, humidity or the availability of breeding sites. The impact of these additional factors will vary with mosquito species; for example, mosquitoes inhabiting extensive salt-marshes are less likely to be affected by changes in precipitation than are mosquitoes that breed in smaller water bodies such as puddles, small ponds or in domestic containers.

The present-day distribution of malaria risk corresponds extremely well with past records of the distribution of malaria in England (Figure 4.6a)[11], and Medium and High scenarios for 2050 highlight parts of Scotland where malaria was once common[6] (Figure 4.7). Thus we are confident that our temperature-malaria model is relatively robust. Under all climate-change scenarios, the risk of transmission is predicted to increase in the south of England, spreading northwards to the Scottish borders.

At present, in only a few months in the south of the United Kingdom are temperature conditions permissive for transmission of *P. vivax* malarial parasites by indigenous vector mosquitoes. Although such transmission occurred in the historical past, it is a minor threat at present because living conditions have improved considerably since Shakespeare wrote of the ague (malaria fever). If the climate becomes warmer, conditions for transmission become more favourable, and last for longer. It is likely that our present standards of living will ameliorate this increasing threat to a large extent, but not necessarily wholly in high risk areas. In regions of extensive saltmarshes in south-east England, local inhabitants are plagued by large numbers of mosquitoes even today.

*** The illustrations referred to in this section include maps and are collected at the end of the section.**

Impact of habitat changes

The distribution of *An. atroparvus* is largely restricted to salt-marshes, because it breeds mainly in brackish water. At present there are 42 251 ha of salt-marsh in Britain, with the largest areas, 8 525 ha, along the Greater Thames Estuary in Essex and Kent[12]. Coastal wetlands are being reduced by drainage and other land 'improvements'. Rises in sea level[12] that breach sea defences and inundate lowlands that are at present prevented from adapting naturally to saltwater, may result in less salt-marsh. Elsewhere, gradual saltwater intrusion into coastal lowlands may increase breeding sites for *An. atroparvus.* With summer droughts, other mosquito species may find more breeding sites in pools left in river beds, and in water butts. There will be greater exposure to mosquitoes as people stay outdoors in warmer summer evenings, or sleep with the windows open[13].

It is possible that climate changes will allow new vector species to become established in Britain. This would be most serious if it involved better European vectors of *vivax*, such as *An. saccharovi, An. labranchiae, An. superpictus* and *An. sergentii.*

Health authorities need to remain alert to the possibility of future European malaria outbreaks, as in Italy after 40 years of being free of malaria[14], or to the arrival in the UK of better European vectors of malaria. Any malaria outbreaks in the UK, however, are likely to be on a small scale and people at greatest risk (i.e. those who live near wetlands) are likely to take precautions against being bitten by mosquitoes. Prompt reaction to any outbreaks will reduce the chances of endemic malaria transmission in the UK.

Travellers' malaria (predicted using the statistical approach)

There are two different threats posed by changes in the distribution of malaria in parts of the world other than the UK[16]. First, aircraft travelling from malaria-endemic countries may bring infected mosquitoes into non-endemic countries. Such outbreaks occur around international airports, and since 1969 there have been 60 such cases reported from Belgium, France, Germany, Italy, Netherlands, Spain, Switzerland and the UK. The last case of airport malaria in England was in the warm summer of 1983 near Gatwick airport[15]. In the same year two British women, who travelled from London to Rome on an Ethiopian Airlines flight originating from Addis Ababa, contracted malaria[15], presumably by being bitten during the flight by an infective mosquito from Africa. Continuing (and enforcing) the practice of disinfesting cabins and cargo holds would guard against this risk.

The second threat is of imported malaria, with its associated health system costs. There is no vaccination against malaria, and chemoprophylaxis is not guaranteed to be fully effective against a growing problem of multi-drug resistant parasites. Any increase in malaria endemic areas, alongside expanding jet travel, will raise the chances of travellers returning to the UK with malaria, including the far more dangerous forms found in the tropics. At present more than 2 000 cases of travellers' malaria are reported each year to the PHLS Malaria Reference Laboratory. Of these, around 67% are infections with life-threatening *P. falciparum*. The numbers of *falciparum* cases are rising (Figure 4.8); of 81 deaths in the last 10 years, 95% were due to *falciparum* malaria.

Global changes in *falciparum* malaria endemicity

The present distribution of *falciparum* malaria[17] is captured well (78% accuracy) by five climate variables, minimum and maximum temperature conditions, precipitation and vapour pressure (Figure 4.9a). Only in Iran and south-east Brazil are there significant areas of false positive predictions (SE Brazil is in fact shown as a low-risk area on some malaria maps). Under the Medium-High climate-change scenario (Figures 4.9b-d), the most significant threat to UK citizens travelling abroad is the progressive spread northwards of potentially malarious areas through Mexico into the southern states of USA. The potential of malaria in Florida is particularly serious given the tourist industry and the common perception of zero-threat there, although Florida's very active anti-mosquito services would undoubtedly react swiftly. Similarly, south-west Turkey, an increasingly important holiday destination, could become a high risk region for *falciparum* malaria. Globally, only central Brazil and Venezuela appear to lose their suitability for malaria.

These same changes, apart from those in South America, are predicted by the 2050s under all except the lowest scenarios of climate change (Figure 4.10).

Certain parts of the world frequently visited by tourists from UK, especially those on package tours, will become increasingly suitable for *falciparum* malaria in the future. These areas include Florida and other southern states of the USA and south-west Turkey. UK health authorities should monitor the variable success of the local authorities at these holiday destinations, to combat any increasing malaria risk to UK travellers abroad.

4.3.4 Tick-borne infections

Tick-borne pathogens are almost all zoonoses, circulating naturally amongst wild vertebrate hosts, but also infecting humans that are accidentally bitten by the vector tick. In Europe, the tick *Ixodes ricinus* is the principal vector of two pathogens that frequently infect humans: bacteria of the *Borrelia burgdorferi* complex, that cause Lyme disease, and the virus that causes TBE. In addition, humans are occasionally infected with viruses that cause mortality in sheep, e.g. louping ill virus, and with protozoa, *Babesia* spp., that cause redwater fever in cattle.

The major biological risk factors for all tick-borne infections are the distribution, abundance and pattern of seasonal activity of the vector ticks[18]. Ticks feed only once per life stage, as a larva, a nymph and an adult, between which they spend long developmental and host-seeking periods on the ground. Not all hungry ticks are infected. Nymphs are regarded as the most significant risk, because infection prevalence in them is usually higher than in larvae, having been amplified as larvae feed on infected hosts. Furthermore, nymphs are more abundant and smaller (less noticeable) than adults.

Interacting with these risk factors are human activities, outdoor occupations and leisure pursuits that bring humans into contact with ticks.

Lyme disease (predicted using the expert opinion method)

Lyme disease is widespread and prevalent throughout Europe and the UK, occurring more or less wherever ticks occur. The number of cases reported annually in the UK (less than 200)[2] is far lower than in mainland Europe despite similar densities of infected ticks. One explanation is that a large number of cases still go undetected and unreported, although UK GPs are increasingly aware of the problem. There is some evidence that the strain of *Borrelia* in the UK is different: intensity of infection in ticks is very low and isolation of live bacteria is very much more difficult[19]. Perhaps this results in lower rates of transmission to humans. Furthermore, the infection prevalence in ticks is geographically highly variable, depending on host factors (see below).

A climate-induced change in risk in the UK?

There is no simple correlation between temperature and incidence of Lyme disease in the UK. Data presented in Cannell *et al.*,[3] show that the annual number of cases reported in the UK from 1986 to 1997 have increased since 1994, but there is no significant correlation with mean summer temperatures in central England.

Tick distribution

Ticks are currently distributed throughout the UK, from northern Scotland to the south coast. Climatically, therefore, the whole of the UK is suitable for ticks. Their presence in any one locality is determined principally by the presence of suitable hosts for the adult ticks; while larvae and nymphs feed on vertebrates of all sizes, from mice and blackbirds to pheasants and deer, adults are confined to large mammals such as deer, sheep and cattle. In addition, the habitat structure must afford the right micro-environment for tick survival, with good vegetational cover above a substantial litter or mat layer that retains moisture. This usually coincides with deer habitats (deciduous woodlands)[20] and rough grazing. Improved pastures for sheep grazing are rendered unsuitable for ticks.

- Any increase in tick-infested areas is more likely to be the effect of changing agricultural and wildlife management practices than the effect of changes in climate alone. This has been seen in Scotland, for example, where grouse moors have been invaded by bracken. Increasing deer populations will support ticks in more places (as appears to have happened in the north-east USA).

Tick abundance

Ticks are most abundant where hosts (particularly for the adult stage) are abundant, and where the overall climate is warm enough to allow rapid development between tick stages and sufficiently wet to allow good survival between feeds. A favourable microclimate created by vegetation is also important.

- It is almost impossible to predict reliably any change in tick abundance with climate change, because it will be the outcome of two opposing forces: higher temperatures, especially over winter, will accelerate development and may eliminate diapause (a period of winter quiescence, when ticks do not feed), while drier summers will limit tick host-seeking activity and increase mortality directly. Only a climate-driven population model, which is not yet available for *I. ricinus*, will answer this question.

Seasonal patterns of tick host-seeking activity

In warmer regions ticks quest for hosts over longer periods of the year, starting earlier in the spring and continuing later into the autumn. During the summer, unusually dry spells cause a sharp decline in questing activity, from which the ticks may not recover if the dry spell is prolonged.

- It is possible that: the main tick activity season may shift to earlier in the spring; there may be a more pronounced autumn peak; and numbers of questing ticks may decline more dramatically in mid-summer.

Host factors

Infection prevalence in ticks depends on the specific tick-host relationships in any locality, which determines the circulation of the genetically diverse *Borrelia burgdorferi* complex. The four genotypes found in UK have distinct transmission cycles by means of different vertebrate hosts[21]. Pheasants, for example, are only competent to transmit two genotypes, *B. garinii* associated with neurological disorders (e.g. Bell's palsy) and *B. valaisiana* that has no associated pathology. In woodlands with large populations of pheasants, circulation of the other genotypes by means of mammals appears to be inhibited. Moreover, because pheasants feed mostly nymphal ticks, the prevalence of infection is high only in the relatively few adult ticks which emerge from these fed nymphs. In woodlands where rodents and squirrels feed most immature tick stages, nymphs have a much higher prevalence of infection with *B. afzelii* (associated with cutaneous symptoms) and *B. burgdorferi s.s.* (associated with arthritis)[22,23]. On moorlands dominated by sheep, the specific transmission cycle again results in high infection prevalence only in adult ticks[24].

- Unless the predicted climate change has an impact on vertebrate fauna (which is possible) the important risk factor of the type and abundance of the various Lyme disease vertebrate hosts will not be affected.

Human behaviour/activity

With warmer weather, humans are likely to interact with ticks in their habitat more frequently and for longer in the year. The creation of new leisure parks in forested areas should be a cause for some concern, since this will increase the contact rates between humans and ticks.

- People engaging in leisure activities are most likely to contact Lyme disease-infected ticks during spring and autumn, when ticks are likely to be most active. Whether, under various scenarios for climate change, there will be an increase in numbers of infected ticks at these times is still uncertain.

Tick-borne encephalitis (predicted by the statistical approach)

At present, TBE is confined to recognisable foci within Central Europe, the Baltic region and extensively through the Russia Federation[25,26]. Currently there is a real risk of infection to holidaymakers walking in these countries. We now understand that virus circulation depends on a particular pattern of tick seasonal activity[27] which occurs only in certain parts of the tick's geographical range, where the seasonal temperature profile is typically continental (as opposed to oceanic): high summer temperatures followed by rapid cooling in the autumn[28]. In regions that are too dry, however, poor tick survival limits TBE virus maintenance.

The extent, although not the focality, of the present distribution can be predicted very well (86% accuracy) from five climatic variables, including four variables of minimum and maximum temperature conditions, together with the maximum vapour pressure as a measure of terrestrial moisture conditions (Figure 4.11a).

A reduced risk of TBE in the future?

The predicted rise in temperature and decrease in moisture in the summer appears to drive the distribution of TBE virus into higher latitude and higher altitude regions progressively through the 2020s, 2050s and 2080s (Figure 4.11b-d). The Alps, however, are always too high to accommodate the virus. In the 2020s, France, Switzerland, Slovenia, Hungary and much of Austria are cleared of TBE virus, and the range of this virus (though not necessarily its vector) has contracted to inland regions of the Baltic states. By the 2050s, TBE has moved into areas at present free of infection, notably the mountains on the Slovak/Polish border and further north-west in Scandinavia, but central Europe is virtually cleared of TBE. This is consistent with the conclusion that increased temperatures have already extended the northern limit of *I. ricinus* in Sweden[29]. The final toe-hold in the 2080s is confined to a small part of Scandinavia, including new foci in southern Finland.

A very similar pattern emerges with increasingly variable scenarios (Figure 4.12): the TBE virus is pushed to the north-east of its present range, only moving westwards in southern Scandinavia. Only under the Low and Medium-Low scenarios does TBE remain in central and eastern Europe to any extent.

- None of the predicted climatic changes suggest that the UK will be threatened by the TBE virus. Overall there may be a marked decrease in the extent of this pathogen, although some areas free at present may be invaded, notably the highlands of the Czech and Slovak Republics and parts of Scandinavia north and west of the present coastal endemic regions.

4.3.5 Possible sources of other vector-borne diseases (predicted by the climate envelope approach)

At present, on the basis of co-varying mean temperature, precipitation and vapour pressure, similar climatic conditions to those found in various parts of the UK are found extensively in northern Europe, Asia west of the Caspian Sea, Japan and neighbouring regions of China and New Zealand (Figure 4.13a).

Under the Medium-High scenario, the changed climate in the UK is predicted to match the present climate in different parts of the world (Figures 4.13b-d). For example, by the 2020s parts of the UK match more of the Mediterranean rim: does this pose a threat of leishmaniasis? Further into the future for UK climates, the regions of similarity with present-day Europe then decrease; by the 2080s the climate predicted for much of southern, central and north-west England does not match any found in Europe today. If climate really is a determining factor for the arrival of new diseases into UK, this exercise highlights the regions of the world from which we might expect to import problems. With data on which diseases occur in these places at the present time, we should be able to make more informed guesses of the future risks of exotic diseases to inhabitants of the UK.

The same exercise has been done for the various scenarios in the 2050s (Figures 4.14a-d).

4.3.6 Other insect-related problems (predicted by the expert opinion method)

We can only list a range of other insect-related problems which may change with the predicted climate changes in the UK.

Of possible high significance

❏ *Flies and diarrhoeal diseases - the 'buffet factor'*. Contaminative spread of bacteria by nuisance flies is likely to increase with any increase in the abundance of such insects.

❏ *Midges - relevant to tourism*. The midge menace is already well known to the local people and holiday makers in Scotland and elsewhere. An extension of warm summer conditions may well increase the seasonal extent and abundance of these insects.

❏ *Fleas - nuisance factor associated with cats and dogs*. Fleas on domestic animals thrive in warm conditions, such as those associated with domestic central heating; hungry cat fleas are particularly likely to bite humans. An increasingly warm climate will increase such problems.

- ❑ *Stinging/biting insects such as bees, wasps and horseflies - serious allergic reactions.* Allergic reactions to bee and wasp stings can be fatal in a minority of cases. Sensitivity appears to increase with increased exposure, a possible outcome of warmer conditions.
- ❑ *Urticaceous caterpillars - allergies.* Caterpillars of certain moths occur in vast numbers and live communally, often spinning characteristic silk 'tents' that attract our attention. On contact with human skin, the hairs of such insects can cause painful swellings and rashes that persist for many days. The causes of outbreaks of such caterpillars are uncertain, but they may increase in frequency in warmer conditions.

Others to be considered

- ❑ Nuisance mosquitoes, or migrant pests such as locusts.
- ❑ Introduced new vector species (e.g. *An. albopictus*, potential vector of both dengue and malaria, accidentally introduced in the USA in used car tyres and spreading rapidly).
- ❑ Black flies (e.g. the Blandford fly) – periodic and newsworthy outbreaks of these blood-sucking flies occur in southern UK counties.
- ❑ House dust mites – associated with allergies and possibly with asthma.
- ❑ Plague – endemic in the USA, transmitted by fleas between rats and also (at least in humans) directly from person to person.
- ❑ Leptospirosis (e.g. Weil's disease) – already present in the UK, related to direct contact with rodents or with areas contaminated with rodent urine and faeces.
- ❑ West Nile Fever. The virus that causes West Nile Fever is probably maintained by mosquitoes of the *Culex* species. Outbreaks have been recorded in the USA and in France.

4.3.7 Priorities for future action and research

Since we are dealing with considerable uncertainties concerning vector-borne diseases, we feel there are two priorities for future action. The first is to monitor changing risks as they are happening, both within the UK and to holiday makers. The second is to examine the impact of multivariable environments on the spatial and temporal patterns of disease distribution and intensity for both temperate and tropical vector-borne disease systems.

Create a database against which to monitor change in incidence:

- ❑ GPs to report centrally on any insect-associated conditions, e.g. wasp/bee stings, rashes from caterpillars, tick bites
- ❑ Any significant change in incidence should be the alert for focused research

Identify the threat to travellers/holidaymakers going to exotic places, mostly in the tropics:

- ❑ Match holiday destinations to disease risk
- ❑ Monitor risk in those places
- ❑ Alert GPs in the UK to recognise disease symptoms and to report centrally

Build on studies to date that have used remotely sensed satellite data for extensive studies of environmental variables that determine vector-borne disease risk (e.g. for malaria, dengue, leishmaniasis, trypanosomiasis and tick-borne encephalitis).

- ❑ Identify the regions of high risk that might threaten inhabitants of the UK
- ❑ Conduct satellite data analysis and related field studies to refine the predictions of risk to the UK

4.3.8 Further reading

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4.3.9 References

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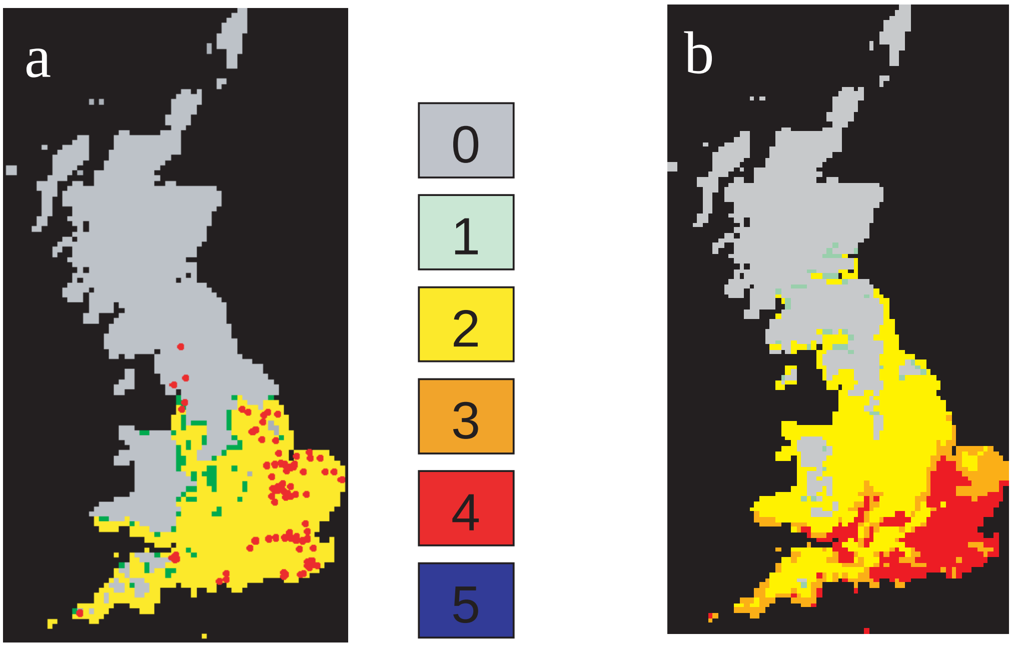
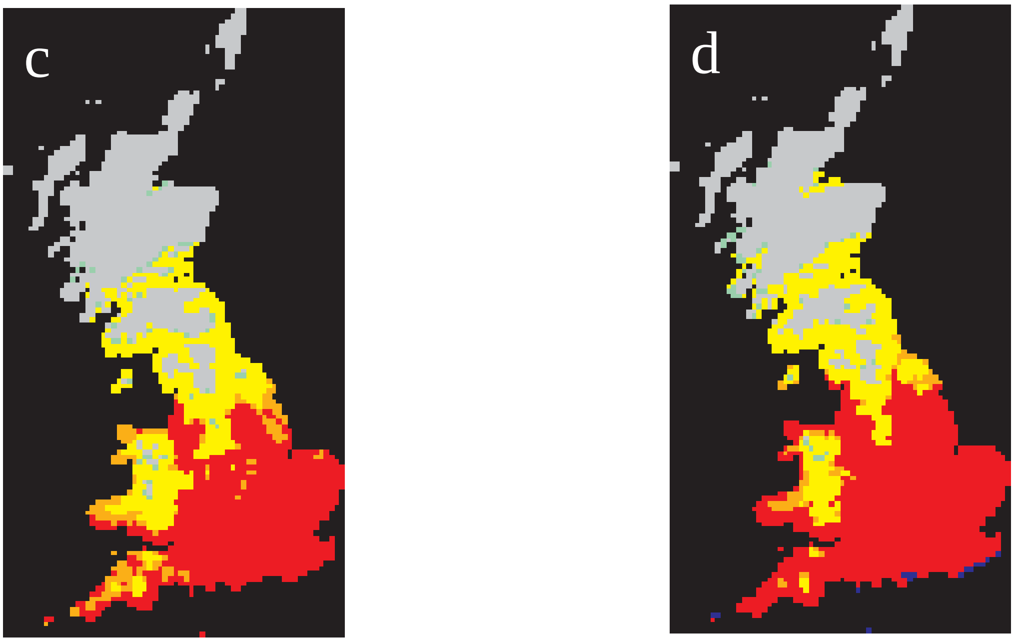
Figure 4.6 The number of months in which *vivax* malaria could be spread in the UK The different colours represent the number of months each year that *vivax* malaria could be transmitted. The red dots in Fig 4.6a show the distribution of malaria in the 19th Century.

Present-day and Medium High Scenario for the 2020s, 2050s and 2080s.



Present day
Scenario: Zgb16190

2020
Scenario: Zgax2020

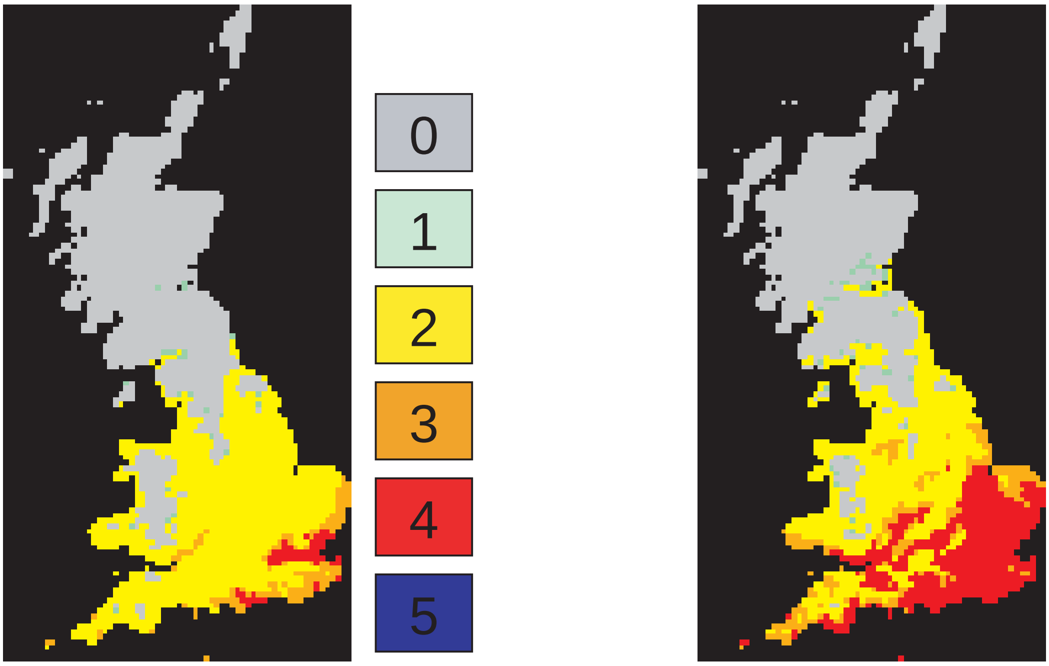


2050
Scenario: Zgax2050

2080
Scenario Zgax2080

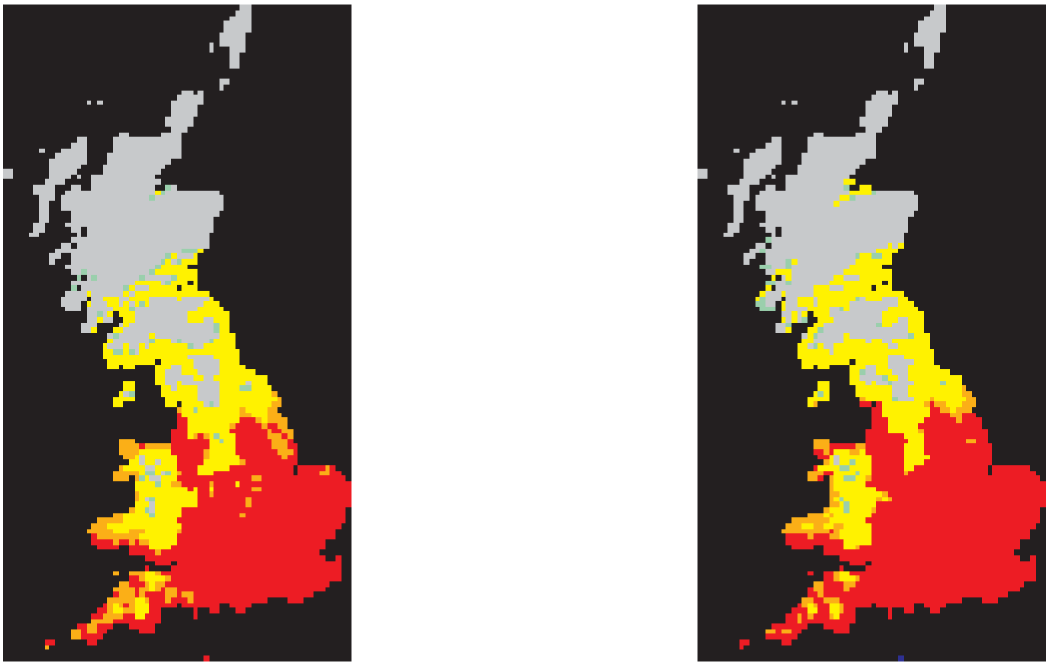
Figure 4.7 The number of months in which *vivax* malaria could be spread in the UK The different colours represent number of months each year that *vivax* malaria could be transmitted

Low, Medium-Low, Medium-High and High Scenarios for the 2050s



2050
Scenario: Zglx2050

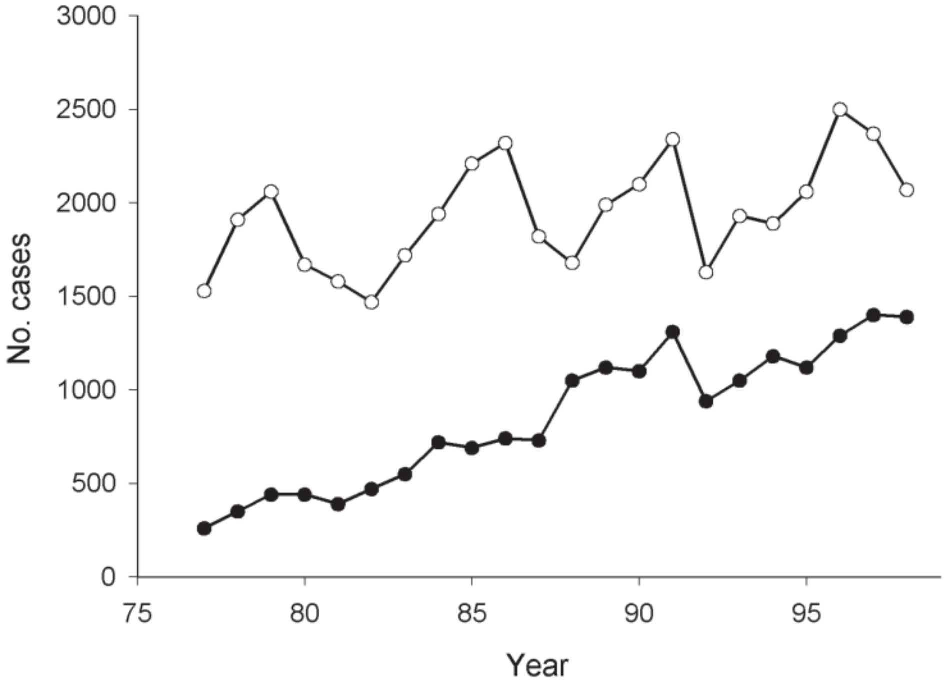
2050
Scenario: Zgdx2050



2050
Scenario: Zgax2050

2050
Scenario Zghx2050

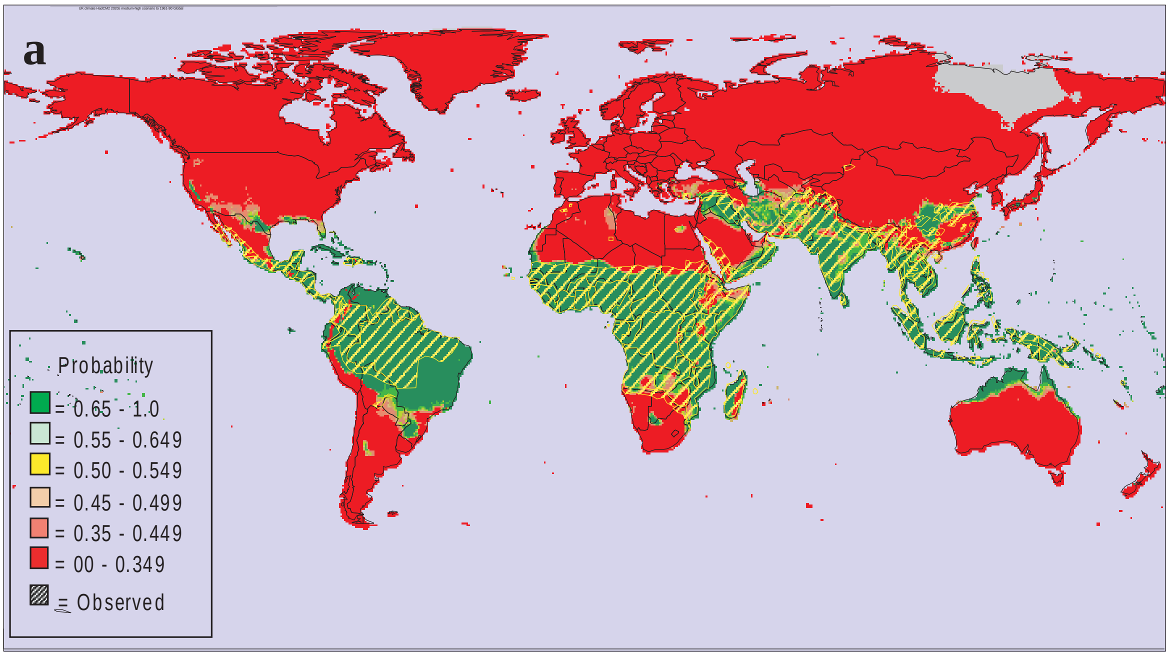
Figure 4.8 Annual cases of malaria reported to the PHLS Malaria Reference Laboratory, UK



Open circles represent all cases of malaria and closed circles are those due to *P. falciparum*. Data courtesy of Dr David Warhurst

Figure 4.9 a & b Global falciparum malaria
The present-day distribution of falciparum malaria is adequately described by temperature, precipitation and vapour pressure data (Fig. 4.9a, 78% correct predictions, 14% false positives and 8% false negatives). The predicted probabilities with which local climates match those in malarious areas are colour coded according to the inset probability scale. Predictions for the HadCM2 Medium-High scenario of the 2020s, are shown in Figure 4.9 b

Global malaria. Predicted areas of suitability, 1961-90 climate



Global malaria. Predicted areas of suitability, HadCM2 2020s medium-high scenario

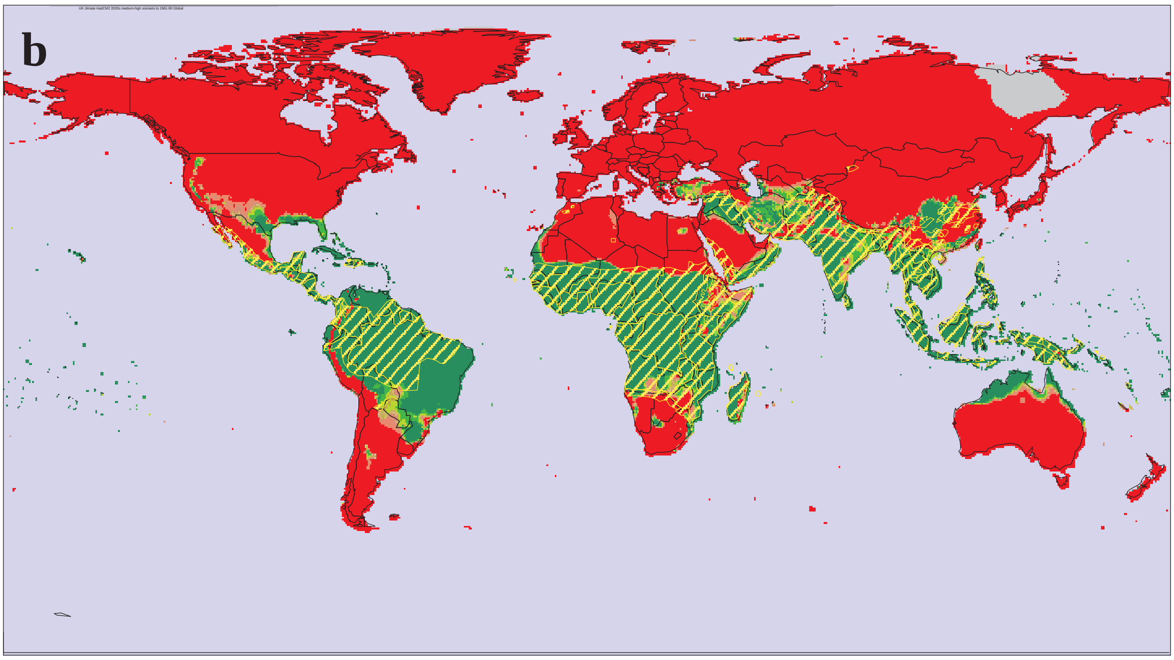
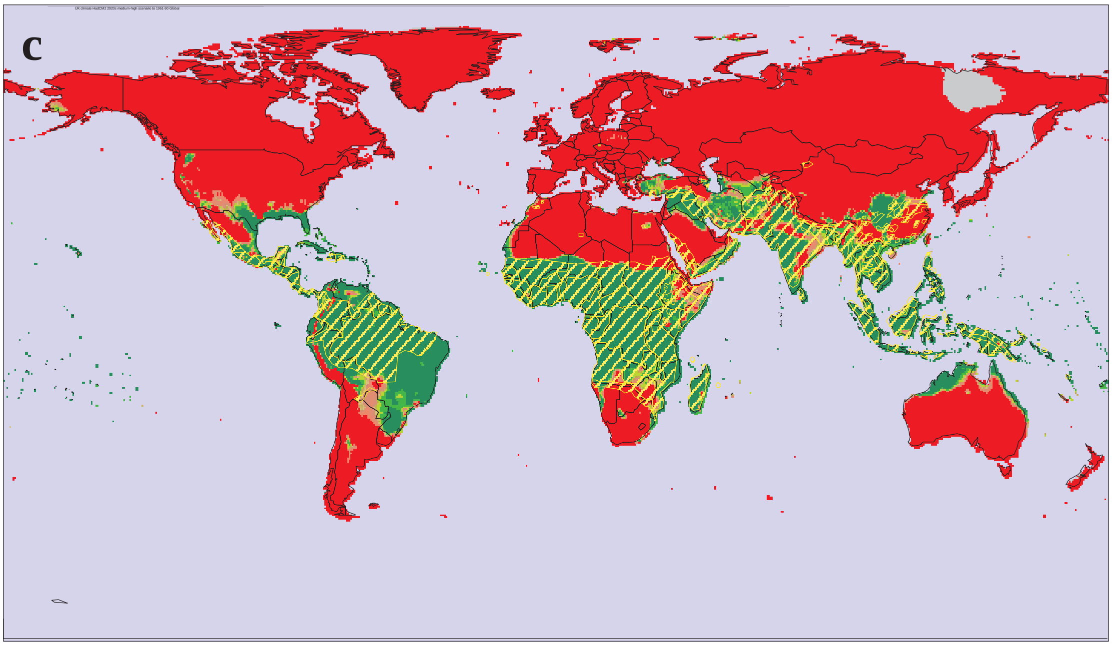


Figure 4.9c & d Global falciparum malaria. The present-day distribution of falciparum malaria is adequately described by temperature, precipitation and vapour pressure data (Fig. 4.9a, 78% correct predictions, 14% false positives and 8% false negatives). The predicted probabilities with which local climates match those in malarious areas are colour coded according to the inset probability scale. Predictions for the HadCM2 Medium-High scenario of the 2050s and 2080s, are shown in Figures 4.9c & d

Global malaria. Predicted areas of suitability, HadCM2 2050s medium-high scenario



Global malaria. Predicted areas of suitability, HadCM2 2080s medium-high scenario

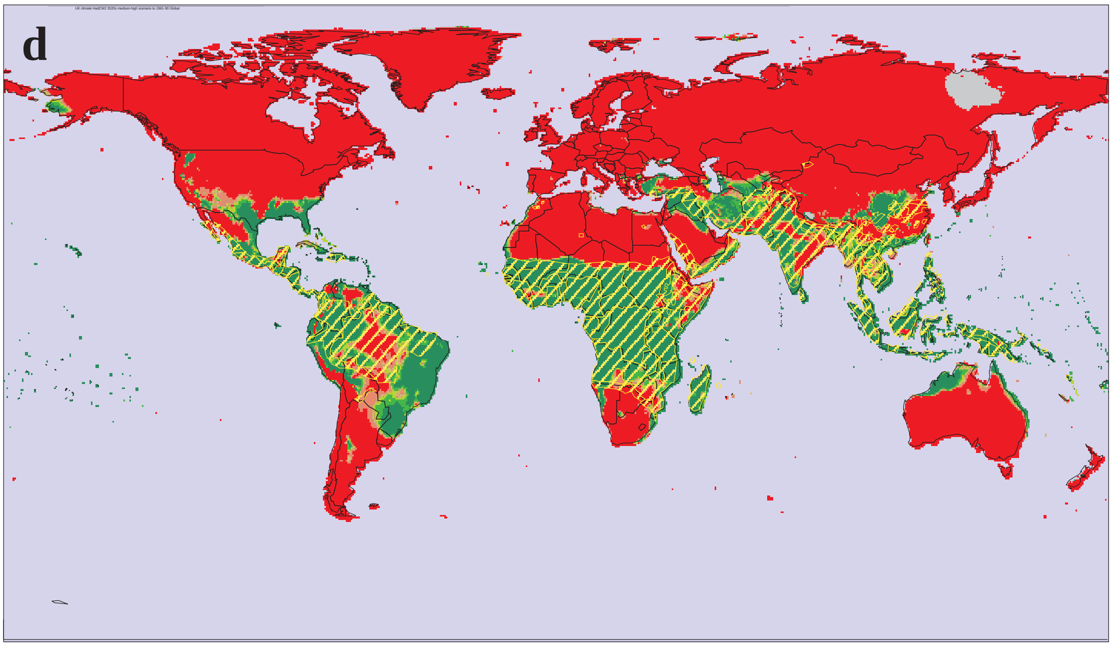
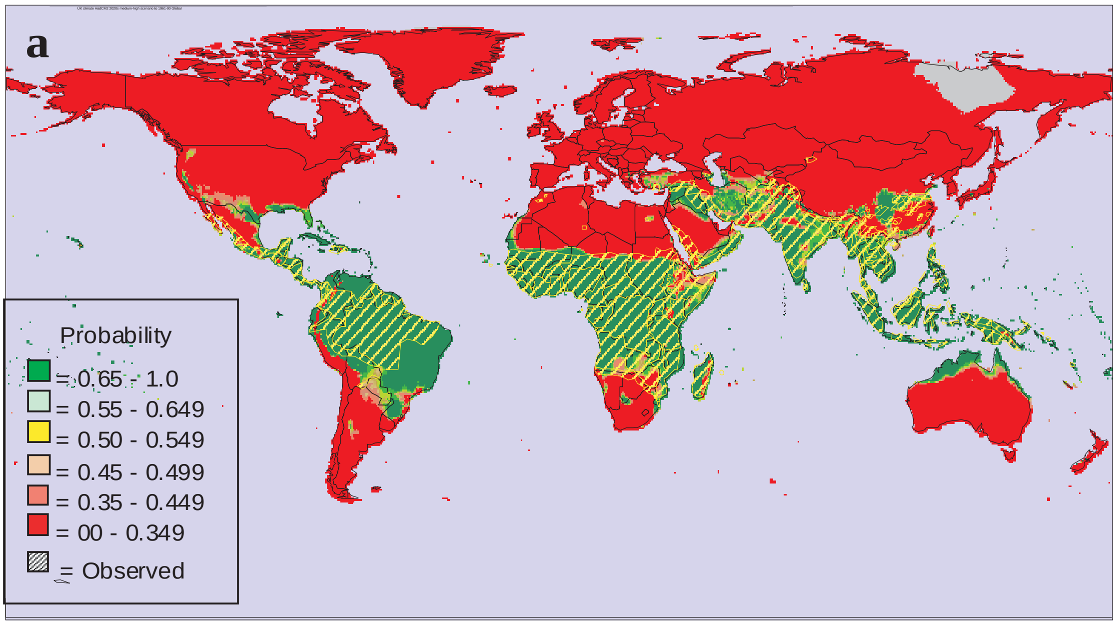


Figure 4.10a & b Global falciparum malaria. The present-day distribution of falciparum malaria is adequately described by temperature, precipitation and vapour pressure data (Fig. 4.9a, 78% correct predictions, 14% false positives and 8% false negatives). The predicted probabilities with which local climates match those in malarious areas are colour coded according to the inset probability scale. Predictions for the HadCM2 Low and Medium-Low scenarios of the 2050s, are shown in Figures 10a & b

Global malaria. Predicted areas of suitability, HadCM2 2050s low scenario



Global malaria. Predicted areas of suitability, HadCM2 2050s medium-low scenario

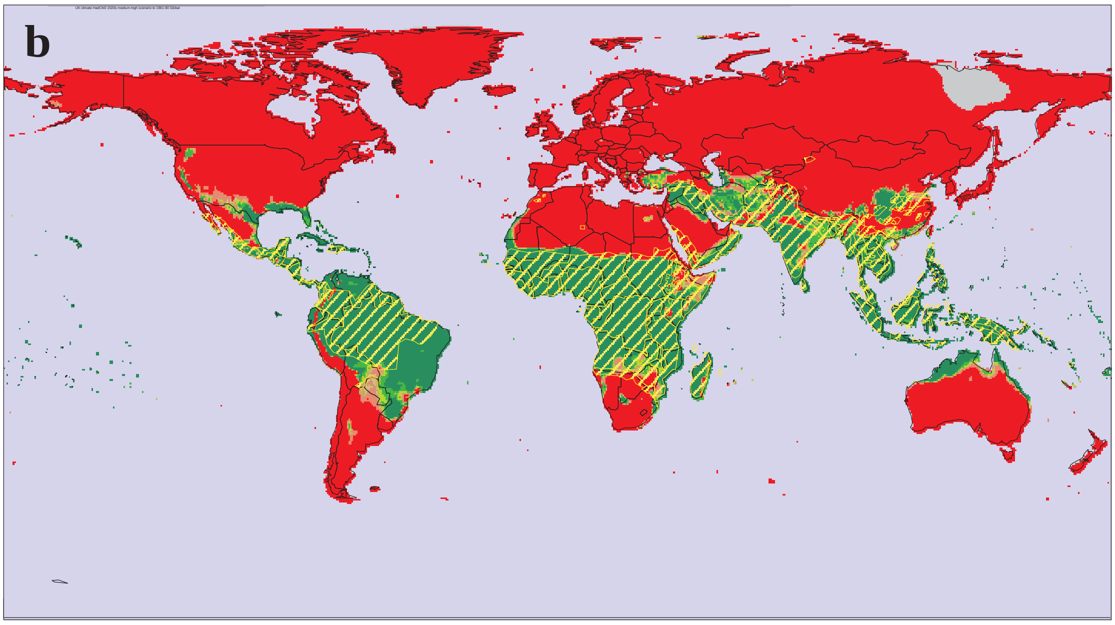
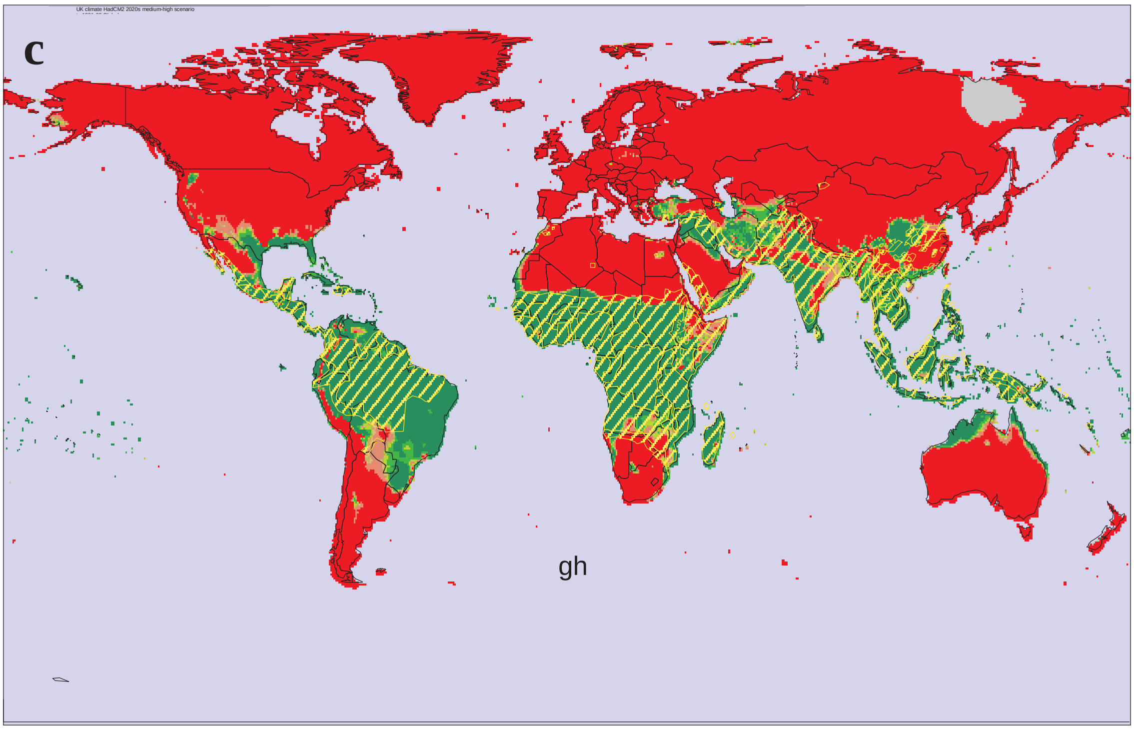


Figure 4.10 c & d Global falciparum malaria
The present-day distribution of falciparum malaria is adequately described by temperature, precipitation and vapour pressure data (Figure 4.9a, 78% correct predictions, 14% false positives and 8% false negatives). The predicted probabilities with which local climates match those in malarious areas are colour coded according to the inset probability scale. Predictions for the HadCM2 Medium-High and High scenarios of the 2050s are shown in Figures 4.10 c & d

Global malaria. Predicted areas of suitability, HadCM2 2050s medium-high scenario



Global malaria. Predicted areas of suitability, HadCM2 2050s high scenario

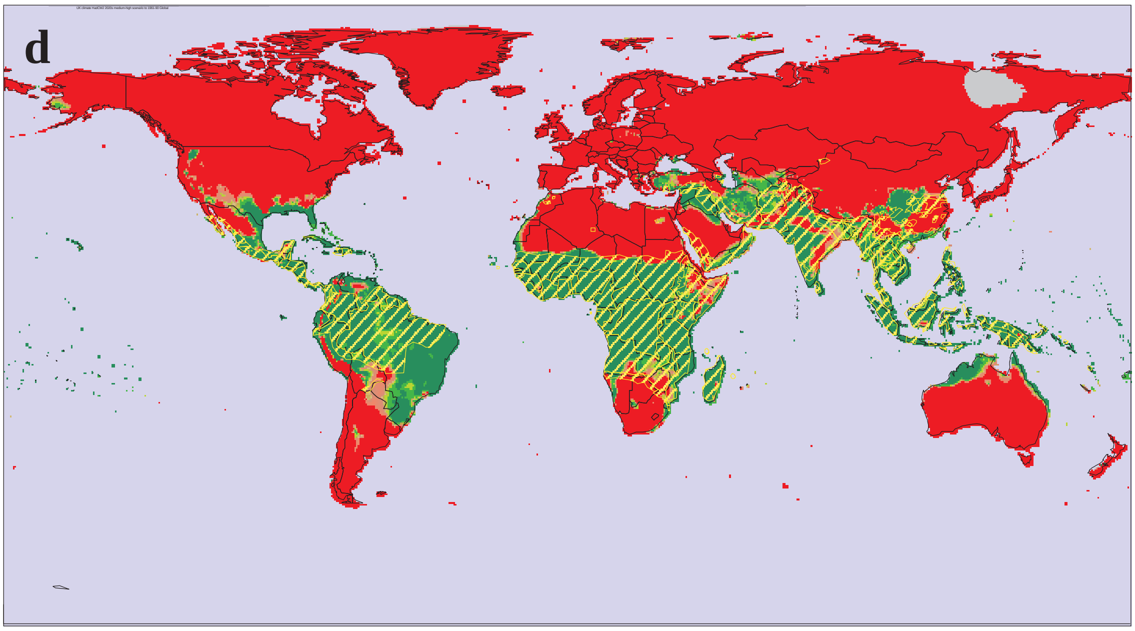
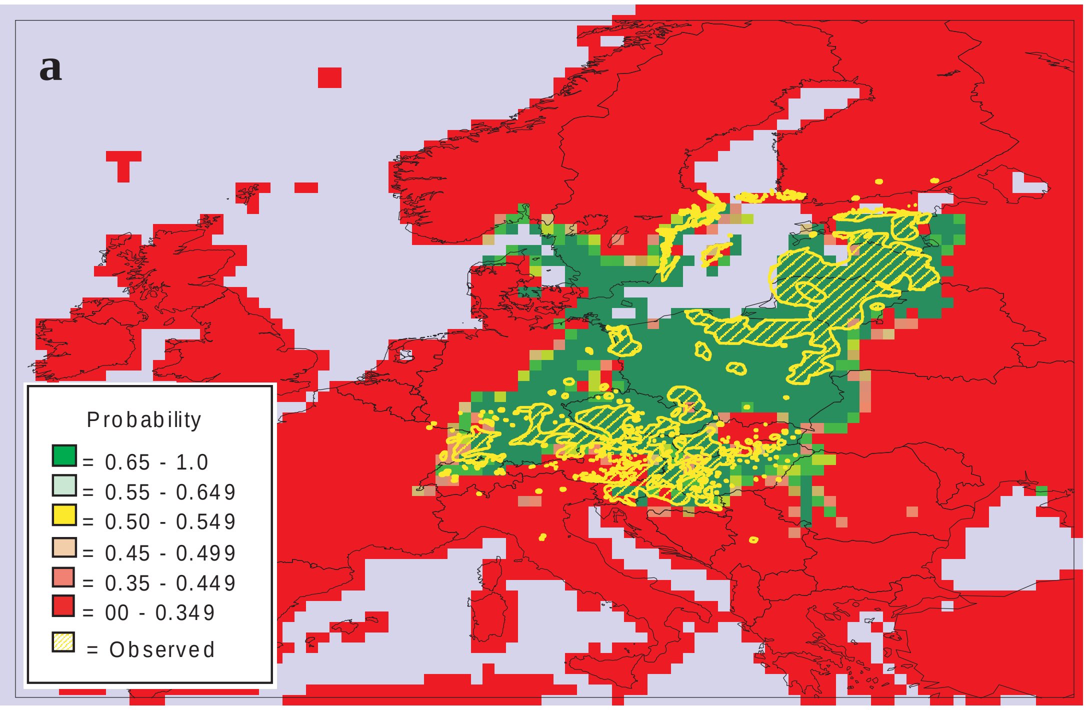


Figure 4.11 a & b Tick-borne encephalitis (TBE) in Europe
The present-day distribution of TBE in Europe is adequately described by temperature and vapour pressure data (Figure 4.11a, 86% correct predictions, 12% false positives and 2% false negatives). Predictions for the HadCM2 Medium-High scenario of the 2020s, are shown in Figure 4.11 b

TBE in Europe. Predicted areas of suitability, 1961-90 climate



TBE in Europe. Predicted areas of suitability, HadCM2 2020s medium-high scenario

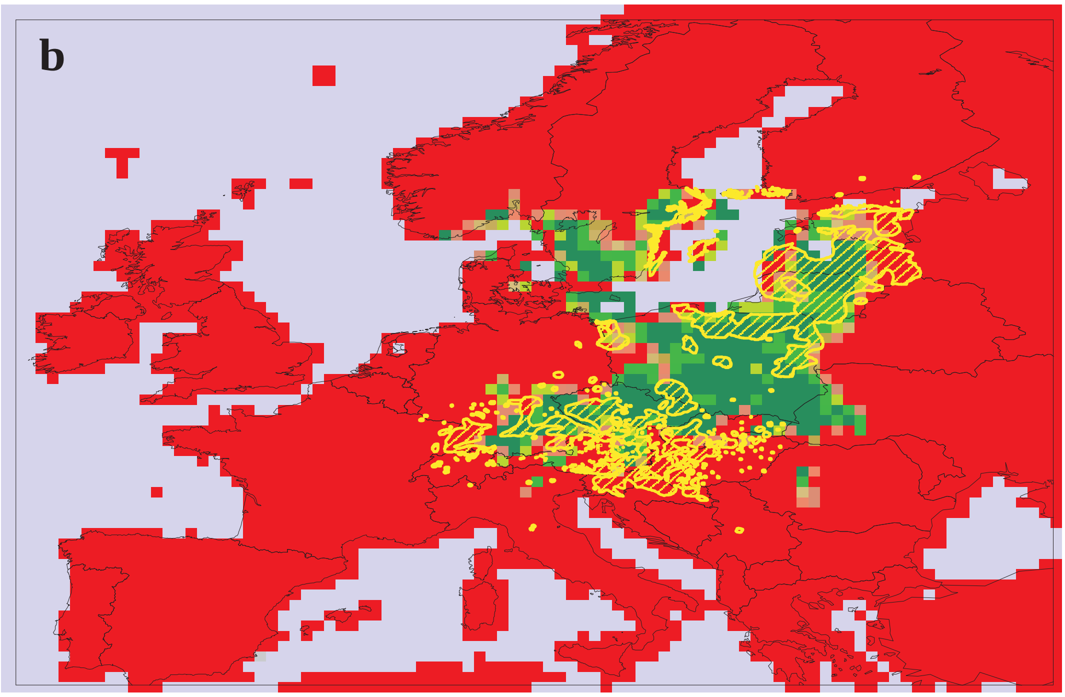
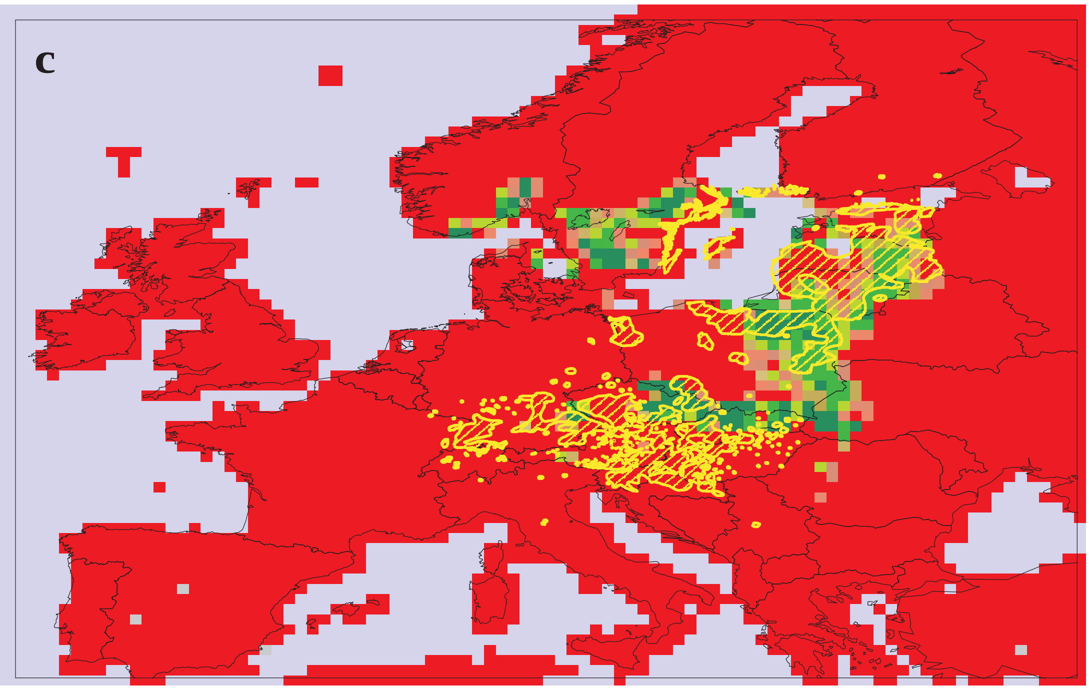


Figure 4.11 c & d Tick-borne encephalitis (TBE) in Europe
The present-day distribution of TBE in Europe is adequately described by temperature and vapour pressure data (Figure 4.11a, 86% correct predictions, 12% false positives and 2% false negatives). Predictions for the HadCM2 Medium-High scenarios of the 2050s and 2080s, are shown in Figures 4.11 c & d

TBE in Europe. Predicted areas of suitability, HadCM2 2050s medium-high scenario



TBE in Europe. Predicted areas of suitability, HadCM2 2080s medium-high scenario

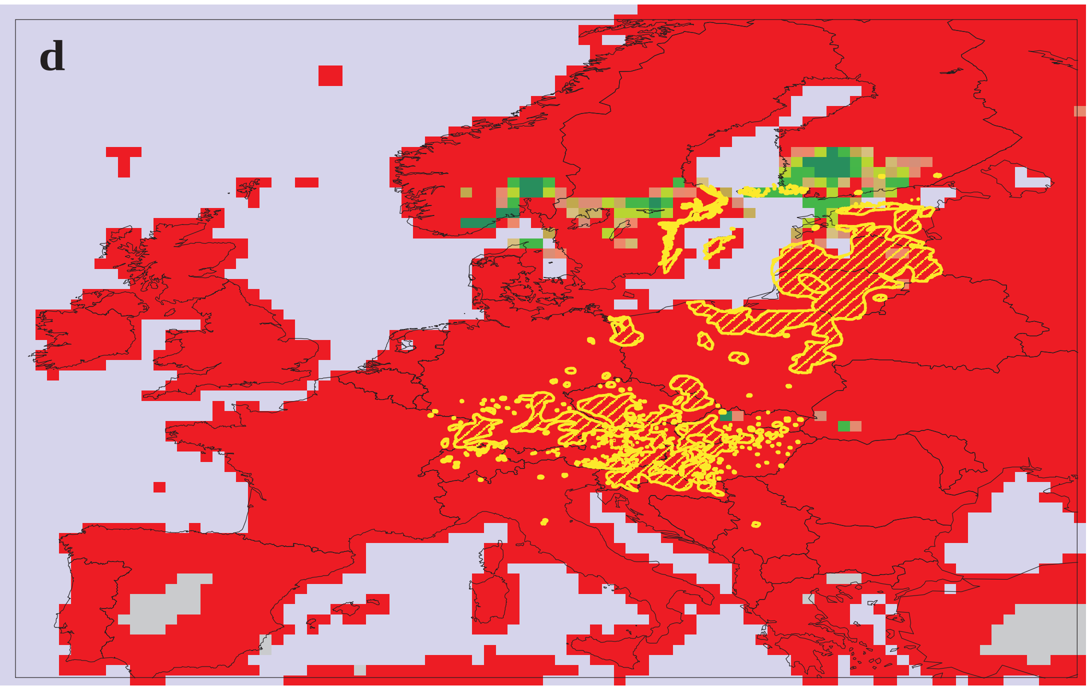
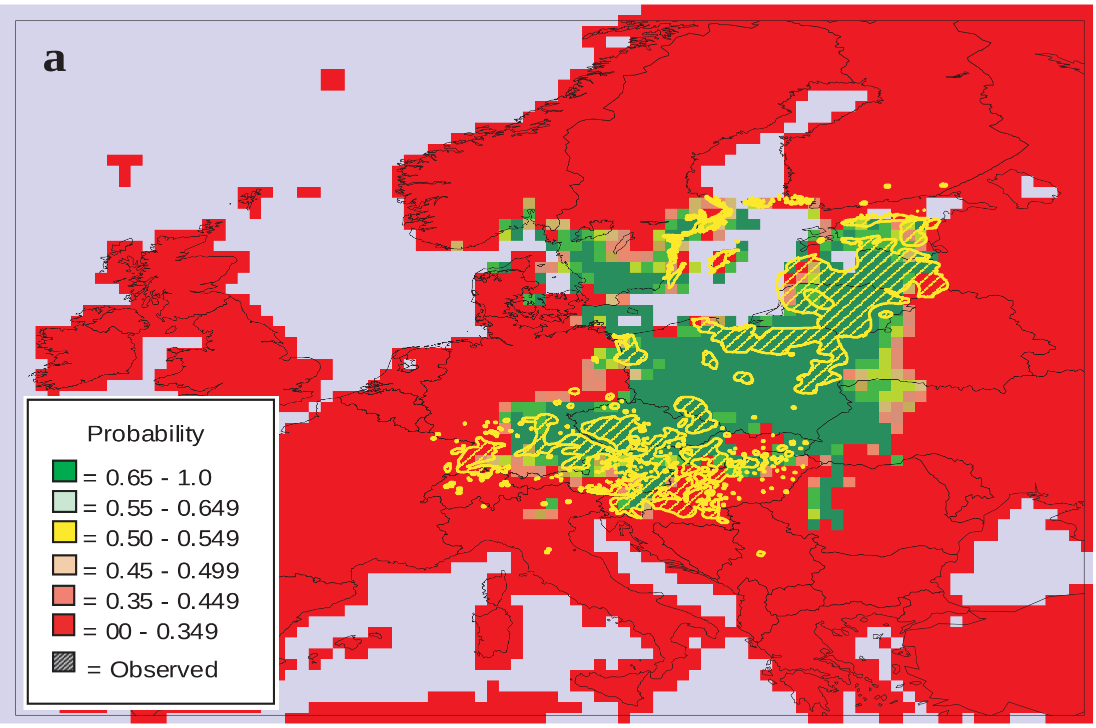


Figure 4.12 a & b Tick-borne encephalitis (TBE) in Europe
The present-day distribution of TBE in Europe is adequately described by temperature and vapour pressure data (Figure 4.11a, 86% correct predictions, 12% false positives and 2% false negatives). Predictions for the HadCM2 Low and Medium-Low scenarios of the 2050s, are shown in Figures 4.12 a & b

TBE in Europe. Predicted areas of suitability, HadCM2 2050s low scenario



TBE in Europe. Predicted areas of suitability, HadCM2 2050s medium-low scenario

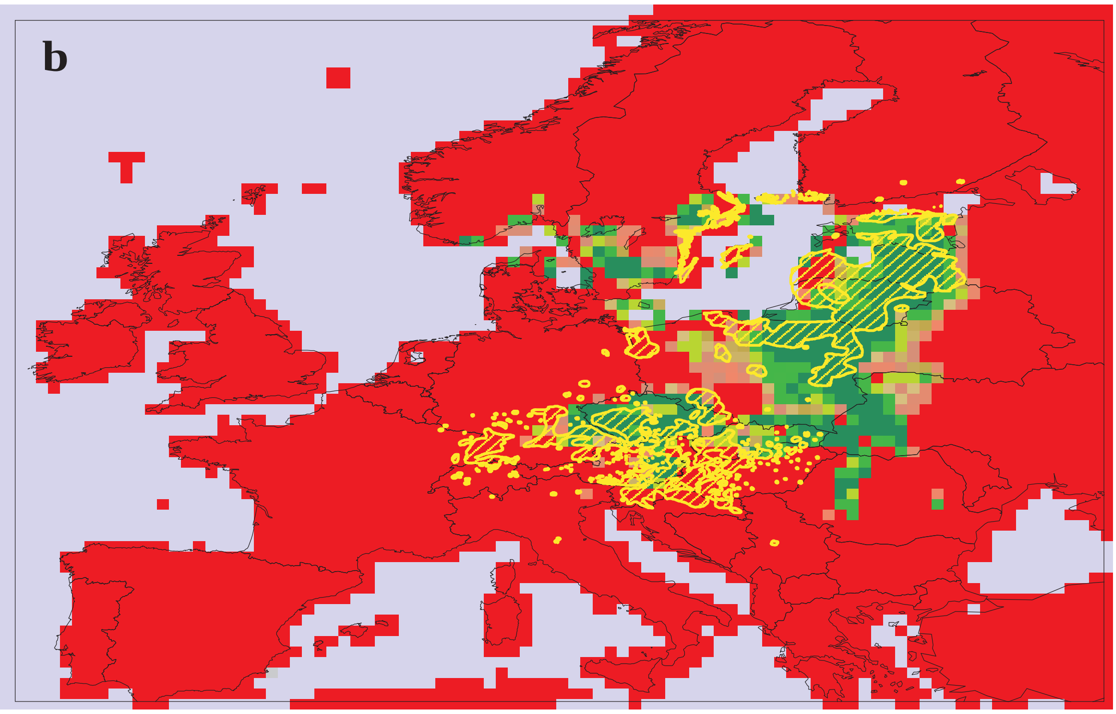
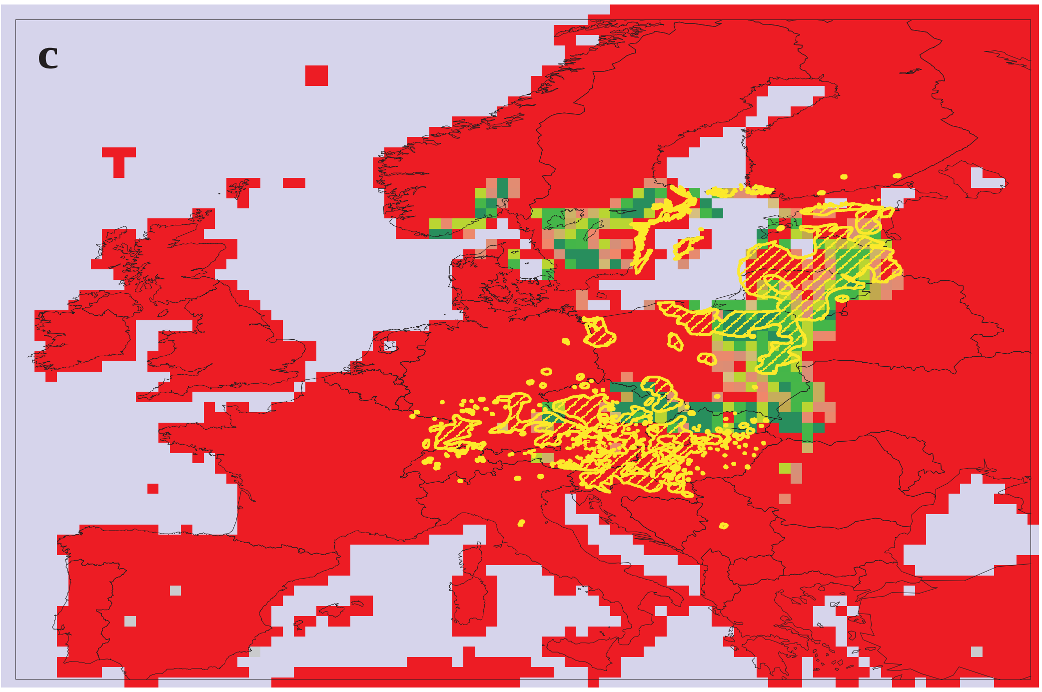


Figure 4.12 c & d Tick-borne encephalitis (TBE) in Europe.
The present-day distribution of TBE in Europe is adequately described by temperature and vapour pressure data (Figure 4.11a, 86% correct predictions, 12% false positives and 2% false negatives). Predictions for the HadCM2 Medium-High and High scenarios of 2050s are shown in Figures 4.12 c & d

TBE in Europe. Predicted areas of suitability, HadCM2 2050s medium-high scenario



TBE in Europe. Predicted areas of suitability, HadCM2 2050s high scenario

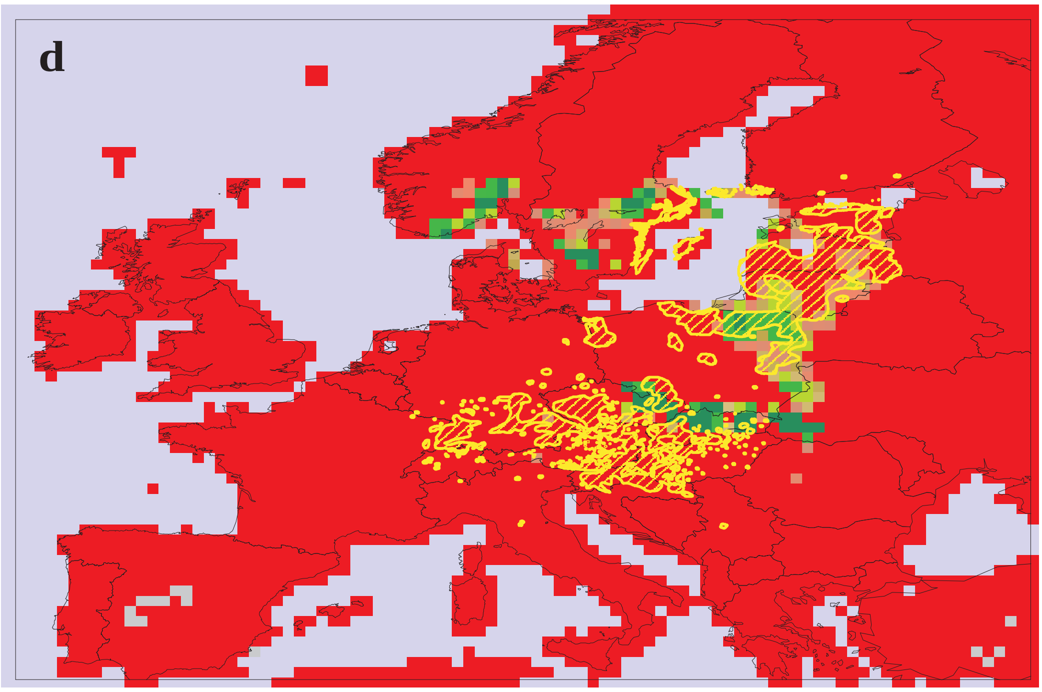


Figure 4.13a Matching UK to Global climates
The UK inset shows the distribution of 10 climatic zones defined in terms of temperature, rainfall and vapour pressure (mean, maxima and minima) for the period 1961–1990. The world map shows the global distribution of zones with same mean values of each climate variable in the same period, with the detail for Europe

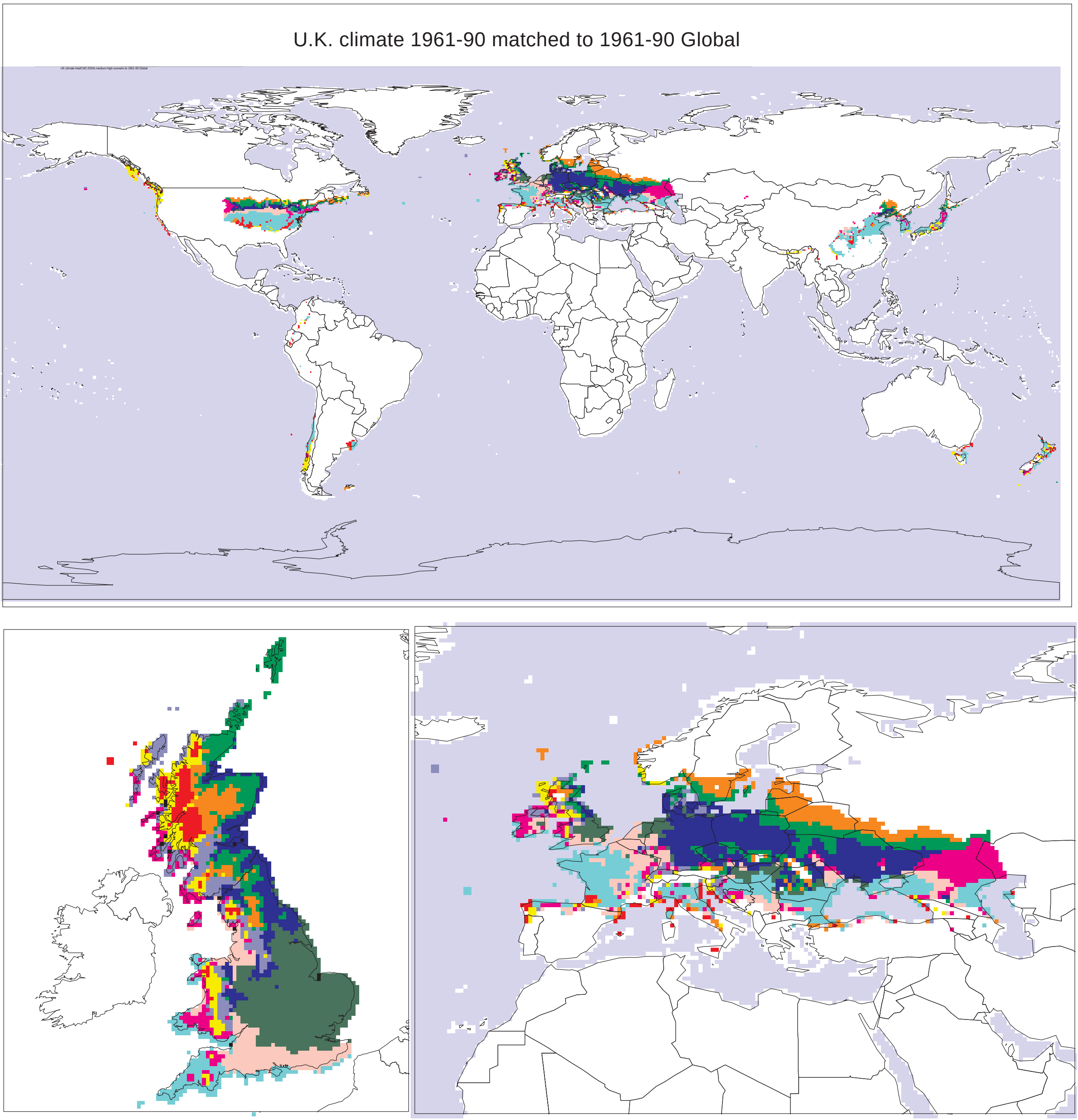


Figure 4.13b Matching UK to Global climates
The UK inset shows the distribution of 10 climatic zones defined in terms of temperature, rainfall and vapour pressure (mean, maxima and minima) for the HadCM2 2020s Medium-High scenario. The world map shows the global distribution of zones with the same mean values at the present time (1961–1990), with the detail for Europe

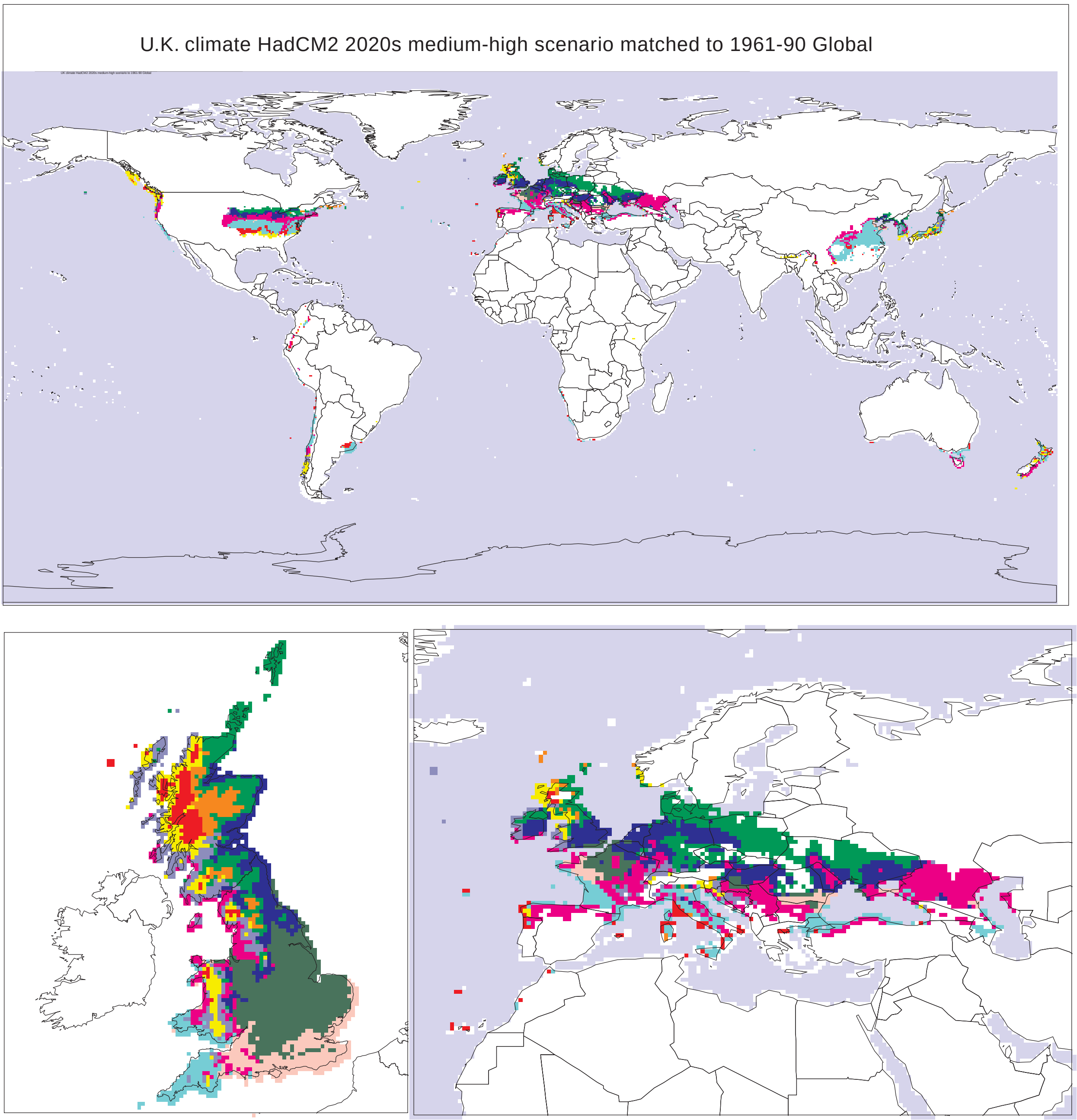


Figure 4.13c Matching UK to Global climates
The UK inset shows the distribution of 10 climatic zones defined in terms of temperature, rainfall and vapour pressure (mean, maxima and minima) for the HadCM2 2050s Medium-High scenario. The world map shows the global distribution of these same zones at the present time (1961–1990), with the detail for Europe

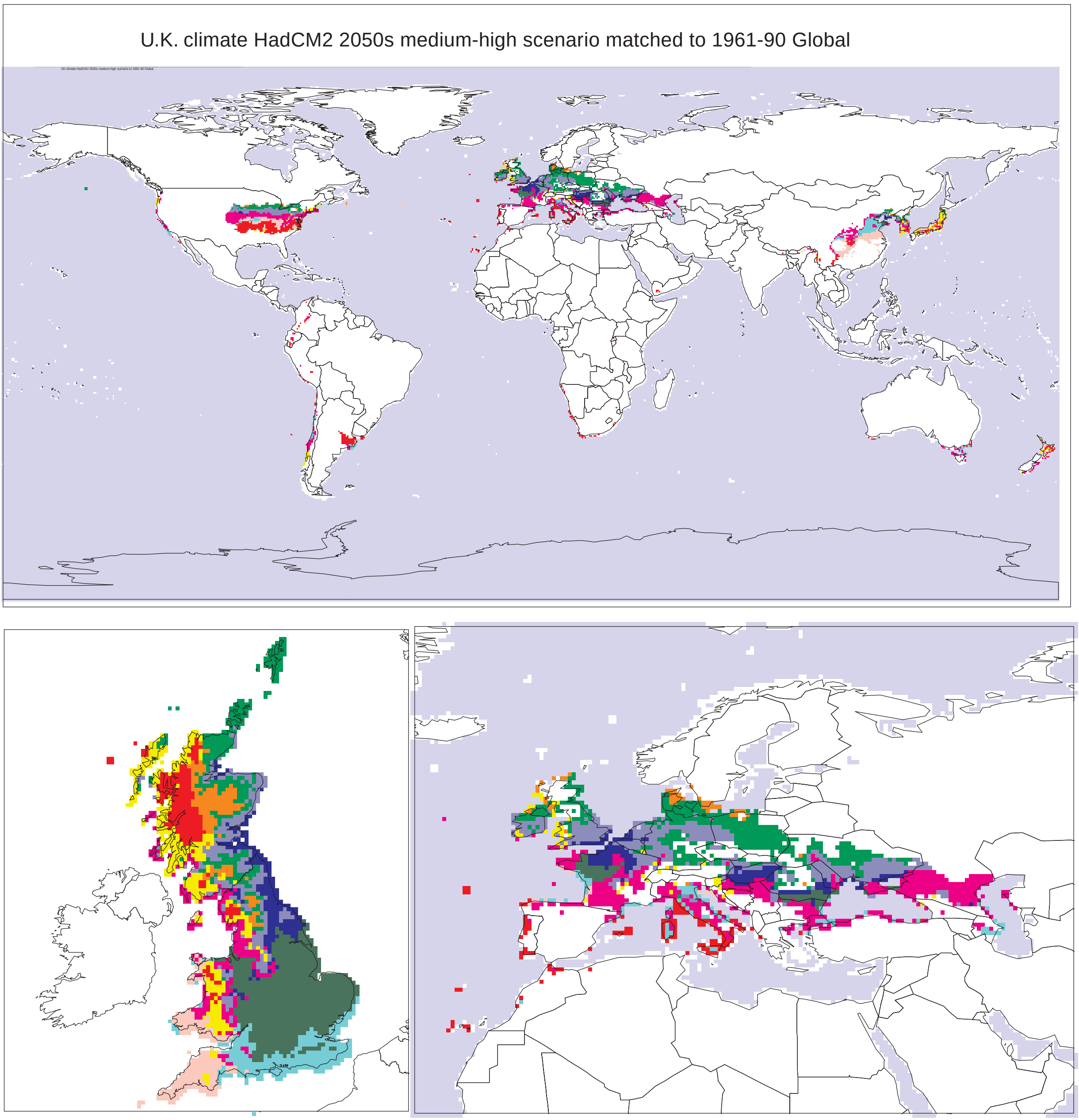


Figure 4.13d Matching UK to Global climates
The UK inset shows the distribution of 10 climatic zones defined in terms of temperature, rainfall and vapour pressure (mean, maxima and minima) for the HadCM2 2080s Medium-High scenario. The world map shows the global distribution of these same zones at the present time (1961–1990), with the detail for Europe

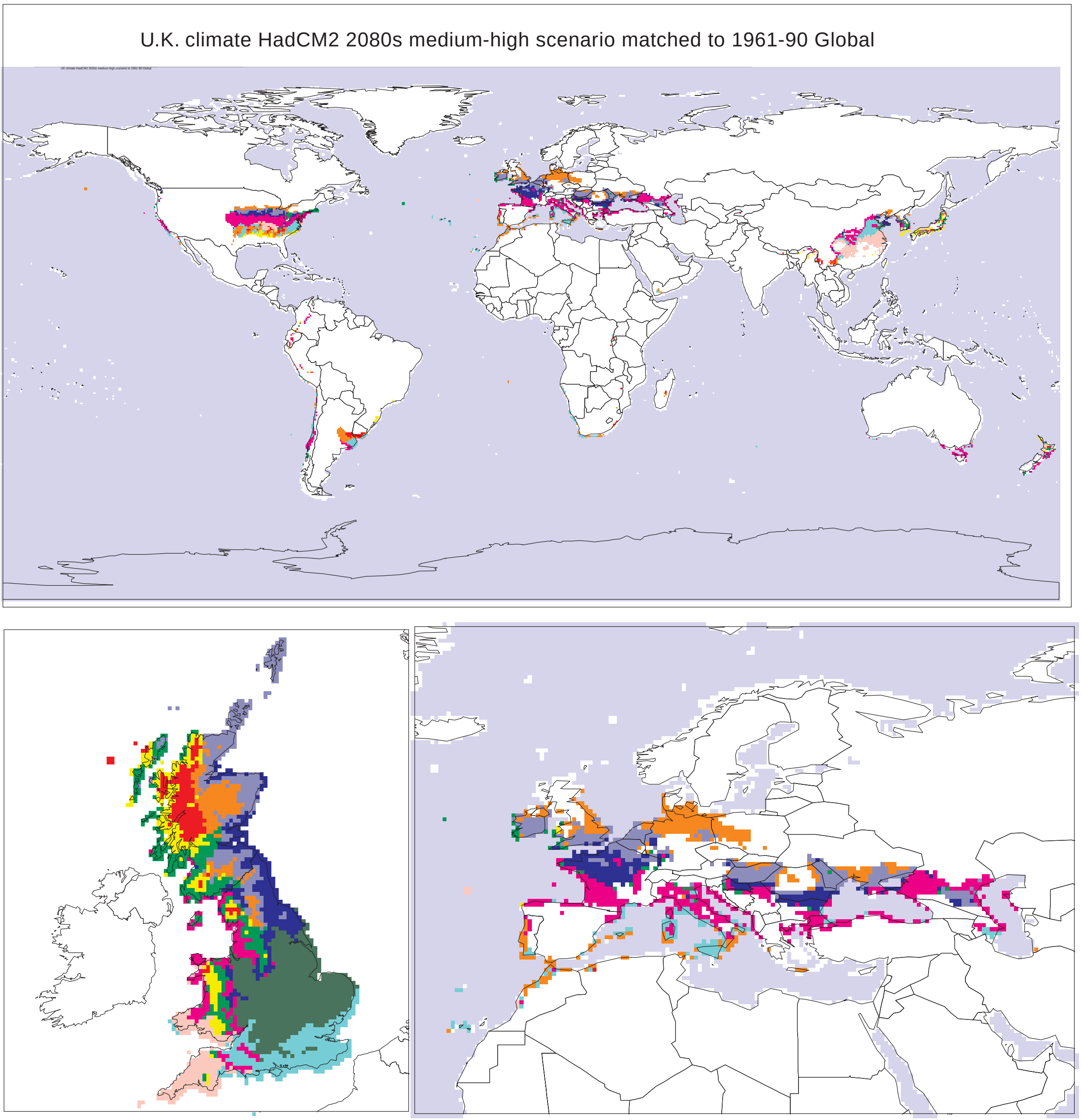
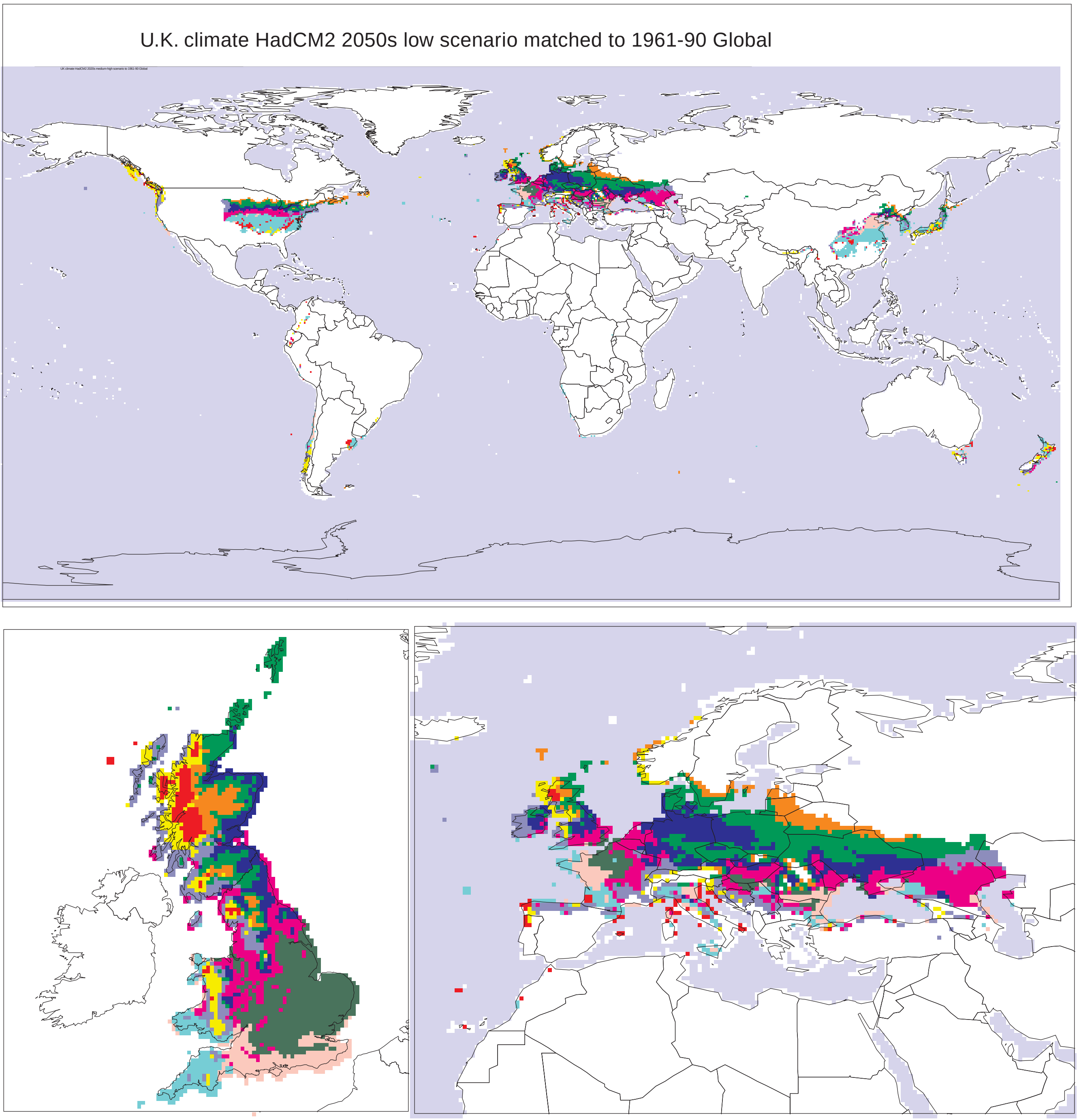


Figure 4.14a Matching UK to Global climates
The UK inset shows the distribution of 10 climatic zones defined in terms of temperature, rainfall and vapour pressure (mean, maxima and minima) for the HadCM2 2050s Low scenario. The world map shows the global distribution of these same zones at the present time (1961–1990), with the detail for Europe



U.K. climate HadCM2 2050s low scenario matched to 1961-90 Global

Figure 4.14b Matching UK to Global climates
The UK inset shows the distribution of 10 climatic zones defined in terms of temperature, rainfall and vapour pressure (mean, maxima and minima) for the HadCM2 2050s Medium-Low scenario. The world map shows the global distribution of these same zones at the present time (1961–1990), with the detail for Europe

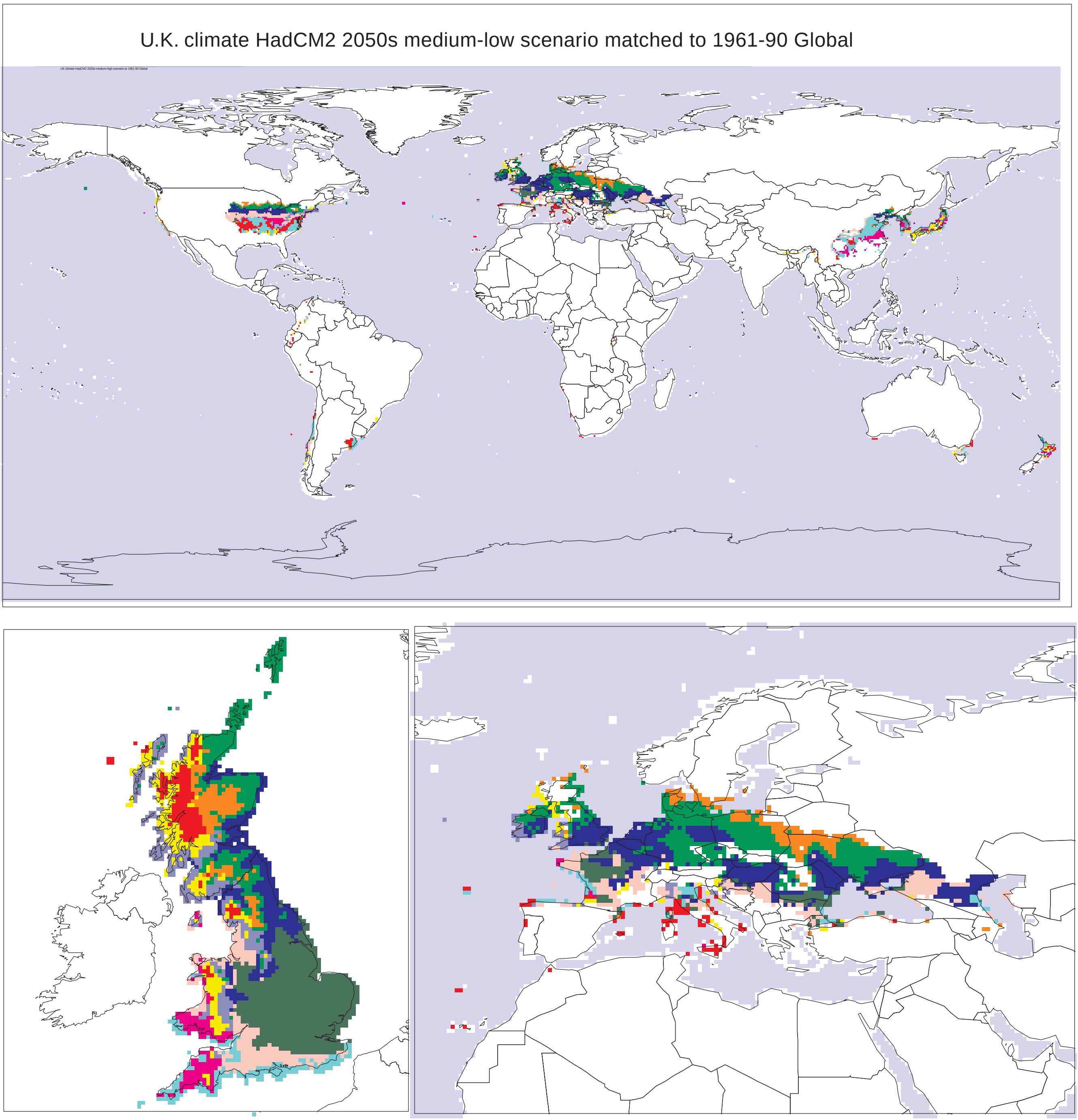


Figure 4.14c Matching UK to Global climates
The UK inset shows the distribution of 10 climatic zones defined in terms of temperature, rainfall and vapour pressure (mean, maxima and minima) for the HadCM2 2050s Medium-High scenario. The world map shows the global distribution of these same zones at the present time (1961–1990), with the detail for Europe

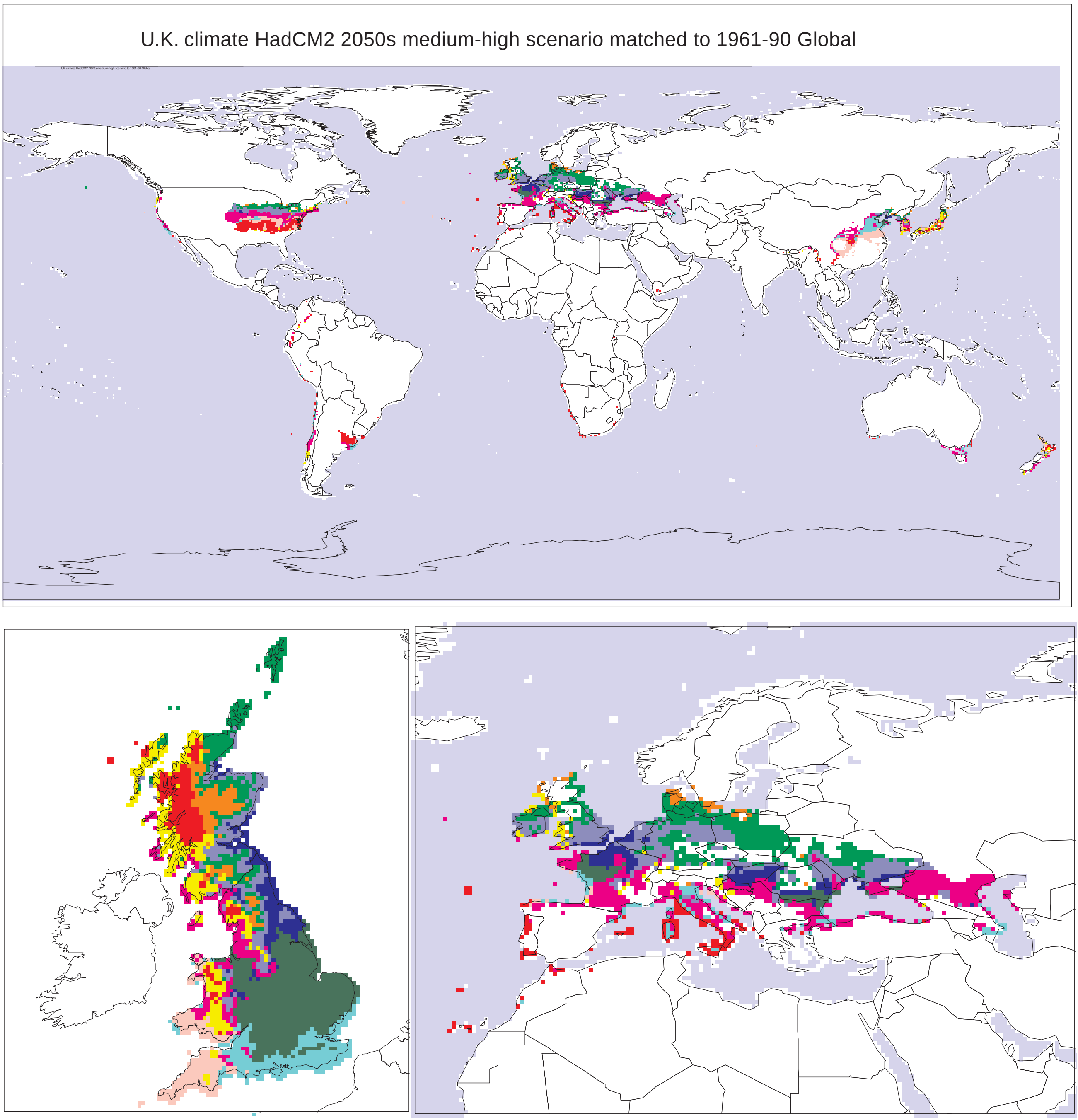
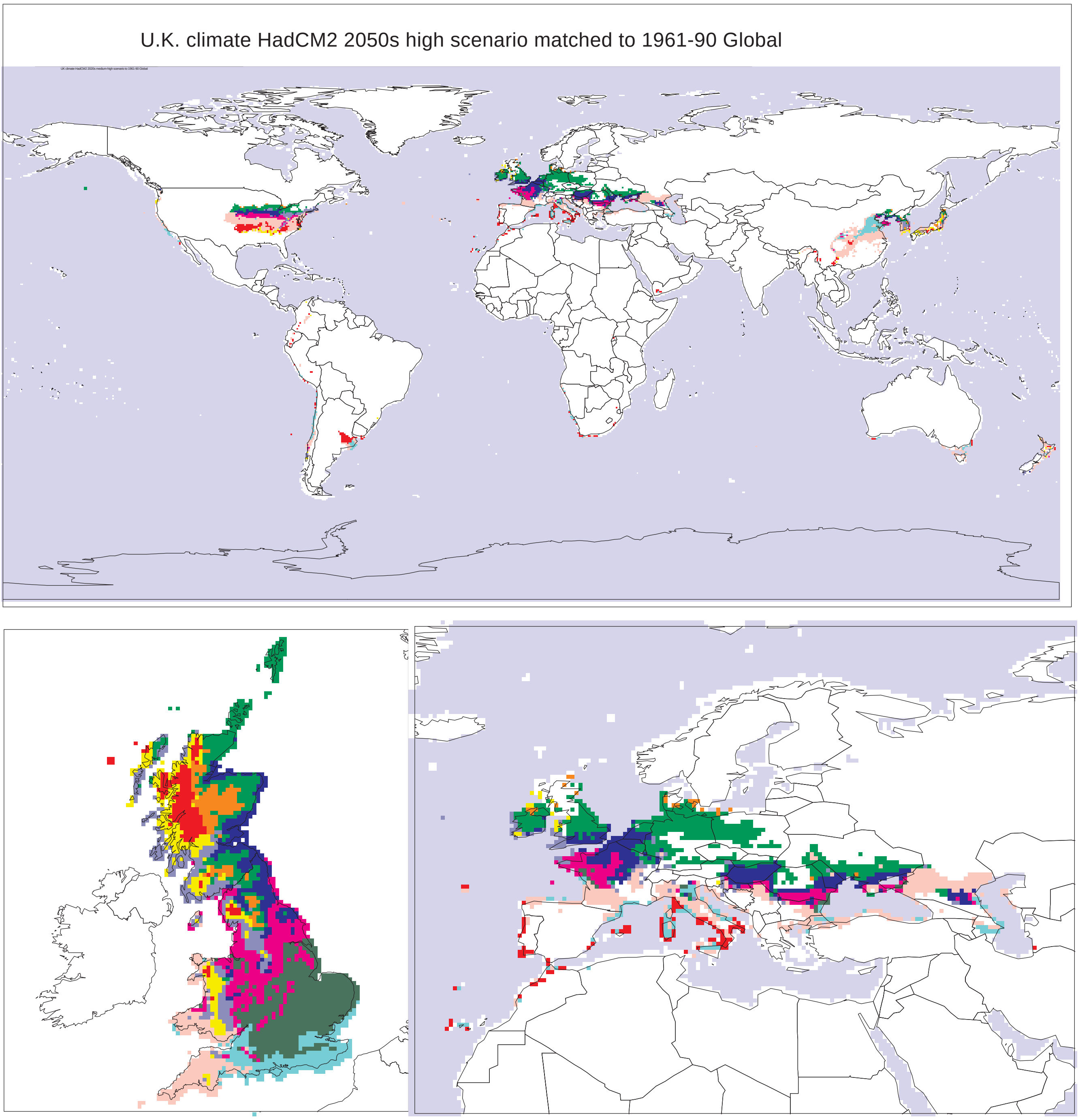


Figure 4.14d Matching UK to Global climates
The UK inset shows the distribution of 10 climatic zones defined in terms of temperature, rainfall and vapour pressure (mean, maxima and minima) for the HadCM2 2050s High scenario. The world map shows the global distribution of these same zones at the present time (1961–1990), with the detail for Europe



Predicting the areas of suitability for European *vivax* malaria using a biological approach

The analyses to produce the maps of European *vivax* malaria in Figure 4.6 are based on the concept of the basic reproduction rate (R_o), which represents the number of future cases of malaria derived from one infective case at the present time, before this case is cured, or the infected person dies. Where R_o is greater or equal to 1.0 the disease can become established; when it is less than 1.0 it eventually becomes extinct. One expression for R_o is shown below:

$$R_o = \frac{ma^2bp^n}{-\ln(p)r}$$

where,

ma = the number of bites per person per day/night. This was set equal to 1.0 in the present model

a = the frequency of feeding on a person, expressed as a daily rate;

$$a = \frac{h \text{ bites}}{u}\text{/person/day}$$

where ***h*** is the proportion of mosquito blood meals taken from people (as opposed to other animals that are not infected with human malaria) and ***u*** is the length in days of the gonotrophic cycle - the interval between each egg-batch and, generally, each mosquito blood meal. The present model assumes a mean value of ***h*** of 0.42 for indoor-resting mosquitoes (e.g. *An. maculipennis*)[1]. ***u*** is length of the gonotrophic cycle, described as follows:

$$u = \frac{f_1}{T - g_1}\text{ days}$$

Where f_1 is a thermal sum, measured in degree days, representing the accumulation of temperature units over time to complete the cycle = 36.5°C, g_1 is a development threshold below which development ceases = 9.9°C, and ***T*** is ambient temperature[2].

p = the daily survival probability of adult mosquitoes. The present model takes the median value of the mortality rate for *An. atroparvus* = 0.029/day (n = 24, range 0-0.294/day)[1]

n = the period of parasite development within the adult mosquitoes, in days (the sporogonic cycle).

$$n = \frac{f_1}{T - g_2}\text{ days}$$

Where f_2 is a thermal sum, measured in degree days, representing the accumulation of temperature units over time to complete the development = 105 degree days, g_2 is a development threshold below which development ceases = 14.5°C and ***T*** is ambient temperature[1].

b = the proportion of vector females developing parasites after taking an infective blood meal. The model assumed a value of 0.19[3].

r = the rate of recovery of humans from infection with malaria. The usual assumption is that the duration of each infection is therefore **1/r** days. The model assumed that an infection would be patent for 60 days, giving a value for ***r*** of 0.0167/day[4]**.**

In the model the above formulae were used together with the various scenarios for climate change in the UK. The model output the number of months of the year when R_0 is greater than 1.0, indicating potential disease spread. Under conditions when R_0 is less than 1.0 for a considerable proportion of the year, the disease probably cannot persist without continuous introduction from elsewhere, or possibly as quiescent stages within apparently recovered people.

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4.4 Water-borne diseases and climate change

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Summary

- The epidemiological study of possible links between climate change and water-related disease is at an early stage. Information on long-term trends and further research are needed to make reliable predictions about the climate effects on water-related health. It is important to note that the health effects are not confined to infection, although this section focuses on water-related pathogens.
- The evidence is at present mainly based on seasonal variation in water-related infections: most organisms show strong seasonal cycles with timing of peaks of water contamination related to latitude (especially *Campylobacter*) and possible response to seasonal changes in temperature and rainfall (especially *Cryptosporidium*).
- No convincing evidence of either drought or flooding effects on the incidence of water-related organisms exists in the UK, possibly because of good water and sanitation infrastructure and management, amongst other factors such as climate and prevalence of pathogens. The absence of 'drought' or 'flood' associated infections in the UK contrasts with experience in other countries, particularly those with less-secure sanitation structures.
- Travel-related water-borne infections are relevant to UK estimates of climate change effects on health, because of an increasingly mobile population and overseas exposure.
- There may be a need for increased attention to the quality of water in swimming pools and of bottled water quality both at home and abroad.

4.4.1 Introduction

Climate change may affect our water supplies in terms of quality, quantity and availability. Evaporation is likely to reduce fresh water resources, with the additional influence of salt water incursion due to higher mean sea levels. Reduction in ground water will affect aquifer water resources and force greater dependence on surface waters, which have higher levels of contamination. Chemical contamination is also likely to increase due to less dilution of industrial pollutants. The likely increased incidence of extreme weather events poses a threat to water supplies and the potential for contamination by means of flooding, increased run off and damage to water and sewage treatment works. Higher mean temperatures of surface water, and increased nutrient load, will promote the growth of cyanobacteria, causing algal blooms. Finally, upland sources from peat covered catchments are likely to contain enhanced levels of dissolved organic carbon, particularly when re-wetting follows drought periods, producing risks of trihalomethane formation on disinfection with chlorine[1].

The health problems associated with these changes will depend on a number of factors:

- the degree to which UK water quality can be maintained;
- the speed of climate change and the associated incidence of extreme weather events; and
- behavioural and adaptive factors.

Water-related behaviour is likely to be strongly affected by climate change, for example warmer summers are likely to lead to an increase in the recreational use of water and increased water consumption. At present, there is very limited information on the way changes in average temperature and precipitation will affect the biosystems that determine the distribution and viability of micro-organisms capable of producing disease. There is also very little information of the association of climate parameters with the incidence of human and animal water-borne infection. This section summarises the epidemiological issues in investigating water-borne disease, the evidence of a link to climate variation, the potential effects of climate on water-related disease and the research required to make further progress.

4.4.2 The epidemiological challenge in attributing water as a cause of disease

The WHO[2] international definition of water-related disease is as follows:

> *Water-related disease is defined as any significant or widespread adverse effects on human health, such as death, disability, illness or disorders, caused directly or indirectly by the condition, or changes in the quantity or quality, of any waters. The causes of water-related disease include micro-organisms, parasites, toxins and chemical contamination of water.*

Current methods of ascertaining water-related disease

In the UK at present there is no statutory mechanism for reporting water-related disease, in contrast to food poisoning. The latter includes gastrointestinal infections of unknown aetiology as well as those where a water based aetiology is suspected or confirmed. How much water-related disease contributes to current levels of food poisoning is unknown. Water companies are required to report incidents that might present a risk to public health to the Drinking Water Inspectorate, to local authorities and to area health authorities. The Inspectorate publishes its assessment of incidents and any outbreaks of drinking water-related illnesses in its annual reports. The uncertainty in attributing cause in water-related disease suggests that water-related disease may be under reported and that it may be frequently unrecognised.

The attribution of disease to a water source is complicated by the fact that so many organisms can be transmitted by water, but most also have other vehicles such as person to person spread. It may be difficult or impossible to confirm a suspected water link for sporadic cases and small clusters. For example, the association of *Cryptosporidium spp.* with water has been established for several large outbreaks, but research and surveillance data on the causes of sporadic cases of *C. parvum* suggests that animal contact may be a more important risk factor[3]. Similarly, epidemiological studies of water outbreaks, particularly those involving private supplies, have implicated *Campylobacter spp.*[4,5], but the cause of most sporadic cases of campylobacter enteritis remains obscure.

With other types of disease associated with the environment, epidemiologists have been able to apply various criteria to attribute cause. For example, the nine criteria proposed by Bradford Hill[6] can be only rarely fulfilled, for both practical and ethical reasons. The first of these criteria, strength of association, has been used to assess reported water-related outbreaks of disease in England and Wales. Using evidence such as identification of the same organism in the water and in human cases, results of analytical epidemiological studies and of documented water treatment failure, outbreaks reported to the Communicable Disease Surveillance Centre (CDSC) have been classified as ‘strong’, ‘probable’ and ‘possible’[7] (Table 4.4). The outbreaks known to CDSC and the strength of association are reported at six monthly intervals. Most of the reported outbreaks are investigated by descriptive, rather than analytical, epidemiological techniques.

Table 4.4 Infections associated with water

Disease	**Organism**	**Mode of transmission**	**Areas of risk**
Aeromonas associated diarrhoea	*Aeromonas spp.*	Consumption/exposure to contaminated water	Worldwide
Amoebiasis	*Entamoeba histolytica*	Faecally contaminated water or case to case	Tropics; areas of poor sanitation & institutions
Amoebic meningo-encephalitis	*Acanthamoeba/ Naegleria*	Exposure to contaminated water	Worldwide: water the main reservoir. Fountains/spas
Campylobacter enteritis	*Campylobacter jejuni*	Contaminated water; chicken/pork; animal contact; case to case transmission very uncommon	Worldwide: carried by many animals and birds. Private or institutional water supplies in UK
Cholera	*Vibrio cholerae 01 / 0139*	Faecally contaminated water	Most continents, including S.E. Europe. Natural reservoir in estuarine waters – shell fish association
Cryptosporidiosis	*Cryptosporidium parvum*	Faecally contaminated water, animal contact	Worldwide: human and animal reservoirs
Cyclosporal enteritis	*Cyclospora spp.* (coccidian parasite)	Faecally contaminated water	Asia, S. America, Caribbean
Dermatitis/ diarrhoea related to blue green algae	Toxins of *Cyanobacteria spp.*	Exposure in freshwater lakes/estuaries; also via consumption of water/ fish	
Diphyllobothriasis	*Diphyllobothrium latum*/other species	Consumption of raw/ undercooked fish from lakes	Subarctic, temperate and tropical zones
Dracunculiasis	*Dracunculus medinensis* (Guinea worm)	Consumption of water containing *Cyclops* larvae	Tropics
Fascioliasis	*Fasciola hepatica*	Consumption of uncooked aquatic plants bearing encysted forms e.g. watercress	Sheep and cattle raising areas in the Americas, Europe, Middle East, Asia and Africa
Giardiasis	*Giardia lamblia*	Faecally contaminated water; case to case	Worldwide; areas of poor sanitation

Disease	**Organism**	**Mode of transmission**	**Areas of risk**
Haemorrhagic colitis	*Escherichia coli O157:H7/ verotoxin producing E.coli*	Faecally contaminated water	Probably worldwide: identified in N. America Europe, S.Africa, Japan S. America and Australia
Hepatitis (viral)	*Hepatitis A*	Mainly case to case: also consumption of contaminated water/ shellfish	Worldwide
Leptospirosis (Weil's disease)	*Leptospira interrogans* serovars	Exposure to contaminated water	Worldwide except polar regions
Melioidosis	*Pseudomonas pseudomallei*	Contact with water contaminated by the saprophyte	S. E. Asia, S. America
Microsporidiosis (dermatophytosis + gastroenteritis)	*Microsporidium spp.*	Exposure to contaminated water	Worldwide
Mycobacterial granuloma	*Mycobacterium marinum*	Contact e.g. swimming in contaminated water	Worldwide; association with keeping tropical fish
Schistosomiasis (Bilharziasis)/ Swimmer's itch	*Schistosoma haematobium* & other species	Contact with free swimming cercariae	Tropics
Shigellosis (bacillary dysentery)	*S. dysenteriae*	Faecally contaminated water: case to case	Areas of poor sanitation
Streptobacillosis (rat bite fever)	*Streptobacillus moniliformis*	Water contaminated by rat urine	Worldwide, uncommon in N. Europe/N. America
Tularaemia	*Francisella tularensis*	Exposure to contaminated water (but mainly arthropod-borne)	Temperate zones: N. America, continental Europe, China, Japan
Typhoid fever	*Salmonella typhi*	Faecally contaminated water	Areas of poor sanitation
Viral gastroenteritis	*SRSV, enteric adenoviruses, rotaviruses, cytopathogenic enteroviruses*	Faecally contaminated water (but mainly case to case)	Worldwide

Table 4.5 Criteria for estimating strength of association between human illness and water

Criteria	(a) the pathogen found in human case samples was also found in water samples (b) documented water quality failure or treatment failure (c) significant result from analytical epidemiological study (case-control or cohort) (d) suggestive evidence of association from a descriptive epidemiological study
Strength of association	(a) + (c), (a) + (d) or (b) + (c) (b) + (d), (c) only or (a) only (b) + (d)

Acute versus long-term water-related disease

There is little known about the long-term effects of exposure to unwholesome water, or of the possible links between chronic disease and exposure to contaminated water at an earlier time. Long-term effects have been postulated, particularly following chemical incidents, and also for *Campylobacter, Helicobacter pylori* and cyanobacterial exposure by means of water, but as yet no long-term, prospective studies have been undertaken.

Types of water covered by surveillance

The types of waters included in the surveillance of water-related disease include surface waters (rivers, lakes), ground waters (any water in underground strata and boreholes), enclosed waters (artificially created bodies of water separated from surface freshwater or coastal waters, including those inside buildings) and sanitation (collection, transport, treatment, disposal and reuse of human excreta through collective systems or small installations). From the risk assessment perspective, public health practitioners need to be aware of the main contaminants in local waters, including industrial pollutants as well as of the infection risk from livestock. The risk appraisal must also include enquiring about infrequently used supplies, change in use of supplies or supplementation of a public mains supply with water from a private well. Many institutions, including hospitals, have a private well and some rely on this type of source or use it to supplement a mains supply.

Drinking water: definitions

Water intended for drinking is subject to vigilant surveillance and, in many countries for example the UK, is controlled via a separate government agency. 'Drinking water' refers to wholesome, clean and safe water intended for consumption by humans. Wholesome water is defined by reference to the standards laid down in the Water Supply (Water Quality) Regulations, 1989. Such water should be free of any micro-organisms and parasites and any substances, in numbers or concentrations, which constitute a potential danger to human health. It includes water used in food preparation and as a constituent in foods. Pollution of water indicates the presence or introduction of products of human activity which have harmful or objectionable effects. In the Dangerous Substances Directive (76/464/EEC), water pollution is defined as the discharge by man, directly or indirectly, of substances or energy e.g. heat into the aquatic environment, the results of which are such as to cause hazards to human health, harm to living resources, to aquatic ecosystems, damage to amenities or interference with other legitimate uses of water. Water contamination differs from the definition for pollution in that the levels present may not necessarily cause harm.

Existing evidence of the effects of climate on water-related disease

The international definition of diseases associated with water refers to water-related, rather than water-borne disease. The latter implies consumption of water, while disease may occur from direct exposure to contaminated water or through exposure to vehicles contaminated by unwholesome water. It includes 'water-washed' diseases related to poor hygiene consequent upon unsafe or insufficient water supplies: examples include Hepatitis A and bacillary dysentery and fungal skin infections or eye infections, such as trachoma. It is important to remember that such diseases may be increased by a lack of water rather than contamination of water. It also includes diseases related to waste water, 'grey water' (recycled) and solid waste disposal where there is a potential for water contamination. The definition also encompasses disease related to chemical contaminants, which may be by direct consumption of drinking water or exposure during swimming or washing.

Infections associated with water include several which are now mainly confined to tropical zones and areas of poor sanitation (Table 4.4). Those of emerging importance such as *C. parvum, Campylobacter spp.* and *E.coli O157* are common in the UK and other parts of Europe[8], although most reported infections with these organisms are not known to be water-borne. Microsporidia have received recent attention, following a report from France of intestinal microsporidiosis associated with water in 1995 and concerns, similar to those about *Cryptosporidium spp.*, of risks to people with damaged immune systems. While immune deficiency is a strong risk factor, microsporidial infection also occurs in the absence of any apparent deficiency. Two species of microsporidia are commonly associated with diarrhoea: *Enterocytozoon bieneusi* and *E. intestinalis.* The source may be farm animals and *E. bieneusi* has been identified in surface water, while *E. intestinalis* and other species have been identified in tertiary sewage effluent. Temperature rises may favour the survival of microsporidia in the environment and hence pose a greater risk of faecal-oral transmission by means of water supplies. As with other spore forming protozooal infections *(Cryptosporidium spp., Giardia spp.)*, disinfection with chlorine is relatively ineffective and other forms of water treatment are required to destroy microsporidia.

In addition to infections acquired by consumption or by direct exposure, many others are water-associated in that water plays a part in transmission or in environmental survival of the reservoirs of infection. Examples include legionnaires' disease and malaria. The incidence of both infections is likely to increase due to:

- ❏ climate effects on the mosquito vectors of malaria;
- ❏ increased use of air conditioning and humidifiers in hot summers and warm climates (travel related legionnaires' disease); and
- ❏ increased travel and exposure in high risk areas.

A detailed discussion of the possible effects of climate change on malaria in the UK is provided in Section 4.3. Many pathogens survive in water, but this is not necessarily the most efficient vehicle of transmission. For example, small, round structured viruses are relatively chlorine resistant and survive in water following sewage discharge or in moist environments, but case to case transmission is by far the commonest cause of outbreaks. Most water-borne pathogens can be transmitted by other vehicles and few are characterised by poor case to case transmission. The exceptions are *Legionella pneumophila* and *Vibrio cholerae. Campylobacter spp.* are of interest because of the negligible case to case transmission, but the commonest species infecting humans, *C. jejuni and C. coli*, inhabit the intestinal tracts of wild birds and domestic animals: poultry are readily colonised and most broiler chickens sold in shops are contaminated.

Seasonal variation in water-related disease

The existing evidence shows seasonal variation in levels of water-related pathogens and increases that may relate to warmer summer temperatures. While suggestive of a link to climate change, there is little or no evidence, as yet, in the UK that the climate changes so far observed have affected water-related pathogens. This is partly because of the generally good quality of our water supplies and the precautions taken by water providers when breaches occur in water supplies. Water treatment has removed traditional water-borne pathogens, such as *Vibrio cholerae* and *Salmonella typhi*, from British water supplies and the very low frequency of these infections in the population ensures that treatment failures carry a negligible risk of contamination by these pathogens. i.e., the risk of water becoming contaminated is very low. The global increase in cholera has, however, been linked to the El Niño oscillation and other climate influences such as enhanced survival in warmer temperatures[9], but poor sanitation remains the most obvious underlying cause of human epidemics. *Cryptosporidium parvum* oocysts have proved able to penetrate water treatment in the UK, USA and other developed countries, but the incidence of cryptosporidiosis, although seasonal, relates also to practices in animal husbandry. *Campylobacter spp.* seasonality has attracted interest in a possible association with climate. Time trends have demonstrated seasonality in several countries, but although the seasonal pattern is more pronounced in Northern European countries, no correlation has yet been found with latitude of country and the month of seasonal peak of *Campylobacter spp.* reports. Campylobacter is now the commonest cause of bacterial gastrointestinal infection in the UK: while typing systems exist, these are not yet sufficiently developed to distinguish different epidemiological effects. Thus the influence of other vehicles, such as poultry and other foods, cannot be excluded from the data to allow analysis of the possible association between water-borne infection and climatic variables.

The evidence available from the investigation of water borne outbreaks of disease does not demonstrate any clear association with climate. Recent outbreaks in the UK have been predominated by *Cryptosporidium parvum*, with a possible trend towards more outbreaks associated with swimming pools and private supplies. The emergence of *Escherichia coli O157* as a cause of outbreaks linked to small private water supplies indicates the wider distribution of this pathogen in animal populations, but numbers are still low and there is no indication of a climate effect.

In summary, the evidence of seasonal variation is of interest to climate studies, but climate is likely to prove only one of the factors influencing the current trends in these pathogens.

If studies show a convincing link with temperature or precipitation variation, the next task will be to tease out all the other confounding factors and develop models of the potential contribution of climate alone. While the lack of information and evidence is to some extent reassuring, there would appear to be no room for complacency. Many of the more recently identified infections are water-related (*Cryptosporidium spp., Campylobacter spp., Legionella spp., Microspora spp.*). This suggests both that we have not had time to observe trends, and also that more organisms may emerge as the climate effects increase.

Potential effects of climate on water-related disease

The potential effects may include:

- ☐ changes in vector breeding patterns, e.g. mosquitoes;
- ☐ increased pathogen survival in natural waters e.g. *Vibrio cholerae;*
- ☐ decreased quality of drinking water;
- ☐ indirect effects due to increased exposure to water used in air conditioning e.g. *Legionella pneumophila;*
- ☐ algal blooms;
- ☐ increased leisure exposure to freshwaters and sea water;
- ☐ effect of extreme weather events such as floods: increased risk of pathogens breaching the water treatment and sanitation safeguards; and
- ☐ increased exposure to water-related pathogens in other countries during travel from the UK.

Concern about the sustainability and safety of water supplies in Europe is beginning to change the relative neglect of water as a source of disease. Water shortage and poor water quality remain a central concern in developing countries and are estimated to cause the deaths of 1.5 million children annually. Concern about the importation of water-related disease is also rising: the concerns relate both to travel associated disease in visitors to countries with poor water control and sanitation and also to foods contaminated by unwholesome water. Recent initiatives with relevance to water surveillance include the proposed European Community Water Framework Directive, with particular reference to sustainable water use and mitigation of the effects of floods and droughts. The European Water Protocol drawn up by the WHO and UNECE (UN Economic Commission for Europe) places a greater emphasis on the health impact of water and the implications for surveillance, indicators of pollution and early warning systems.

Blue green algae

Climate change may increase the incidence of problems related to blue green algae (cyanobacteria), of which swimmer's itch is one of the less severe, but irritating, effects[10]. Skin reactions are the most commonly reported effect in the UK. Contact with cyanobacteria has also been associated with rhinitis, gastrointestinal complaints and atypical pneumonia[11]. Some algal toxins have tumour-enhancing properties, suggesting the possibility of disease developing years after exposure, or after prolonged exposure to relatively small doses of toxin. Little epidemiological research has been done on the risk to human health from freshwater or coastal algal blooms.

While temperature is an important factor, the observed increase in freshwater toxic algal blooms in recent years may be related to changes in agricultural run-off or to reduced river flow and associated increases in nutrient load. Increases in freshwater algae blooms have been observed in unusually hot summers in the UK[12,13]. The major bloom-forming species produce potent toxins, including hepatotoxins and neurotoxins[14]. However, there is little correlation between the composition of a particular bloom and the concentration of toxin present. Blooms cause serious water pollution problems, requiring the use of alternative water sources and closure of waters used for recreational and leisure activities. For example, during August and September 1989, substantial growths of blue green algae were observed in UK inland waters. The most publicised was at

Rutland Water in Rutland (Anglia Water), because of a putative association with the death of 20 sheep and 15 dogs which had contact with the water. However, no human health effects were reported, despite a wide range of recreational water sports and activities at Rutland Water. Anglia Water excluded their reservoirs from recreational purposes for a six-week period[15]. Later that summer, hospital treatment was required for two soldiers exposed to water during a canoeing course in Staffordshire: the illnesses developed one day after the course and included abdominal pain, vomiting, diarrhoea, skin blistering and atypical pneumonia[16]. The illness was attributed to ingestion and/or inhalation of toxic blue-green algae.

In coastal waters, the main risk from algal blooms is through contamination of shellfish. In the UK, dinoflagellates have caused sporadic cases of paralytic shellfish poisoning (PSP) in spring, along the north east coast of England and north and west coast of Scotland[17]. Problems with toxic dinoflagellates have also been associated in summer months with coastal waters of France and Spain. During the summer of 1999, the scallop fishery along the west coast of Scotland was closed because of the risk of amnesic shellfish poisoning (ASP). There is no evidence that coastal algal blooms have been affected by observed climate change.

Sewage in coastal waters

It is UK policy that all significant discharges of sewage are treated to at least secondary level whether the discharge is to inland surface water, groundwater, estuaries or coastal waters. Some discharges which impact on bathing waters or shellfish waters can receive even higher levels of treatment such as UV disinfection or microfiltration. The dumping of sewage sludge to sea was banned from the end of 1998. The treatment of sewage significantly reduces, but does not eliminate, the potential for pathogens to be discharged into the aquatic environment and studies have shown a small but significant risk of minor infection following exposure to seawater contaminated by sewage[18,19]. Climate change may alter the effect of such exposures, for example, warmer waters will reduce the survival of sewage-derived pathogens but the frequency and duration of exposure may be increased by warmer spring, summer and autumn weather.

The health implications of droughts and floods

The health implications of droughts and of floods vary greatly with location and circumstances. In the UK there is no evidence to suggest significant health problems arising from either drought or floods in recent years. This absence of health effects may be related to a number of factors and not least to a well developed water and sanitation system and an informed public. However, water availability has indirect influence on disease via hygiene and floods elsewhere in the world with an increased spread of cholera, leptospirosis and infections associated with rodents[20].

Droughts have a gradual onset and can occur anywhere, a critical factor being water usage. Droughts may kill due to a lack of water for drinking and can lead to forced migration and complex emergencies. Vulnerability to drought comprises a mix of social and political factors and, in terms of global change, climate change is but one factor to consider amongst many others, such as population growth.

The monitoring of drought and seasonal forecasting in many parts of the world provide forewarning for drought management. Unlike many climatic and natural hazards, there should be adequate time to implement, but not necessarily to plan, mitigation responses. Drought has profound socio-political effects which extend beyond the issue of water management. In drought-affected countries, the assessment of social vulnerability has matured, with new operational schemes and vulnerability mapping are used to target food aid and development assistance. In the UK, government institutions need to plan to adapt to water shortages through a variety of social and individual behaviour measures. Future patterns of individual usage of water may have health consequences, for example if water is metered and costed accordingly.

In the UK we already have droughts and hose-pipe bans in the summer season. According to the meteorological models, climate change could result in a substantial increase in winter precipitation, but evaporation will also increase. The result could be more frequent water balance deficits in the summer months. Precise impacts of changing rainfall and evaporation are of current concern to hydrologists, agriculture and water management, as water companies are undertaking aquifer modelling, studies of future reservoir levels, etc. Drought management is not a simple matter of the availability of water supplies, but involves understanding and controlling patterns of usage. A very detailed piece of work will be needed to explore these patterns and the appropriate adaptive measures required at a political and social level. A large number of pressures are already putting extensive demands on water usage, with climate effects forming just one aspect of an existing and complex problem. Health issues surrounding water shortages are therefore already with us but work in this area on health consequences should take into account the measures being introduced and planned under current water management.

Water infection problems associated with drought in the UK

The last significant drought period occurred in the early 1990s. Two cryptosporidiosis outbreaks in this period were attributed, in part, to changes in water management prompted by the need for alternative or additional water supplies. One occurred in the north east[21], where the predominantly bore-hole supply was supplemented during periods of high demand by water abstracted from a river. The other outbreak occurred on the south east coast, also associated with augmentation of a water supply during a drought period[22]. Yorkshire experienced a drought in the summer of 1995, despite normal rainfall in the previous winter[23]. Formal restrictions on water use were introduced, in addition to a large-scale tankering operation. The surveillance issues included assessing the risk of water-washed disease, that is, disease controlled by adequate washing (see above). However, the public health issues were dominated not by infection, but by the largely uncooperative public reaction to the crisis[24-28].

Water infection problems associated with floods in the UK

Studies have not shown a convincing increase in infection associated with flooding in the UK. There was no evidence of increased level of cases of leptospirosis, nor of serological evidence of exposure, after floods in Herefordshire (1997/1998) (Dr Coleman, Director Hereford PHL, *pers comm*). A detailed study was attempted after widespread flooding in North Wales in February 1990, due a storm induced surge[29]. More than 750 properties and numerous caravans were damaged. The infections observed were minor, such as slight increases in dysentery and rotavirus infections. Of greater health significance was the effect of cold, psychological shock and displacement, particularly as a third of the local population was aged over 60 years.

Implications for climate-related surveillance of water-related disease

More comprehensive surveillance in Europe of organisms related to water and of travel related disease is needed. This is unlikely to develop without specific funding and defined targets. Risk assessment is beginning to be applied to water supplies in much the same way that the HACCP (Hazard Analysis Critical Control Point) system has been applied to food preparation. The difficulties in identifying water as a cause of disease have delayed the development of scientifically satisfactory risk assessment systems for water-related infections. One possibility is the analysis of outbreaks: these provide the opportunity to document the events and errors preceding an outbreak and to identify control points. Incidents of water treatment failure, burst mains or floods could also be examined from the risk perspective in terms of the investigations required to ascertain any health effects and the differences between incidents leading to outbreaks and those in which no increase in disease is identified in the community. Another under-researched topic in risk assessment is the influence of human behaviour, for example the variation in water consumption associated with travel away from home and perceived environmental risk. Little is documented about variation in water habits between different ages, classes or occupational groups.

Key areas include more comprehensive and detailed active surveillance of reported outbreaks and incidents; development of a database on incidents of reported water failure and linkage to any reported cases of infection; climate change surveillance, including linkage of water-related disease reports and reports of increase in organisms with a strong water aetiology, to meteorological data. Surveillance should also include the follow up of floods, droughts and other adverse weather events. There is a trend towards using small area statistics and postcode analysis to identify clusters and regional concentrations of disease possibly attributable to water, although this involves as yet unresolved issues of both confidentiality and resources.

Data available for analysis

Data-sets have been obtained from CDSC which could be used for analysis of the effects of climate change on water-borne or water-related diseases. These include weekly reports of *Campylobacter spp.* and *Cryptosporidium spp*. over the last decade. To make appropriate use of these data it will be necessary to subdivide according to known or suspected aetiology, including travel exposure. As the laboratory reports are used primarily to assist with clinical management and in the control of acute outbreaks, there may also be confidentiality and access limitations in the light of new guidelines on data use. For many reports, the data set is limited to clinically relevant information such as date of isolate, age of the patient and in some cases to the severity of infection. However, such data would be a good starting point and would allow examination of crude trends and links with different lag periods following temperature or rainfall peaks.

4.4.3 Research needs

❏ An investigation of variation of *Campylobacter spp.*, *Giardia spp.* and *Cryptosporidium spp.* with temperature and precipitation data, including analysis of different lag periods between peak temperatures and rainfall with date of onset of isolation of increased number of bacteria is needed. Data on infections need to be supplemented with information on travel exposure and to be subdivided by other possible or confirmed aetiologies, e.g. case to case transmission, foodborne disease and water treatment failures unrelated to extreme weather events. Because of the need for large data sets, covering extremes of temperature and precipitation, there is also a strong case for sharing data across the European region.

❏ A review of studies on the health effects of recreational exposure to inland and marine waters, with associated analysis of water quality and seasonal/climate variation is needed.

❏ Risk and public health intervention analyses based on predicted changes, associated with behavioural studies and likely impact of public health interventions such as health warnings about bathing, water consumption, travel related behaviour etc are needed.

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4.5 Windstorms and climate change

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Summary

❏ The predicted increase in the frequency of severe gales is likely to be associated with significant damage to buildings and trees. Personal injury from flying debris and falling trees is likely to increase.

❏ Injuries resulting from people being blown over in high winds is likely during severe windstorms. An increase in traffic accidents is also probable.

❏ Analysis of a worst-case scenario - a windstorm in the late afternoon in London and south-east England - suggests that such an event might be associated with several hundred deaths, several hundreds of admissions to hospital and many minor injuries. It is likely that the NHS would cope adequately with a disaster of this scale.

❏ The need for a review of building regulations for roofs and other vulnerable structures is clear; with adequate planning many injuries and deaths might be prevented.

4.5.1 Introduction

Severe wind events can be classified in two groups, as temperate wind storms and tropical cyclones (hurricanes and typhoons). Living in the British Isles and exposed to North Atlantic depressions we experience more frequent gales than continental Europe and the effects of climate change on wind systems could have more adverse implications. The main features of temperate windstorms are that strong winds occur across a track that may be 1000 km wide, and they occur relatively frequently. It has been argued that any one point sees a random population of storm speeds in the course of each year which, from the viewpoint of statistical data manipulation and predictions, is equivalent to experiencing about 50 independent storms. Tropical cyclones, in contrast, are much less frequent and very high wind speeds are restricted to a relatively narrow track, perhaps 150 km wide.

Although both winds and the associated low atmospheric pressure influence the risks of sea surge[1], in a temperate climate these risks are usually secondary to the structural damage caused by the wind gust pressures, which are proportional to the square of the wind gust speed. Gust speeds in the UK reach 50 m/s, but higher values are experienced in tropical cyclones, up to 70 m/s, giving pressures typically double the UK values. Death and injury from tropical cyclones are very commonly associated with flooding (extremely severe concurrent rainfall is typical, over a larger area and extending further inland than the high winds), consequential landslides, and from the sea surge. The climate change scenarios for the UK[2] suggest that gust velocities and windstorm frequencies could increase, but it is not believed that climate change would be enough to replace the present storm patterns by a tropical cyclone pattern.

In addition to the large storms introduced above, extremely severe winds occur locally in tornadoes, but these are individually very small, each event affecting an area of only 1 km^2 to 10 km^2. On average, 32 tornadoes occur each year in the UK, mostly in England; they represent a minor wind hazard in this country, but their reported numbers are increasing[3]. Uncertainty in the UK climate is particularly reflected in the October 1987 'hurricane' in which exceptionally high wind speeds were recorded within a relatively narrow track across the south east corner of Britain. Current meteorological computer models have not yet reached the point where the trigger for such an event is sufficiently understood to provide a robust view of the place of such events in the future risk scenario.

This section focuses on the health impacts of temperate windstorms in the UK. The country's worst 'wind' disaster was the collapse of the Tay Bridge on 28 December 1879, causing a train carrying 79 passengers to plunge into the Tay. However, in most years, deaths and injuries from the direct and indirect impacts of gales are small (on average, in 1962-1993, 6 deaths and 144 minor and serious injuries per year[4]). Recent reference events that led to more substantial building damage and significant loss of life in the UK were the windstorms in October 1987 and January/February 1990. It is the impacts and return periods of these types of events that we consider need to be addressed when assessing the effects of climate change on human health and safety.

4.5.2 Forcing factors

According to the Medium-High scenario of climate change[2] the overall gale frequencies in the UK will decline in the future, though very severe summer and winter gales could increase. Wind speed (at 10 m above the ground) could increase by 4% in the south-east and by 7% in Scotland by the 2080s. On the presumption that the basic storm processes and storm patterns remain similar, while scaled up by increasing severity of the large scale synoptic meteorological scenario, the above increases could alternatively be viewed as a reduction in the return periods of given levels of storm speeds by a factor of three. It would also be presumed that events such as the October 1987 example would be increased *pro-rata*.

An increase in wind speed of 7% is the equivalent of the difference in gales already experienced between Scotland and south-east England at the present time. Wind storms with gusts in excess of 90 knots can be occasionally expected over the north of Northern Ireland and over western and northern Scotland, but are remarkable for southern England[5]. The impact of this change on structural loading of buildings in the UK would be relatively small. However, the following analysis shows that wind storms already present significant hazards in the UK, and future climate trends would need careful assessment for their impacts on human life and infrastructure.

4.5.3 Reference events

The main reference events to consider are the windstorms in 1987 and 1990.

❑ 15-16 October 1987. This storm made a swathe through south-east England with its maximum intensity occurring at 2-6 am. Maximum gusts were at 90-100 knots in the most southerly areas (Figure 4.15a and 4.16a) within a triangle bounded by Southampton, Great Yarmouth and Dover[5]. About 25 million people were affected. There were 21 deaths ascribed to the storm, but relatively few injuries as the majority of people were in bed at the peak of the storm. Caravans and mobile home parks sited with a view and so completely exposed to the wind were particularly impacted. Trees were uprooted on a scale not seen before in living memory. A combination of the trees being in full leaf and a high soil moisture at the time contributed to the loss of an estimated 15 million trees (ten times higher than in 1990).

- The storm on 25 January 1990 struck in daytime during working hours so the death toll was greater than in the 1987 event[6,7]. The wind speeds were highest (90 knots) in an area of southern England and Wales below a line from Aberystwyth to Aldeburgh and the storm intensity peaked between 9 am and 3 pm (Figure 4.15b and 4.16b). Forty-seven deaths were attributed to the storm, with two children being killed and a further 69 injured from failure of school buildings. On 26 February 1990, another storm struck southern England, the windiest hours between 6 am and 6 pm. The damage was mainly concentrated in areas of high population density: Greater Manchester, West Yorkshire, Newcastle upon Tyne and general impacts across the Midlands to East Anglia and London. The storm led to at least 14 deaths. These two major storms were linked by a period of increased winds over the British Isles, including a storm on 7/8 February.

The overall impression of the 1987 event is that within the narrow track of peak effects (say, the worst-affected 100 km track) this was a more unusual storm; i.e. it represented a longer return period than the 1990 storms, which had effects spread much more widely but in a rather patchy and variable fashion. The difference in deaths and injuries between the October 1987 and January/February 1990 events was marked, and can be mainly ascribed to the different times of the day and night when the storms struck. In October 1997 the peak of the storm occurred while people were asleep. In the 25 January event people were able to avoid going to work and to prevent many children going to school, as the storm was already reaching its peak by 9 am and so the impact was not as severe as it might have been. The 1987 event, in particular, took the public by surprise and the Met Office was heavily criticised by the media at the time[8]. These storms provide the basis for developing a worst foreseeable scenario for future extreme weather events. First, we analyse the factors associated with death and injury.

Figure 4.15a

Highest reported gusts (knots) over southern England and the near continent, 16 October 1987[5]

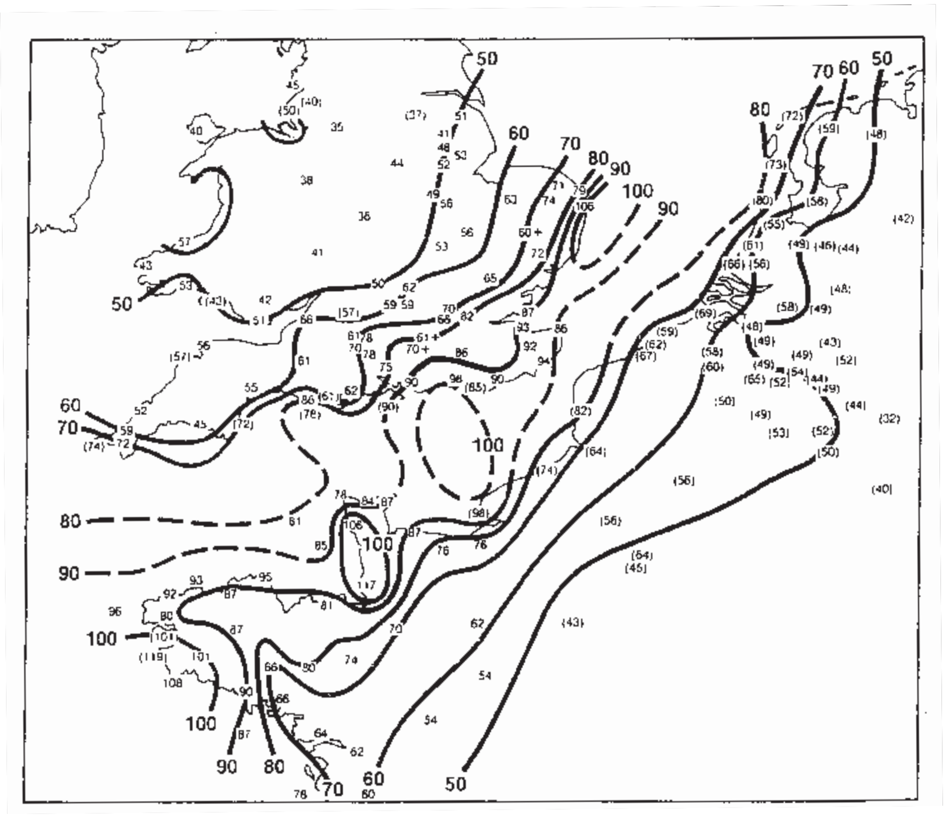

Figure 4.15b

Maximum gusts recorded on 25 January 1990 and return periods (years)[6]

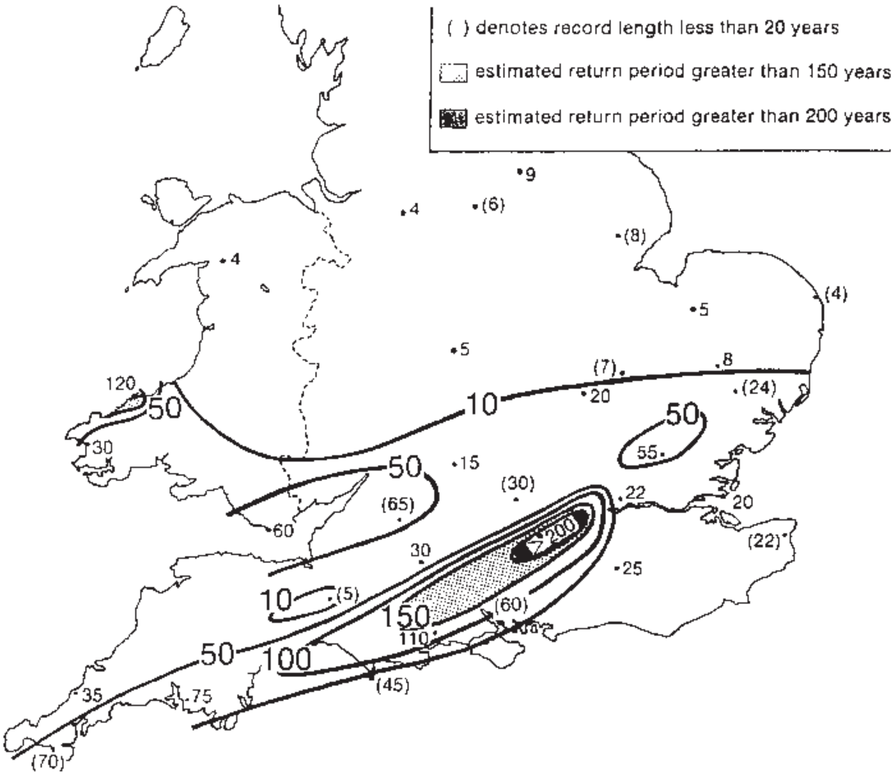

Figure 4.16a

Analysis of maximum winds (knots) for 16 October 1987[7]

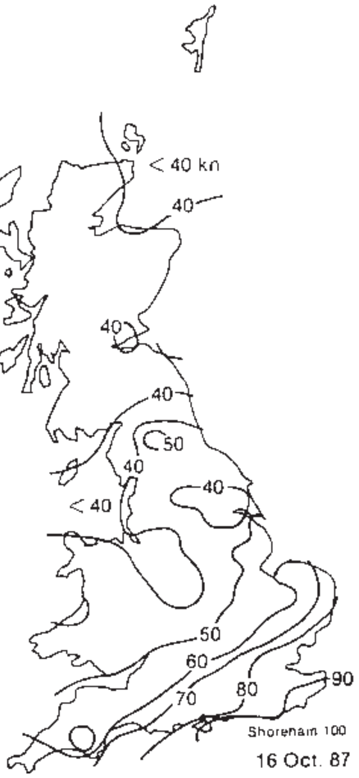

Figure 4.16b

Analysis of maximum winds (knots) for January 1990[7]

4.5.4 Impacts of strong winds

An increase of wind speed of up to approximately 10% would have the effect of increasing the structural loading by 20% (the pressure of the wind on a structure is proportional to the velocity squared). This would have little effect on the vast majority of well built structures, but we estimate that between two and five times more minor damage would occur overall as a result of the increased loading. This is a potential problem for the insurance industry in the UK rather than for the National Health Service. If wind speeds increased beyond 10% this could present a problem to structures, but over time more rigorous building regulations could compensate for the growing hazard.

Compared with the relatively small effect on buildings (except in insurance terms from claims), the direct effect of stronger winds on people would be considerably greater. The propensity to be blown around by the wind can depend upon the clothing that is worn, so that winter clothing such as floppy coats can effectively double the drag coefficient which, in turn, could as much as double the risk of being blown over in the open for a given wind velocity. The risk is greatest in streets and by the corners of buildings where wind can accelerate. Thus the increase in the risk of being blown over with the potential for injury by changing to winter clothing outweighs the risk of injury from structural failures due to a 20% increase in loading from increased gust velocity.

Gusting winds will cause weak structures such as garden sheds and other outbuildings to collapse, and flying debris from these may cause injuries. Uprooting of trees is a significant problem in wind storms and is related to the water content of the soil as well as wind velocity, so that trees more readily blow over if the storm occurs after a period when the soil is wet. Collapsing trees and flying debris may block roads and railway lines, and road links may also be blocked by accidents caused by vehicles being blown over or blown off the road. Damage to utility poles and overhead lines may disrupt communications and power supplies. The consequences of vulnerable infrastructure being impacted (transport, communications, power supplies) are of major significance to human health and safety.

Deaths and injuries caused by wind gusts

Buller 1993 has compiled statistics for deaths and injuries caused by the wind in the United Kingdom in 1962-1993 using newspaper cuttings as the main data source[4]. His findings are likely to be limited by under reporting, and the classification of injuries as major and minor is also likely to be affected by reporting bias, so we combine the two types here. The mean annual numbers were 6 deaths and 144 injuries. Road transport-related accidents dominate the total number of deaths (280/464 or 60%), followed by accidents from building failure (184/464 or 40%). The greatest number of deaths in wind events from any one cause of direct building failure was falling chimneys (34), or falling chimneys, roof elements and walls (78). The two most important causes of deaths not related to building failure were being blown over and subsequently hit by a vehicle (16), and just being blown over (22).

In the October 1987 and January/February 1990 windstorms, a total of 99 deaths were reported. 57 Deaths involved vehicles with 41 deaths caused by road traffic accidents as a result of falling trees. Building failures led to 13 deaths. The most important cause of reported minor and serious injury was being blown over in the open, with about a third of the 2 287 reported injuries being attributed to this.

Only broad conclusions can be safely made from these simplified data, but they suggest that road traffic accidents are the most important in terms of deaths and therefore possibly severe injury – as a result of trees falling onto roads and vehicles, as well as vehicles being blown about, or colliding, in the wind. The major single cause of injury in individuals in the open is being blown around by the wind, including into the path of traffic. Building failure, such as the collapse of chimney stacks and walls, are a less significant but still important cause of death and injury.

Injury agents

Trauma in windstorms is due to impacts on the human body from objects being displaced by the wind, or by the body being blown over and then being injured by impact against hard surfaces or by falling in front of traffic. Falls may also be from roofs or into rivers, etc. Unfortunately, few studies of wind injuries in the UK have been published. On 1 February 1983 gales were particularly severe in the Leeds area with gusts up to 96 mph (43 m/s) being recorded. 116 Patients were treated in the two main hospitals in Leeds, which served a population of about 735 000, for injuries caused by the wind. Three people died, and the types of injury were analysed[9]. The majority of the accidents occurred when people were blown over whilst walking outside. Eighty-one patients were blown over. Nine people were injured when parts of buildings collapsed. Four patients were injured by falling slates and twelve by other falling or flying objects, including window glass, a tree, a milk-crate and a dustbin. Four patients were injured in road accidents caused by the wind. The patients sustained injuries of all degrees of severity: chest crushed, head injuries, other fractures, shoulder dislocations, sprains, lacerations, abrasions, contusions, and eye injuries (Table 4.6). All age groups were equally affected. The authors concluded that many injuries could have been prevented, especially if elderly people had stayed indoors for a few hours until the very high winds had abated. One hundred and four (90%) of the patients were seen at the hospitals on 1 February, and they comprised 23 % of new patients attending.

Table 4.6 Injuries caused by wind (some patients sustained more than one injury): Attendances at two Leeds hospitals, 1st February 1983 gales.

Injury	No. of attendances	
Crushed chest (multiple fractures)		1 (fatal)
Head injuries		
(with loss of consciousness)		7 (2 fatal)
Fractured skull	1	
Other fractures		22
Facial bones	1	
Cervical spine	1	
Shoulder	6	
Wrist	8	
Hip	2	
Hand or foot	4	
Dislocations		3
Sprains		9
Ankle	6	
Other	3	
Lacerations		39
Head	27	
Limbs	12	
Abrasions		39
Head	12	
Limbs	27	
Contusions		32
Head	13	
Limbs	14	
Chest	5	
Eye injuries		4
Other injuries		3

In a separate study[10], wind-related injuries treated in two inner city London accident and emergency departments during January and February 1990 were analysed. 58 Patients were seen, of whom eight required admission to hospital. The majority of patients were either hit by flying debris or falling masonry (36%), or were blown over by the wind (33%). The vast majority of the injuries were sustained during daylight hours, with head injuries, limb fractures and foreign bodies in the eye being the most common (Table 4.7). The number of injuries resulting from falling masonry, scaffolding, advertising hoardings and various loose debris was only increased on days when wind gust speeds exceeded approximately 60 knots (70 mph or 30 m/s). The authors suggest that this gust speed could be used as a warning threshold for issuing advice to the population to stay indoors[9]. In contrast to the experience in Leeds, the overall numbers of patients attending for treatment was unchanged on windy days.

Table 4.7 Injuries caused by wind: Attendances at two inner-city London hospitals, January-February 1990 gales

Type of Injury	Number	Anatomical site of Injury	Number
Head injuries – no fracture	15	Head	17
Head injuries – compound	2	Eyelid	12
Fractures	18	Lower limb	12
Foreign body in eye	13	Upper limb	9
Lacerations	9	Face	4
Soft tissue injury	8	Chest	4
Abrasion	4	Back	1
Other	1	Neck	1

A study of wind-induced accidents of road vehicles in England and Wales in the 25 January 1990 storm[10] confirmed the vulnerability of vehicles when being driven in wind gusts exceeding 20 m/s. Overturning accidents were the most common type, accounting for 47% of the total. Course-deviation accidents made up 19% and accidents involving trees 16 % of the total. Sixty-six per cent of the accidents involved high sided lorries or vans, whilst only 27% involved cars and this number included most of the accidents that were caused by collision with falling trees[11].

4.5.5 Windstorm severity index

The potential for accidents and injury needs to be related to a wind damage scale so that we can more readily examine the local intensity of storms and threshold criteria for structural damage and human trauma. Damage is caused by wind gusts (defined as lasting for three seconds) and not average wind speeds, which in storms will have much lower values. There is no designated wind scale for temperate windstorms and here we propose that an approximation with existing severe weather scales may nevertheless be useful. The Beaufort scale gives wind speed from 0, meaning calm, to 12 for hurricane force winds. Hurricane intensity is classified on the Saffir Simpson scale by categories 1-5 (minimal to catastrophic damage) according to wind speed. Tornadoes are classified by the Fujita F scale of F_0 to F_6. The TORRO Tornado Intensity Scale was devised in 1972 by the UK-based Tornado and Storm Research Organization[3], and this picks up where the Beaufort scale ends. The T_0-T_4 part of the damage scale with the lower wind speeds[12] as shown in the truncated version of the T_0-T_{12} scale in Table 4.8. The lower end of the T_2 level (33 m/s) is the beginning of sustained hurricane wind speed.

Table 4.8 The Torro Tornado Intensity scale (T_0–T_4)

TORRO Intensity	Description of Wind speeds	Description of Damage
T_0	17–24 ms^{-1} (39–54 mph)	Loose light litter raised from gound-level in spirals. Tents marquees seriously disturbed; most exposed tiles, slates on roofs, dislodged. Twigs snapped; trail visible through crop
T_1	25–32 ms^{-1} (55–72 mph)	Deckchairs, small plants, heavy litter made airborne; minor damage to sheds. More serious dislodging of tiles, slates, chimney pots. Wooden fences flattened. Slight damage to hedges and trees
T_2	33–41 ms^{-1} (73–92 mph)	Heavy mobile homes displaced, light caravans blown over, garden sheds destroyed, garage roofs torn away, much damage to tiled roofs and chimney stacks. General damage to trees, some big branches twisted or snapped off, small trees uprooted
T_3	42–51 ms^{-1} (93–114 mph)	Mobile homes overturned/badly damaged; light caravans destroyed; garages, outbuildings destroyed; house roof timbers considerably exposed. Some bigger trees snapped or uprooted
T_4	52–61 ms^{-1} (115–136 mph)	Mobile homes destroyed; some sheds airborne for considerable distances; entire roofs removed from some houses or prefabricated buildings; roof timbers of stronger brick or stone houses completely exposed; possible collapse of gable ends. Numerous trees uprooted or snapped.

Conversion factors: 1 knot is one nautical mile (1.15 statute miles or 1.85 km) per hour, or approx. 0.5m/s

Gusts in temperate windstorms are unlikely to exceed 100 knots, i.e., attain the upper end of the T_3 scale (51 m/s), except by acceleration at the corners of buildings, etc. It is at wind speeds in excess of 70 m/s that trains could be overturned, cars lifted off the ground and thrown, and roofs and some walls torn off well-constructed houses: such a speed sustained in a hurricane would be catastrophic and in the uncommon super-cyclone range.

Certain gust speed thresholds for temperate windstorms are apparent. It is possible for a fit motivated person to stand up against winds in the T_1 level (30 m/s), but people could be blown over whilst walking or cycling in gusts over 20 m/s. This wind gust speed (20 m/s) has been proposed above as a threshold for road traffic accidents, particularly in high-sided vehicles at risk of being overturned by the wind. Most building damage and injuries from falling or blown building elements will occur in gusts exceeding 33 m/s. Tree knock-down and overturning of inadequately tethered mobile homes and caravans occurs when gusts exceed 45 m/s.

High density materials from building or wall failure

The main reported cause of death as a result of direct building failure has been the collapse of chimneys. Chimney-stacks, which can weigh several tonnes, may fall through several floors of a building before causing death. However, most of the casualties occur outside, whatever their cause, as a result of falling chimney stacks and pots, falling walls of buildings, breaking windows, and overturning caravans/mobile homes[4]. Falling bricks and tiles can cause severe trauma, especially head injury (skull fractures, cerebral contusions/haemorrhage). Lacerations would be common, and fractures of limbs or ribs could occur.

Falling trees

These can cause multiple trauma by directly falling onto a vehicle or pedestrian as well as cause road accidents by falling onto the road. Falling trees were the most important category of impacts associated with deaths in the 1987 and 1990 events.

Body displacement

Wind can blow people to the ground, against walls and posts, or into the path of oncoming traffic. As mentioned above, this was the most common reason for non-building related injuries. The hazard is greatest where urban patterns produce local points of high wind speeds close to the ground - especially corners of high-rise structures, in 'piazza' or 'podium' rather than narrow-canyon planning. Head injuries and limb fractures would be common resulting conditions, as well as internal chest and abdominal injuries in the worst instances, i.e., multiple trauma.

Vehicle instability

Cars and lorries may collide as a result of being blown off course by the wind or even overturned. Vehicles become increasingly unstable in high winds as their velocity increases, and drivers should be warned to slow down in high winds. Motor and pedal cyclists can be blown into other traffic.

Missiles

The velocity of a flying object is determined by the product of its density and thickness. Thus a 15 mm plywood sheet flies at the same speed as a 1 mm corrugated iron sheet. Plywood panels, e.g. from disintegrating garden sheds, will start to fly about at wind speeds greater than 20 m/sec. Wooden timbers commonly used in the construction industry (2 in x 4 in) will fly short distances in wind speeds in excess of 30 m/sec. Windows, guttering, loose canopies, street furniture, etc. may be dislodged by the wind and could become flying missiles in the strongest gusts of wind. People in the open would risk being struck, especially on the head, as in other types of building failure.

Miscellaneous

Fallen power lines may cause electrocution. Loss of power in cold weather will lead to people looking for other sources of heating, including home heaters, which may be hazardous if they were previously poorly maintained. Deaths from carbon monoxide poisoning could occur. The use of gas cylinders or candles could start house fires.

In summary, most deaths and injuries are caused as a result of people being outside at peak hours of a windstorm. Road traffic accidents may occur due to trees falling on cars and just driving in windy conditions, and roads could consequently become blocked and traffic grid-locked. The worst scenario would be when peak gusts coincided with periods of heavy traffic, e.g. during rush hour. Vulnerable houses and other buildings with weak roofs present a significant but lesser hazard from falling roof elements.

4.5.6 Vulnerability

The vulnerability of structures and infrastructure plays a key role in a risk assessment of the impacts of windstorms.

Buildings

A study of the vulnerability of the UK building stock to windstorm was made by Cambridge Architectural Research[13]. There were two important conclusions from this study.

- ❏ The frequency of damage varies considerably according to building type, and both age and building configuration are important. Table 4.9 shows a proposed classification of the UK building stock, indicating relative vulnerability indices for 24 classes of building. These indices were based on the relative areas and frequency of occurrence in each of the 24 classes of building of the key vulnerable elements (chimneys, tiled roofs, windows), their propensity to damage based on data from the Building Research Establishment[14] and their condition based on the English House Condition Survey[15]. Vulnerability here refers to damage repair costs, an issue of special interest to the insurance industry, but it also denotes those buildings most likely to suffer some degree of damage to chimneys and tiles, for example.
- ❏ The frequency of damage rises steeply with increasing wind speed according to a logarithmic relationship. Thus a 5 m/s increase in wind speed from 40 m/s to 45 m/s would be expected to result in an increase in the numbers of damage incidents by a factor of 5.

Table 4.9 Proposed composite vulnerability indices for the UK building stock[13]

	% Of stock	pre 1919	1919–1945	1945–1964	post 64
% Of stock		26.4	19.7	21.5	32.5
Terraced houses	28.1	1.32	1.15	0.79	0.40
Semi-detached houses	26.7	1.54	1.32	0.93	0.49
Bungalow	23.5	2.0	1.72	1.21	0.65
Converted flats	6.9	1.01	1.13	0.83	0.47
Low-rise flats	12.7	0.81	0.7	0.48	0.25
High-rise flats	2.0	0.49	0.42	0.29	0.17

A notable event was the ‘Sheffield Gale’ of 1962, during which large numbers of buildings were damaged over a wide area of northern England. Much of the damage appears to have been to old and neglected properties as reflected in the many casualties caused by chimneys falling through roofs and by roofs themselves being blown off[4].

Transport system

Motorways can become blocked following a collision of two vehicles, or even by a single lorry being blown over. Main roads and their tributaries can be blocked by accidents and falling trees. Clearing the accidents may be delayed because police and other emergency services are overwhelmed with calls from all kinds of other incidents. Railways can be brought to a standstill by falling overhead electric lines, trees falling across lines and wind damage to signals, as well as power supply problems. In the October 1987 event, large numbers of commuters were forced to stay overnight in London because the rail system stopped; the London Underground service in the centre of the city was maintained. In cities these impacts will result in large numbers of people taking to the streets to walk home or find somewhere to stay, thereby exposing themselves to the wind and falling building elements, and therefore a greater risk of injury. In cold weather people trapped for prolonged periods in cars may suffer hypothermia. The transport of casualties and the acutely sick to hospital might also be hindered and endanger their lives.

In the October 1987 storm more than a hundred flights were cancelled from Heathrow and Gatwick airports. Sea ferries were also disrupted.

Power and communications

In the 15-16 October 1987 storm the whole of south-east England was without power between about 0300 and 0930 GMT: London was blacked out for the first time since the Blitz[5]. Trees fell onto power lines and wind-borne debris caused short-circuits. Army helicopters were drafted in to aid with the identification of downed power lines. Even two weeks later some 2000 homes were still without electricity.

Telephone and power lines are carried to country and remote areas by overhead lines on utility poles. The lines can be damaged or brought down, and weaker poles may snap off. It can take several days to restore these services after the event when repair gangs are over stretched dealing with large numbers of breakdowns. In towns and cities power transmission lines are underground and power supplies are less likely to be threatened, but the experience in London described above should not be ignored.

4.5.7 Risk scenario

The worst reasonably foreseeable scenario would be a situation during the day in which people were travelling or moving about outside buildings in large numbers at the peak of a major windstorm in London and south-east England. The overriding factor would be the time of day that the storm peaked, with the worst time being just after people have started to leave early from work in the afternoon to travel home. In a city like London the traffic and rail and underground services could come to a halt as a result of storm damage. Large numbers of people would congregate at railway termini and similar locations causing considerable congestion. Some buildings with wide-span roofs used for shelter might be vulnerable to collapse in strong winds and cause further catastrophe. Flying debris would add to problems of people in the open and, as mentioned above, being blown around by the wind is a major cause of injury, particularly among the elderly.

In the 1987 event the return period for the maximum gust measured (90 knots) exceeded 200 years in places[6]. Of course, this is the return period for the exceedence of the expected wind speed at a point, and it does not mean that these events occur only once in every 200 years in the UK. It would appear that at least some part of the UK could be affected in this way perhaps as frequently as once every 10-20 years on average, though the reference windstorms of 1987 and 1990 contained gust velocities in excess of any gales in southern England in recent decades[6].

4.5.8 Risk assessment

We estimate in this worst reasonably foreseeable scenario that the numbers of people killed and injured might be at least double that of the events in January/February 1990. As discussed already, about 60% of the deaths in windstorms occur on the road or rail. An analysis of unpublished Department of the Environment, Transport and the Regions (DETR) traffic flow statistics (1993) indicates that the evening rush hour traffic is typically five or six times the late evening traffic, and thirty times the traffic counts in the small hours of the night.

A reasonable estimate, assuming no warning was given to the population who, therefore, failed to take anticipatory action, such as stay at home instead of going to work, could be 100 dead, 90 seriously injured (mainly head injuries, limb fractures and multiple trauma in road accidents) and at least 400 people suffering minor injuries. But as the effect of rush hour traffic could be as high as a factor of five, the numbers of deaths in a worst scenario could be as high as 200. In addition, failure of a large building with a weak roof, for example, could greatly add to the toll of death and injury as a single catastrophic event.

The individual risk of being severely injured or killed in such an event in the UK is really quite low ('minimal' or between one in a million and one in 100 000 annual risk, on the scale proposed by the Chief Medical Officer[12]). The overall impacts would be greatest in densely populated areas such as London and other cities reliant on commuter transport.

The societal risk of, at worst, several hundred deaths in an event every 10–20 years is also small, but unacceptable in a society unused to experiencing natural disasters and aware that risk reduction measures are available.

The duration of the peak winds in the above scenario is measured in hours rather than days, but the damage impact would be greater if two or more severe windstorms occurred back to back. The windy period at the beginning of 1990 had far greater impact because it featured the successive recurrence of storms with damaging gusts on 25 January, 7/8 February and 26/27 February, as well as there being intervening spells containing widespread and persistently strong winds. Most of the deaths and injuries would occur in the first storm phase, when people are first caught unawares.

4.5.9 Measures to reduce exposure

Risk reduction measures would need to be directed to providing timely and adequate warnings to the population so that people could protect themselves from the storm impacts. The key factor in reducing human risk would be for the public to stay indoors during periods of high wind. This analysis points to four levels of warning:

Gust speeds	Groups to be advised (examples)
20 m/s	Pedestrians, cyclists, drivers of high-sided vehicles
30 m/s	Above groups + households + all drivers
40 m/s	Commuters, schools, rail companies, utilities, emergency services
50 m/s	Maximum gusts: widespread damage and disruption to population in impacted areas

Appropriate mitigation measures would include the following:

- ❏ Forecasts and warnings: at present advice is given on weather forecasts on TV and radio that strong winds are likely, but no further advice is given on what to do. This contrasts with tornado warning systems in the USA, and an elaborate warning system in place in Hong Kong for tropical cyclones which results in people going home well in advance of the peak impact of the cyclone. A similar system could be established in the UK to advise people to leave work in good time (or prevent them leaving home for work). The accuracy of forecasts and the range of lead times which may be available to the public between warning and being able to take effective evacuation measures also needs to be considered. Special traffic and rail flow systems may need to be put in place to speed up what would in effect be an evacuation of commuting workers from a large city.

- ❏ Community preparedness: people need to know what to do in strong wind events, especially when they are warned that these are imminent by meteorologists. People should be aware that it is quite dangerous walking outside in strong winds, that there are major hazards when driving due to strong winds blowing over vehicles as well as causing trees to collapse on to vehicles and the roads. Travelling to work should be avoided, as should taking shelter in vulnerable buildings such as caravans and mobile homes, or structures with wide roof spans. Other measures include encouraging householders and others to inspect building elements vulnerable to strong winds, such as chimneys, tiles and outbuildings, scaffolding, advertising hoardings, as well as to be more prepared to cope with the impacts of windstorms.

4.5.10 Implications for the National Health Service

The two studies of emergency department attendance in two inner city areas suggest that the influx of injured patients will be manageable within existing capacity. The number of new attendances increased by 20% in one study with no overall increase in the other. Most injuries did not require admission, but some patients with serious multiple trauma may be anticipated. Of course, storms occurring in winter may coincide with a period in which hospitals could be already fully stretched through an influenza epidemic, for example, when resources for acutely ill patients could be put under severe strain. Power failures will not affect hospitals with emergency generators. An important issue in hurricane-prone countries is the proofing of hospitals against very strong winds, and audits of UK hospitals should be undertaken to ensure that their buildings and infrastructure are capable of withstanding gusts exceeding 46 m/s (100 mph). Advice to ambulance and other emergency services drivers about safe driving speeds in storms and the hazards of falling trees, etc., should also be provided. Hospital accident and emergency staff should be trained in the effect of high winds in causing injury and the types of injuries that may occur.

Addendum - a re-run of the Gale of the Century in France[16,17]

A severe windstorm ('the storm of the century') struck Paris and northern France at 0300 hr on 26 December, 1999. The gales turned some of the French capital's most elegant districts into a tangled mass of wood, metal, masonry and Christmas decorations, which were ripped from department store buildings. After the night, residents stared with disbelief through broken windows at the trail of cars crushed under branches and hoardings. Throughout the north of the country roads were blocked, airports were closed and two million people were without electricity. Several hundred thousand people were left without telephones. Like the English storm of October 1987, the meteorologists failed to predict its force – gusts of 107 mph on the outskirts of Paris – the strongest since records began. Most deaths resulted from trees falling onto cars. Between the

Champs Elysees and the Grand Palais century-old trees were toppled and statues were damaged. At Montparnasse main-line station there was near hysteria when lumps of wood and metal hurled through a roof onto the waiting area. All trains were cancelled in northern France as there were trees falling on lines. Seven of the city's Metro lines had to be shut down as well as nearly all the commuter rail services. Aircraft were damaged on the tarmac at Paris's two international airports, Orly and Charles de Gaulle, which were both closed.

A sense of panic in the Paris region was fuelled when the emergency phone number went down. At one stage the fire service, which had been called out 1300 times in the capital, drove round looking for emergencies. At least 73 people died in the worst affected areas, most of whom were crushed by falling trees or masonry and other debris. Many more were injured.

Another major storm hit southern France the next day. Southern Britain did not entirely escape the repercussions of the storms. As well as having to provide south coast flood warnings, the Environment Agency was reported ominously reminding us of the sea surge risk[1]: "We have had to raise the Thames Barrier on five successive nights during the past week. We probably raised it only five times in total during all of the 1980s. Climate change means we are going to have to look at radical alternatives to the present arrangements..."

4.5.11 Summary

According to the Medium-High scenario of climate change in the UK, the overall gale frequencies are likely to decline in the future, though very severe summer and winter gales could increase. Wind speed could rise by 4% in the south-east and 7% in Scotland by the 2080s. An increase in wind velocity of up to 10% would not present major problems from gusts to existing buildings and other structures, but there is likely to be a substantial increase in minor damage leading to a rise in insurance claims. Increases in wind velocity over 10% could require, in the longer-term, further strengthening of building regulations for roofs. Severe gales are already with us as is shown by the reference events in 1987 and 1990 which we have drawn on for this report.

Most deaths in temperate windstorms occur in road traffic accidents, especially as a result of trees falling onto vehicles or roads. Structural failure, such as collapsing chimneys and walls, ranks next as a main cause of death. Most injuries arise from being blown over in the wind with or without being subsequently struck by a vehicle. The impacts of a worst foreseeable wind on infrastructure, especially power, transport and communications, have many direct and indirect consequences for human health and safety. Our analysis suggests that the threshold for injury starts at gusts of 20 m/s, when elderly people could be blown over or people on cycles blown down, and more frequent and serious incidents arise at gusts over 30 m/s, when everyone should be warned to stay indoors. Gusts of over 20 m/s can also endanger high-sided vehicles, which become increasingly unstable the faster they are driven. At gusts in excess of 45 m/s trees fall down and may cause fatal accidents on roads, and falling masonry may cause deaths inside as well as outside houses.

The human and infrastructure impacts of future temperate windstorms warrant more detailed investigation to expand the present sparse statistical base and to inform risk reduction measures. It is evident from this analysis (and confirmed in the impacts of the Paris gales on 26 December 1999) that inner city environments in the UK (and France) are highly vulnerable to windstorms, both in their buildings and their infrastructure. The potential for a large loss of life exists as well as for huge disruption with attendant economic consequences.

The worst reasonably foreseeable scenario is a winter windstorm in London and south-east England that increases in intensity over the hours after 3 pm when the maximum numbers of commuters would be out in the open or in cars and trains. Failure of the transport system (road and rail) would leave these individuals highly vulnerable to accidents and exposure to the impacts of gusting winds. Congested crowds of large numbers of people in buildings could be vulnerable to wind-induced roof collapse, and other forms of catastrophe to trains and air traffic could also strike. We estimate that the overall number of deaths could be as high as 200, with hundreds of other people injured, several scores of these seriously. As these would occur over a wide area, the management of the injured should not overwhelm the existing hospital services unless a major incident occurs or hospitals are already under stress for other reasons, such as an influenza epidemic. The number of mass casualty events is hopefully likely to be few, but inner city areas are especially at risk. These human impacts of windstorms would be seen as foreseeable and inherently preventable in a modern technological society, and government could be criticised for failing to take preventative action. This potential for disaster, in our view, justifies the need to consider the setting up of emergency planning with advance warning systems to forecast major windstorms, and a programme of increasing awareness and education in mitigation measures in the general population. However, climatologists using existing climate change models or past gales records cannot constrain the return periods of the extreme windstorms we base our work on here, and these uncertainties are amongst the most important limiting factors in completing a human health risk assessment.

4.5.12 Priorities for future action and research

- ❏ Further development of computer models to improve the capacity to predict windstorms is needed.
- ❏ Review of building regulations with a view to improving the capacity of roofs and other vulnerable structures such as chimneys to resist very high winds is recommended.
- ❏ Improved emergency planning for severe windstorms is recommended.
- ❏ A campaign to raise public awareness of the dangers posed by very high winds and the steps that can be taken to counter these effects is recommended.

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4.6 Flooding and climate change

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Coastal Flooding

Summary

- ❏ Climate change in the UK is likely to be associated with an increased risk of severe flooding in low-lying coastal areas and the return time of severe flooding events is likely to be significantly reduced.
- ❏ Emergency plans to mitigate the effects of such floods should be reviewed urgently.
- ❏ A detailed risk assessment of the likely effects on health of a major flood of low-lying areas is urgently needed.
- ❏ Further research into methods of coastal engineering leading to design guidelines for coastal defences is needed.

4.6.1 Introduction

On a world scale, global warming and a consequent significant rise in sea level would have severe impacts for some low-lying coasts and islands. The consequences for the UK are in general perceived as amenable to technological control, such as through the construction of more resilient sea defences. Perhaps the best example is the Thames Barrier, which was erected to protect London from severe floods with a design that allowed for a predicted sea level rise until the year 2030. This chapter is possibly one of the first attempts to address the issue of coastal floods, from the perspective of human risk and the health consequences as a result of rising sea levels and a potential increase in storminess. Our analysis presents a complex picture in which we find significant limitations in the current state of hazard and risk analysis of coastal floods and recommends that these need to be addressed before the impact of climate change on human health can be satisfactorily estimated.

4.6.2 Key questions for future risk scenario development

This chapter focuses on coastal flooding (sea defences) and omits discussion of coastal erosion (coastal defences). It assesses the human consequences of potential flooding events which could have impacts on a disaster scale. The reference event in this analysis is the East Coast Floods of 1953 in which 307 people died.

The following questions are to be addressed.

- ❏ If there were a recurrence of a major flood, as exemplified by the 1953 flood event, what hazards would it present today and in a future scenario of climate change?
- ❏ Can the current probabilities of major coastal flood events be estimated and how would these be affected by the future climatological estimates, both in terms of return periods and severity?
- ❏ What would be the loss of life and health implications for society of such a future event?

- ❑ Can increases in the risk of major coastal flooding be prevented by engineering measures (improved coastal defences) alone?
- ❑ What other mitigation measures may be needed to reduce vulnerability to such events?

The reactions of society to climate change also need to be considered. To answer these questions we have reviewed:

1. Flood disaster model: East Coast floods, 1953
2. The forcing factors: climate change scenarios
3. Flood characteristics
4. Sea defences and coastal management issues
5. Causes of vulnerability
6. Human health consequences of floods
7. Mitigation measures

4.6.3 East Coast floods 1953

This remarkable event was documented by Greave (1956)[1] and Summers (1978)[2], and is presented here as a model for future flood disaster events. On Saturday 31 January and Sunday 1 February 1953 a great storm surge, accompanied by gale force winds, swept over the north of the UK, causing widespread flooding of coastal areas. The waters of the North Sea, whipped by the northerly gales to huge tidal levels, smashed through the sea wall defences in hundreds of places from Spurnhead to Kent. The damage extended over 1000 miles of coastline, and involved breaches in the defences at some 1200 sites. In some places not a mile of sea wall remained intact. 307 people lost their lives and over 32 000 had to be evacuated from their homes. Whole communities were isolated. 24 000 houses were flooded and damaged – some beyond repair.

During the Saturday morning the winds reached force 10 with gusts up to 125 mph. In east Scotland the wind flattened thousands of acres of forest. The mean sea level rose by 0.6 m. Winds lashed the surface of the water with waves over 4.9 m height, the high waves being generated by the very long fetch, i.e. the sea track over which the winds were blowing. It seems probable that the surge had an elevation of about 2.6 m all along the Norfolk coast. Levels were particularly high at King's Lynn (3 m for comparison, a category 3 hurricane creates a surge of 3–4 m). Fortunately there had not been heavy rain or melting snow in the uplands and so rivers were not in flood or swollen at the time, if they had been the results would have been far greater in extent, widening the area and scope of the disaster. The East Coast defences and the authorities responsible for them were totally unprepared.

The sea attacked in two ways:

- ❑ wave action or scour against sea walls and dunes until they were breached (e.g. Lincolnshire, north Norfolk and parts of Kent); and
- ❑ sea surging up estuaries and overtopping and breaching river banks (e.g. Suffolk and Essex).

Some descriptions of deaths are given by Greave[1] (Appendix). The worse effects were in Canvey Island. A few people had been warned in time to take refuge in their house lofts. However, most were awakened at about 1.10am by a roar as the nearby sea wall was breached and the water thundered past their doors in an irresistible avalanche. Within 15 minutes the water was above window sill level. Much damage to walls, doors and windows was caused by floating debris being flung against houses. Many people were drowned in their beds. Others died of shock or exposure as they scrambled on to house roofs and waited in the dark and cold for help to come. Some people collapsed and slipped from places of refuge into the water and drowned. Especially vulnerable were the old, those living alone and those prone to respiratory or rheumatic illness. Fifty-eight people died that night on Canvey, but it was noted that the death rate climbed significantly during the two months following the disaster, as compared with the same two months the previous year[2].

This description illustrates some of the impacts of the flooding that need to be considered as far as human risk is concerned. The most devastating consequences were from the breach of the defences or banks by a wave of water carrying with it debris that smashed open houses, swept away people and caused drowning with little warning. Bungalows were at greatest risk for the occupants who had no upstairs for refuge. Since the flooding occurred in winter, many who survived the initial drowning subsequently died from exposure. Thus the elderly and small children would be the most vulnerable in such events, and the low temperature of the water would induce drowning on sudden immersion and also cause death in survivors by the subsequent development of hypothermia. The timing would be crucial, depending on whether the flooding occurred during a time of the day or at night when people would be least prepared. Other factors need to be considered. For example, at Tilbury the sewage works were submerged, creating additional problems and a nightwatchman was killed by coal gas escaping from a fractured main. Today, technological hazards would be substantially greater, for example, with the storage of chemicals and fertilisers in many places.

According to the Environment Agency (1999)[3] :

> *"The 1953 flood was the most devastating flood of recent times. Although the tide of 31 January 1953 was only a moderate spring tide, a large surge had been generated which was amplified by winds as it progressed southwards along the east coast. Sea levels in the North Sea rose over 2m higher than tidal predictions. The severity of the disaster was certainly increased because it all happened in darkness. There has been a series of less destructive floods since 1953."*
>
> *"After the flood defences failed in the 1953 storm, many of them were rebuilt and improved using 1953 levels as a maximum. The Thames Barrier was built as recommended in the Government's report on the 1953 flood, although not completed until 1982. The design recognised that sea level was rising by 0.8 cm per year and allows for the rise to continue until 2030. The barrier, which will cope with events up to a return frequency of 1 in 1000 years, was designed to protect London and upper parts of the Thames estuary from storm surges. As well as tidal defences, about 126 500 domestic and commercial properties rely on sea defences for their protection and some 366 000 people live in houses liable to flooding from the sea. For Wales, the figures are 33 000 properties and 84 000 people."*

However, these estimates of the numbers of people at risk may be open to question. Even in the 1953 East Coast floods it appears that adequate assessment of the extent of the flooding was not made, for example, records were based only on the areas where existing houses were impacted.

4.6.4 Forcing factors: climate change scenarios for the United Kingdom

Climatologists agree that there are two main issues involved in the assessment of future coastal flooding risk: the rate of sea level rise and whether storminess will increase as the result of climate change.

Sea level rise

The UK Climate Impacts Programme Technical Report No 1, 1998, describes four possible climate futures for the UK. Global mean sea level is set to rise in all four scenarios, the rate of increase ranging from 2.4 cm per decade to 10 cm per decade. The change in mean sea level around the UK coast closely follows that at a global scale and leads to a large reduction in the return periods for certain high tide levels around parts of the UK coast. Natural vertical land movements must also be considered. Thus the report concludes that the relative sea level rise by the 2050s under the Medium High scenario could be 41 cm in East Anglia and 21 cm in the west of Scotland. At the East Coast we can take 6 mm per year as the best estimate of sea level rise as a result of a fall in the land and rise in sea level. Thus the report concludes that for Harwich a high tide level of 5.6 m above datum that currently has a return period of 1 in 100 years (probability of 1% per annum) would have a 10 year return period (probability of 10% per annum) - an extreme example of the UK coastline for the 2050s. Furthermore, this return period and the resultant increased risk of flooding makes no allowance for a potential increase in storminess.

> *"A rising sea level puts low lying land at greater risk of inundation. This may happen simply by the sea covering the land if it has no defences, but also by storms acting together with higher sea levels to overtop sea defences if they are not adapted. The overtopping of sea defences, during storm surges, is likely to occur more frequently if mean sea levels rise. For example, floods which currently occur on the east coast of England once in 100 years could have a return period of 50 years by 2050, and on the west coast (for example at Avonmouth) the return period for a 100 year flood could reduce to 1.5 years."*[3]

Other experts talk about an increase in return rates of an order of magnitude so that the 1953 flood which is regarded as a 1 in 500 year event could become at least a 1 in 50 without including the increase in storminess. A trend of rising sea level is already discernible around the UK coastline (Section 1.2.2)

Storminess

The potential for changes in storminess are regarded as 'quite modest'. Summer gales could become a little more frequent, as could very severe winter gales. The average number of gales per year since 1881 is 12-15. By the 2080s, Scotland could see increases of severe gales up to 7%. Relatively little is known about modifications in the patterns of depressions that could lead, for example, to storms arising back-to-back with one weakening the sea defences and the other overtopping them. However, for trends that appear to show an increase in storminess in recent decades the records over the century show that this could also be explained as part of the normal variability. Wave heights have also been increasing in the North Atlantic, but this finding is also regarded by scientists as within normal variability.

Flooding

According to the Environment Agency (1999)[3]:

> *"Areas which are less than 5m above ordnance datum are at greatest potential risk of flooding from the sea. Some 5% of the population and 1.5% of the land lie below this level, but sea defences have reduced the risk in many places. Furthermore, over 50% of all grade 1 agricultural land in England and Wales lies below this level. The east coast of England, particularly the area between the Humber and the Thames, is at the greatest risk of flooding from the sea. This is due to a range of factors:*

- ❏ *much of the land along the east coast is flat and low lying;*
- ❏ *a history of land reclamation has resulted in a substantial proportion of the coastal strip and some inland areas lying below the high tide level and reclamation has interfered with the natural process of deposition;*
- ❏ *the relatively shallow waters of the North Sea result in the tide forming a special sort of wave which causes complex tidal patterns; and*
- ❏ *storm surges may coincide with high tides to cause abnormally high water levels in the North Sea.*

> *It is this interaction of the tide and storm surges that is the crucial factor in determining extreme water levels and the potential for flooding. Surges that occur at or near a neap tide are unlikely to cause dangerously high sea levels, but at or near a high spring tide even a modest surge can cause flooding. The greatest danger is when a large storm surge coincides with the time of high water during an abnormally high tide, although there is a tendency for the maximum surge to occur about four hours after high water. The east coast of England experiences an average of 19 storm surges over 0.6 m above 'normal' tide height each winter. The west coast has a similar frequency of surges and the south coast fewer. Severe wave action can add considerable height to water levels and can also contribute to the damage through battering. It can be a crucial factor in the breaching or overtopping of sea defences."*

Tables 4.10 and 4.11 show the history of major floods before and after 1953.

Table 4.10 Major floods since the start of historical records

Year	Estimated effects of flooding
1362	Up to 30 000 people lost their lives across northern Europe and many parishes disappeared
1570	Up to 400 000 lost their lives across Europe
1634	Up to 6000 people lost their lives and land loss was similar to 1362
1703	About 8000 people died across Britain and the storm surge caused extensive flooding
1717	Up to 11 000 people lost their lives across Europe
1953	In eastern England 300 people drowned, 65 000 ha of farming land were flooded, 24 000 houses were flooded and 200 major industrial premises were inundated, cost about £900m
1990	In north Wales 2800 homes were inundated and 5000 people were evacuated

Table 4.11 Less destructive floods since 1953[3]

Date	Effects of flooding
January 1976	Port of Hull flooded, tides and waves breached sea defences at a number of points along the east coast of England, with large area of Norfolk under water
January 1978	Still water levels higher than in 1953, some areas suffered worse floods in 25 years
February 1983	Hull dry docks gates collapsed under weight of water. Walcott, Scarborough, Filey and Whitby suffered flooding
October 1996	Tide levels rose to the highest in a decade, the closing of the Thames Barrier prevented flooding in London

From Environment Agency, 1999

Range of East Coast Flood scenarios

The insurance industry has made some damage predictions for a flood disaster along the east and south coasts of England. The results of this research have not been made public, but five different scenarios were produced, at least one of which had worse implications than the 1953 event. A storm surge might occur when heavy rainfall had already swollen rivers, and be superimposed on spring tides with a higher predicted range and a peak coinciding more precisely with the predicted time of high water. Wind might have the effect of increasing the wave action on the open coast. Fiercer storms associated with climate change and higher surge levels could add extensively to the 1953 scenario in terms of the area affected. It is important to note that this type of coastal flood is not like a river in flood filling up a low lying area. Instead, a wall of water moving at speed in the form of a density current as in a dam break might occur and produce rapid inundation. The implications of this dam break analogue for the study of flood impacts will be discussed below under risk scenario development.

4.6.5 Flood characteristics

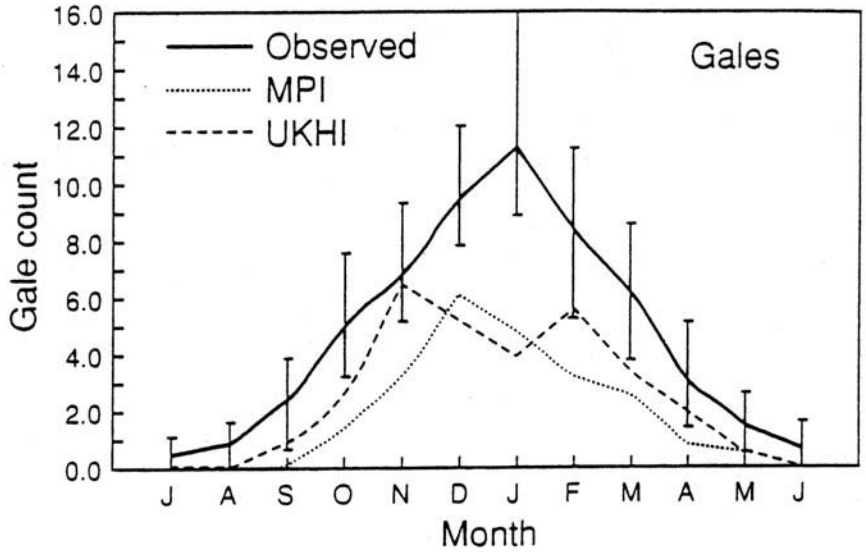
One element in the assessment of future coastal flooding risk, and its implications for human health, is to assess the likely ‘goodness of fit’ of the predictions outlined above to actual flooding events; to understand why there might be a mismatch between prediction and reality; and thus to identify future areas of research for the better understanding of coastal flooding. This requires both a) an identification of the additional factors involved beyond large-scale ocean-atmosphere modelling (and ultimately how these factors might be incorporated into improved numerical models) and b) a study of the historical archive on forcing factors and flood characteristics to give clues to the understanding of future events.

To simulate a reasonable global scale atmosphere or oceanic circulation, relatively coarse resolution numerical models are sufficient; good reproducibility between different models is apparent. However, at the regional scale of interest, the key forcing functions are found at sub grid-cell levels and these have proved difficult to model satisfactorily.

Where specific attempts have been made to evaluate the ability of models to reproduce realistic weather patterns the results have not been encouraging. Thus, for example, Hulme *et al.*,[4] have shown that two General Circulation Model experiments (UKHI and ECHAM/MPI) underestimate the number of gales over the British Isles by approximately 50%. Furthermore, while the ECHAM model simulates the correct form of the annual cycle, the UKHI model greatly underestimates December-January frequencies and thus produces a bimodal distribution (Figure 4.17). Spatial impacts have been similarly difficult to assess satisfactorily. The majority of large-scale models fail to specify even crude presence/absence coastal configurations. Operational storm surge models, such as those operated through the Proudman Oceanographic Laboratory, take account of shallow water bathymetry to some degree and have been used to model specific events (e.g. Flather's, 1984 modelling of the 1953 storm surge[5]). However, there is a need to further evaluate the effect of different coastal configurations (estuaries, barrier islands, open coasts) on flooding levels. Coupled wave-tide-surge models are beginning to be developed but these also need to be evaluated across a range of estuarine configurations. One aspect of such interactions is the potential interaction of wave-tide-surge effects with enhanced river flows under the severe cyclonic conditions associated with surge events[6].

Figure 4.17

Observed and model-simulated mean monthly frequencies of gales over the British Isles (range bars = range in 10 year averages from 100 year observed record)[4]



There has been considerable interest over the last decade in trying to prove or disprove a perceived increase in the long-term storminess in the North Atlantic Ocean and the possibility that such an increase might be linked to global warming changes due to atmospheric carbon dioxide concentrations. Much of this work has focused on using records of wave climate to infer changing storm frequencies. Unfortunately, however, most of these records are short (of less than 30 years' duration) which makes confirmation of long-term changes difficult and, at one further step removed, assessments of whether or not storm forcing is changing under greenhouse gas-induced atmospheric warming next to impossible. Nevertheless, several studies have indicated linear trends in significant wave height in the North Atlantic[7], although individual analyses are not always in agreement[8,9,10]. Evaluations of longer-term marine climate change are generally based on windspeed records from coastal and/or weather ship stations. These records tend to be of longer but still limited duration (40-50 years); furthermore such records vary greatly in quality over time. Thus, for example, the analysis of historical weather maps for severe storms (core pressure <990 hPa) suggested a substantial increase in the number of such storms in the North Atlantic 1930-1990[11]. However, analyses of windspeed records from coastal stations in the German Bight 1870-1990 have revealed no such increase (Figures 4.18a&b[12]), suggesting that differences may be more apparent than real and represent the increasing quality of environmental monitoring. This example also illustrates the point that trends in meteorological variables tend to average closer to zero given a longer averaging period[13]. More recent analyses for the whole of the NE Atlantic suggest a small increase in storminess over the last two to three decades, albeit tempered by the overwhelming signal of inter-annual and decadal variability[14] and the finding that different analytical methods give different results[15]. A better alternative methodology to both the wave height and station windspeed approaches, however, is to use longer tide gauge records (e.g. Newlyn, Cornwall: >80 years) to reveal, when de-trended for long-term sea level change, storm surge characteristics over time[16].

Figure 4.18a

Windspeed records from coastal stations in the German Bight[11]

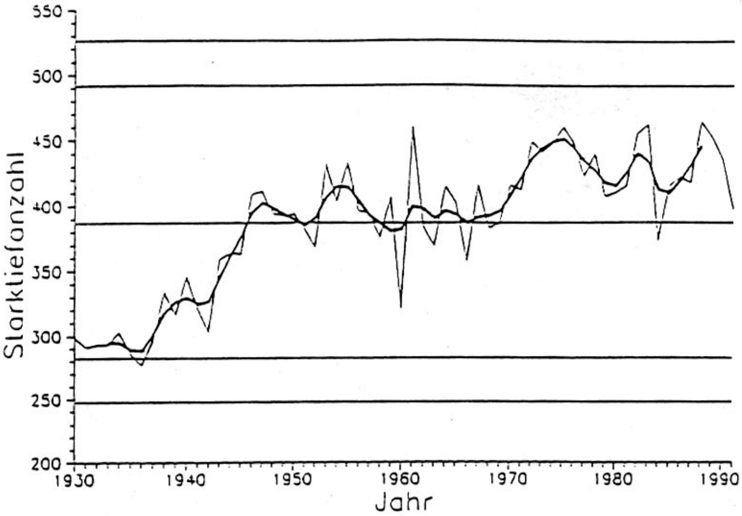
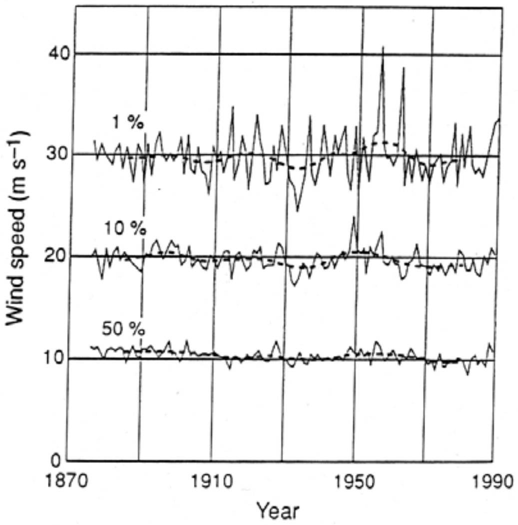


Figure 4.18b

Time series of 1, 10 and 50% exceedence percentiles derived from annual distributions of daily geostrophic windspeeds in the German Bight[12]



Astronomically predicted tidal water levels around the UK coastline differ from recorded water levels as a result of meteorological influences. The suction created by low atmospheric pressure and the effect of long duration, unidirectional high wind stress causes actual water levels to exceed predicted levels during storm surge events. Such events can therefore be seen as residuals from expected tidal heights on a tide-by-tide basis. Distributions of surge elevations in what might be termed 'fairweather' conditions are normally distributed, whereas years of extreme surge activity are typically positively-skewed (Figure 4.19).

Extreme surge activity - the number of days in a year in which at least one hourly surge value exceeded the highest 1% value of all surges on the record - is shown for Newlyn, Cornwall, in Figure 4.20. These statistics, when allied to extreme tide elevations, can be used to identify variations in the annual frequency of extreme flooding events (Figure 4.21). Particularly interesting is the Orford *et al.* (1996)[16] construction of the temporal variability of surge generation (Figure 4.22). The five-year moving average identifies reduced surge activity in the mid-1930s and the late 1950s. Turning positions are identified as 1931 and 1970, suggesting the possibility of a decreasing surge potential in the 1980s and 1990s.

Figure 4.19

Surge distribution in fairweather and cyclone active years[16]

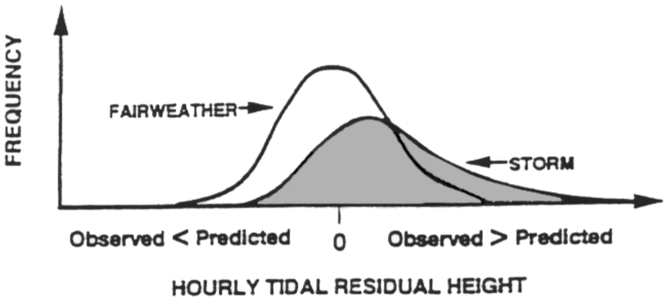


Figure 4.20

Variation in annual frequency of extreme surges (<1%) at Newlyn, Cornwall, 1912-1992. Includes a 5-year running mean[16]

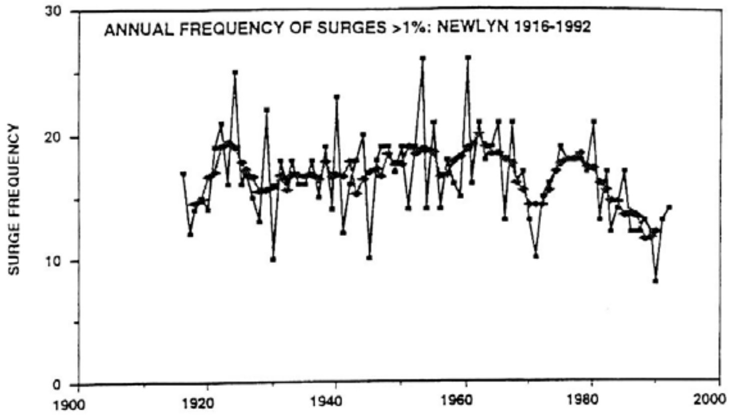


Figure 4.21

Variation in annual joint occurrence of extreme tidal elevation surge levels at Newlyn, Cornwall, 1912-1992. Includes 5-year running mean[16]

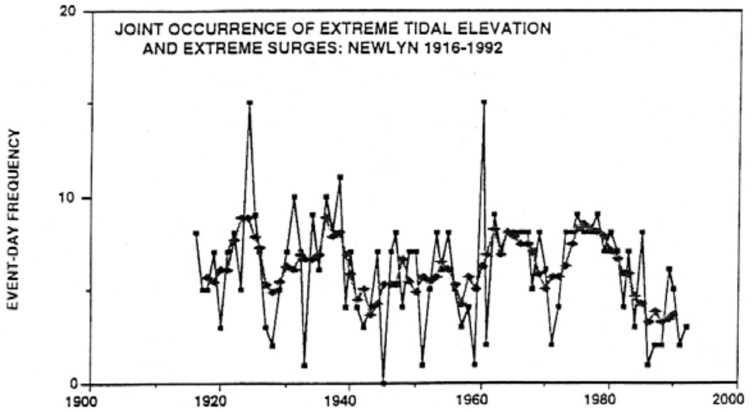
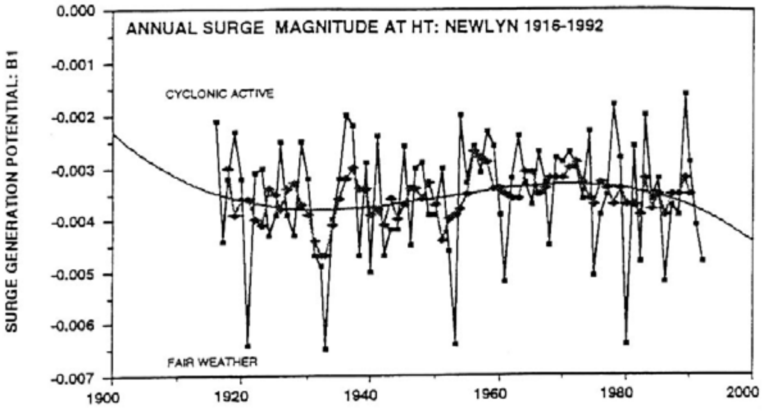


Figure 4.22

Variation in annual surge generation at high tide, Newlyn, Cornwall, 1916-1992. Includes 5-year running mean[16]



As the effect of wind stress is inversely proportional to water depth, these effects are particularly pronounced on the margins of shallow shelf seas like the North Sea. Thus standard deviations of non-meteorological residuals are high at southern North Sea stations (e.g. Southend, Essex: 0.23 m) compared to Atlantic coasts stations (e.g. Newlyn, Cornwall: 0.15 m). As long time series of water level data are available from North Shields (77 complete years), Southend (44 years) and Sheerness (51 years)[17], this form of analysis might be profitably applied to tide gauge datasets from the southern North Sea.

In the North Sea, storm surges are either forced by the passage of extratropical storms across the northern entrance ('external surges') or result from the passage of strong cyclonic systems across the North Sea itself ('internal surges'). Surge elevations with 50-year return periods range from +0.7 m in the northern North Sea to +4.0 m in the German Bight[5,18]. In January 1953, January 1978 and January 1995, water levels typically exceeded predicted tidal levels by 2.4 m, 1.6 m and 1.4 m respectively. Analysis of observed tidal records shows that surge events are common during the winter months in the southern North Sea. Thus, for example over a 4.5 month period during the 1994/1995 winter 18 surge events of 0.5 m or more were recorded at Thornham, North Norfolk. It is, however, the large events which exceed the level of the Highest Astronomical Tide (e.g. 4.0m O.D. at Brancaster, North Norfolk) and which threaten coastal defence lines which attract attention. Suthons (1963)[19] lists the occurrence of 15 storm surges on the east and south coasts since 1883. There is also some suggestion that the frequency of surges has been increasing. Thus at King's Lynn, R. Jenkins (in Steers *et al.*,[20]) has shown from an analysis of annual tidal maxima since 1860 that there were five years in which tides exceeded 4.98 m O.D. in the period 1860-1948 (89 years) and six in the period 1949-1978 (30 years). By way of illustration, Table 4.12 gives a selective record of storm surge heights for which detailed height information is known on the North Norfolk coast between 1897 and 1996. In addition, major North Sea surges are known to have occurred in July 1817 and on 8 January 1949, 20-21 March 1961, 15-17 February 1962 and 19 February 1969.

Maximum levels of inundation have increased over the last 190 years as a result of the long-term geological subsidence of S.E. England (Figure 4.23)[21]. Over the last 8750 years, the rate of submergence has been 0.76 +/- 0.16mm per year, with mean rates in the Thames estuary varying between 0.83 and 1.42mm a-1 over the last 7500 years[22]. Records of sea level rise during this century are reported in Table 4.13. Global warming is expected to add an additional eustatic sea level rise term to these long-term trends and it has been argued that this increase might be particularly significant in the North Atlantic. However, a composite 'relative sea level index' has shown no century-scale acceleration in Mean Sea Level (Figure 4.24). This is in line with earlier predictions that a sea level acceleration might not be detected until 2010 (Figure 4.25)[23]. As sea level rise estimates have been revised downwards in recent years (Figure 4.26), then this 'early warning' might not be detected until even further into the twenty first century.

Figure 4.23

Storm surge levels at London Bridge 1780-1970 and defence levels prior to construction of the Thames Barrier[21]

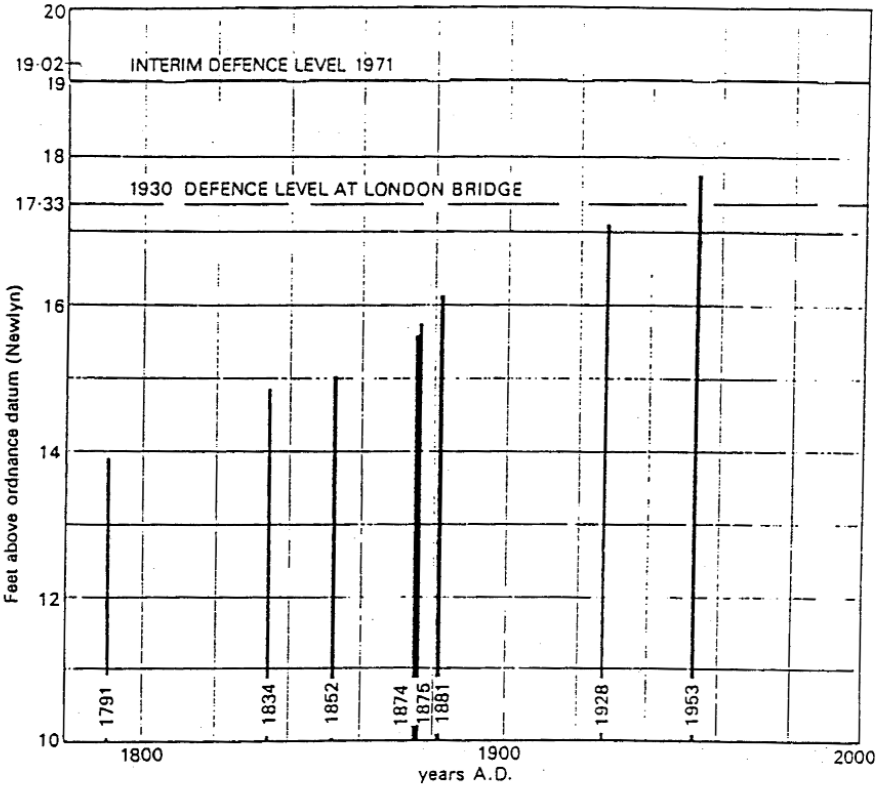


Figure 4.24

Detrended, composite sea level index for the twentieth century computed from Mean Sea Level data from 5 stations (Aberdeen, North Shields, Sheerness, Newlyn and Liverpool)[23]

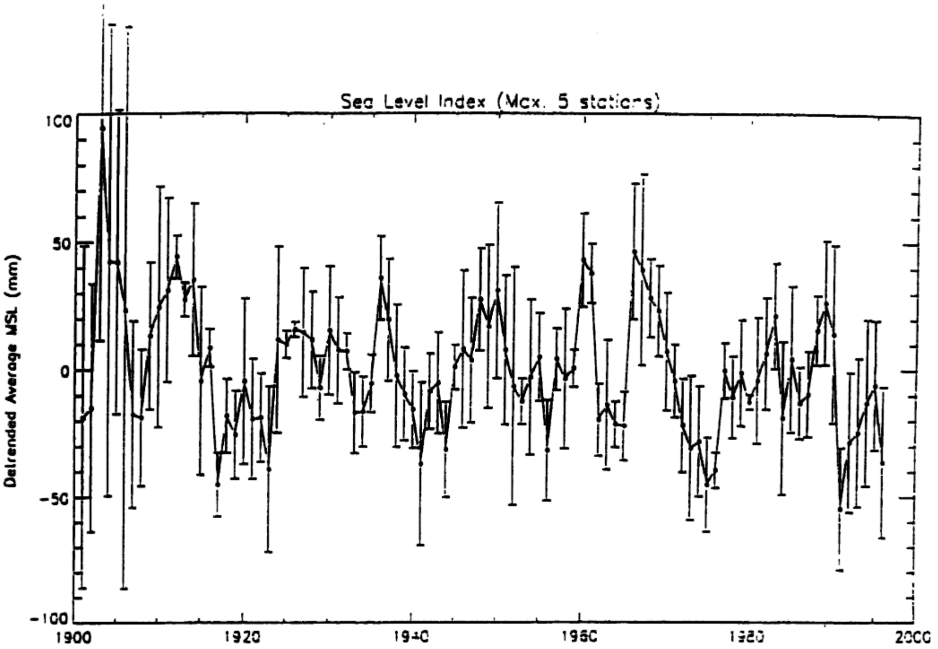


Figure 4.25

Simulated mean sea level time series based on perceived rates of near-future sea-level rise in the second half of the 1980s. Dotted line describes linear trend of 1.72 mm a^{-1} [23]

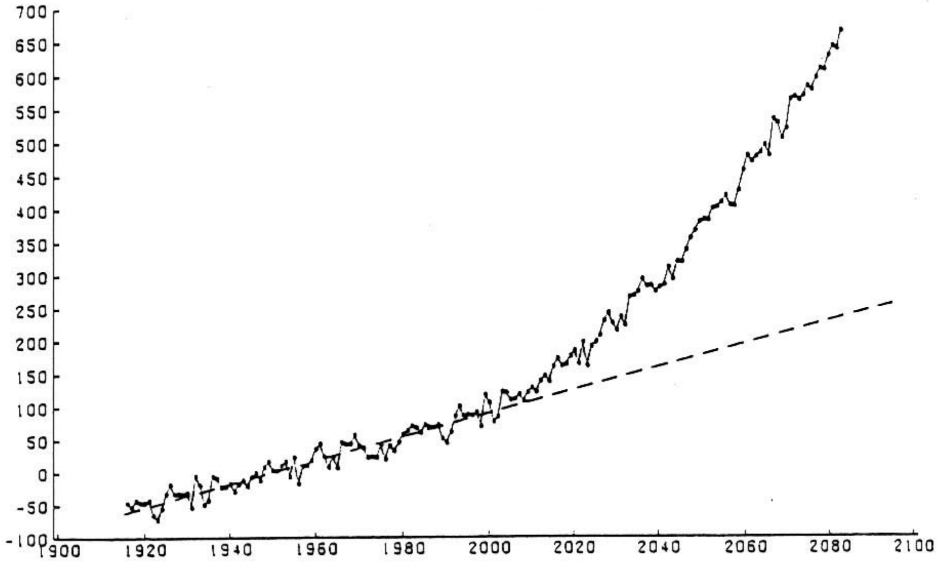


Figure 4.26

A history of sea level change predictions[38]

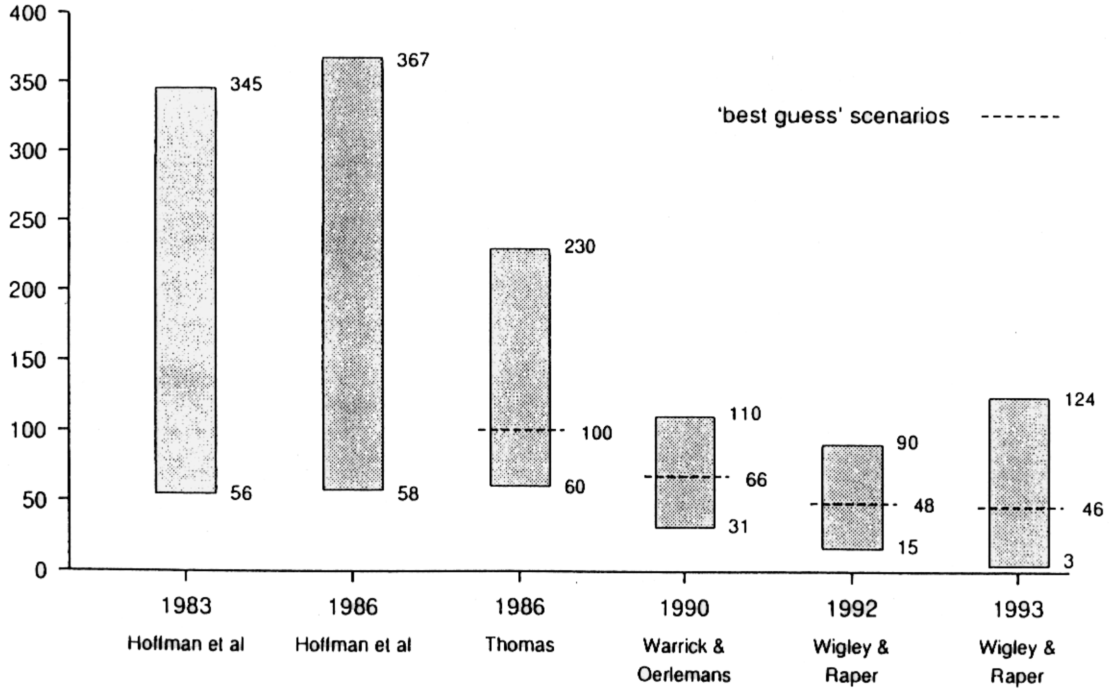


Table 4.12 Storm surges on the North Norfolk coast from published records and field surveys (compliled by the Cambridge Coastal Research Unit)

Location	Recorded water levels (m above Ordnance Datum)								
	1897	**1912**	**1953**	**1969**	**1976**	**1978**	**1990**	**1993**	**1995**
Blakeney	4.96		4.88–4.27						
Blakeney Quay			6.07			4.90			4.66
Stiffkey		4.66	4.57			5.55			4.45
Wells			5.13	4.27	4.55–4.66	4.91			
Burnham Overy			5.49			5.51	4.67–4.10		4.54
Burnham Deepdale				4.43	4.35	4.62	4.55–4.37		4.55
Scolt Head Island			5.37			5.22–4.71		4.45	4.61

Table 4.13 Historical trends in Mean Sea Level (MSL) in the British Isles[17]

PSMSL country station code	GLOSS code	No. of complete years of RLR data	First-last year in RLR data-span	Measured trend and standard error on the trend (mm yr^{-1})	Standard deviation of the annual mean values about the fitted linear trend (mm)	Station name
170/001	236	35	1957–1996	-1.09 ± 0.40	27.9	Lerwick
170/005		25	1965–1994	0.76 ± 0.75	33.3	Wick
170/011		48	1932–1996	0.67 ± 0.20	25.9	Aberdeen I
170/012		64	1901–1965	0.93 ± 0.18	27.4	Aberdeen II
170/027		27	1964–1993	1.99 ± 0.92	41.1	Rosyth
170/041		37	1914–1950	0.47 ± 0.31	20.5	Dunbar
170/053		77	1901–1996	1.86 ± 0.15	33.5	North Shields
170/061		33	1960–1995	1.11 ± 0.52	31.2	Immingham
170/068		36	1956–1995	1.81 ± 0.48	32.5	Lowestoft
170/081		44	1933–1983	1.22 ± 0.24	24.1	Southend
170/083		22	1961–1983	1.58 ± 0.91	28.5	Tilbury
170/101		51	1901–1996	2.14 ± 0.15	34.5	Sheerness
170/111		27	1961–1993	1.94 ± 0.50	25.3	Dover
170/131		28	1962–1996	1.45 ± 0.60	32.0	Portsmouth
170/157		30	1962–1996	3.04 ± 1.01	57.1	Devonport
170/161	241	80	1916–1996	1.69 ± 0.12	25.6	Newlyn
170/191		42	1938–1996	2.12 ± 0.45	45.1	Holyhead
170/211		19	1959–1983	2.58 ± 0.88	28.8	Liverpool Princes Pier
170/225		24	1962–1996	1.04 ± 0.62	33.5	Heysham
170/231		31	1938–1977	0.26 ± 0.70	39.6	Douglas
170/236		25	1968–1995	0.91 ± 0.61	24.7	Portpatrick
170/272		45	1918–1963	-0.25 ± 0.34	30.5	Belfast 2
175/011	239	26	1959–1994	-0.58 ± 0.68	34.8	Malin Head
175/071		58	1938–1996	0.23 ± 0.30	38.3	Dublin

4.6.6 Coastal management issues

Current responsibility for the maintenance of sea defences

In England, the responsibility for flood and coastal defence policy lies with the Ministry of Agriculture, Fisheries and Food (MAFF). This includes the administration of legislation, which enables flood and coastal defence works to be carried out. The legislative framework is based on the Coast Protection Act of 1949, the Land Drainage Acts of 1991 and 1994, and the Environment Act of 1995. The Coast Protection Act was created for the protection of the coastline against erosion from the sea, whilst the Lane Drainage Acts, the Water Resources Act and the Environment Act provide the political framework for flood defence. MAFF provides national strategic guidance and specialist help supported by a comprehensive research and development programme[24]. A variety of authorities have powers for the implementation of flood and coastal defence policy and the construction of defence works. These include local authorities, Internal Drainage Boards, private landowners, and the Environment Agency. The Environment Agency has a supervisory role for all aspects of flood defence in England and Wales, including flooding from the sea. The Agency also has permissive powers for establishing and maintaining sea defence works and flood defence works on watercourses designated as main rivers. The work of the Agency is discharged through a national network of Regional and Local Flood Defence Committees. Over 240 organisations have been involved in the administration, financing and delivery in the coastal zone[24]. Whilst individual flood and coastal defence works are designed, constructed and maintained by local operating authorities, MAFF may provide a substantial contribution to the funding of capital defence works undertaken by the Environment Agency, local authorities or drainage boards.

According to the Agricultural Select Committee report on Flood and Coastal Defence[25], there are significant gaps in the delivery of national policy priorities at the local level. This is due to the disparate legislative framework for flood and coastal defence activities, and the patchy and inadequate coordination between operating authorities. This problem is now being addressed through coastal groups and the development of shoreline management plans. Such changes in the organisation of responsibilities will need to be taken into account in future coastal flooding risk analyses.

The nature and the current state of the sea defences

Due to the varied nature of the East Anglian coastline and the division of coastal protection and flood defence responsibilities, there exists a wide range of sea defence solutions. Over one-fifth of the region between the Humber and the Thames is below flood risk level[26]. Approximately 1500 km of defences protect the region from tidal flooding. In agricultural and sparsely populated areas of South Humberside, Lincolnshire and parts of Norfolk and Suffolk, flood protection is generally provided by earth and stone banks, some of which have some form of seaward slope protection[27]. In low-lying, more populated areas with appreciable wave action, the sea defences include concrete stepwork or concrete slabs on the seaward side of the bank, topped by a splash wall, which, by wave reflection, reduces overtopping of the structure. The Wash defences consist of banks fronted by extensive saltings, which under most conditions act to break the waves long before they reach the structure. Reinforced concrete sea walls and associated groyne systems protect urban areas. Most cliffed sections of the coast where there is development are protected with sea walls and revetments. In some cases flood protection is provided by the maintenance or enhancement of natural features, such as the profiling of the shingle bank at Blakeney in Norfolk. Beach nourishment has also been done in several places along the East Coast. Most recently, shore-parallel breakwaters have been constructed near Sea Palling and Caister in Norfolk.

The risk of flood damage to property, infrastructure, and human health will depend to a large extent on the state of the sea defence systems in any given location. While major reinforcement and extension of the sea defence infrastructure was undertaken along the East Coast after the devastating floods of 1953[26], many of these defences are reaching the end of their design life. In many parts of the East Coast, the defences are becoming increasingly vulnerable to wave damage due to a lowering of fronting beaches. Estuarine embankments have often been built of indigenous materials not suitable for sea walls, such a peat, silt and weakly structured clays[27]. A further problem with the construction of banks is the unconsolidated strata underlying the structures. Settlement is another common problem, leading to fissuring and attrition on the side facing the water[27]. The national Sea Defence 1995 Survey Update, dealing with the condition of sea defences, [24] revealed that in the Anglian Region, 36.3% (Phase 1; NRA maintained defences); 41.9% (Phase 2); Local Authority maintained defences); and just 3.4% (Phase 3); privately owned defence) sea defences were in good condition. The survey also showed that 12.2% (Phase 1) and 64.9% (Phase 3) sea defences in the Anglian region were in poor condition (i.e. that moderate work and maintenance is required to return the defences to a good condition as originally built). A flood risk assessment that takes into account the state of the sea defences is now urgently needed and is necessary if the health risk from future storm surges is to be determined.

Present and likely future shoreline management planning approaches

Flood defence works carried out by the Environment Agency are funded by central taxation revenues through a combination of Capital Grants and Revenue Support Grants (through local councils). All coastal defence schemes have to be justified by cost-benefit analysis. Due to ever increasing demands from local authorities for grant-in-aid, a priority scoring system for sea defence schemes was introduced in April 1998[25]. Every project proposal is screened against national criteria to determine the order of priority in which eligible projects will be funded by MAFF. The scoring procedure is made on the basis of the priority, urgency and economics of the scheme proposed. In keeping with MAFF's national strategic aim, projects based on flood warning, the provision of urban coastal defences, and urban flood defences are given greatest priority. This system has been heavily criticised because it is extremely difficult for any rural scheme to qualify for funding. Sites of international environmental significance were given added weight under the revised priority scoring system in 1999. The Select Committee[25] found that at present there seems to be a shortage of finance for all but the most urgent of works and that operating authorities could maintain vital local flood and coastal defence programmes only with major difficulty. The Environment Agency has estimated that £1.3 billion will need to be spent on renovating sea and flood defence capital works over the next 10 years - this equates approximately to the current rate of spending. As a consequence of the downward movement of the East Anglian region relative to the UK land mass as a whole and the sea level rise caused by global warming, a relative sea level rise of 6mm per year is taken into account in the crest heights of flood defences when they are renewed or replaced.

While such upgrading of sea defences will have to be carried out in urban areas, alternative approaches are being sought for agricultural coastal areas. Greater priority has recently been given to so-called soft engineering approaches to flood and coastal defence. The mitigation of erosion and flooding is achieved through increased reliance on natural features, such as beaches, mudflats and flood plains. It has been recognised that the traditional hard engineering approach, based on substantial human intervention in the natural processes, often had adverse effects on the adjoining coastline, or on the site intended for protection itself, due to lack of understanding of the sediment transport mechanisms prevailing in the area. Soft engineering can replace reliance on the existing ageing system of hard defences, but in most cases it is used to provide protection to the defences already in place. For example, on the Lincolnshire coast MAFF is investing approximately £120 million over a 40-year period in the UK's largest beach nourishment project[25]. One of the most significant changes in coastal engineering in the last few years has been the introduction of offshore breakwaters. The use of offshore breakwaters is considered a soft engineering approach because the structures influence the wave-induced circulation near the coastline and encourage the accumulation of beach material. Whilst breakwaters have been successfully used in shoreline stabilisation efforts, particularly in the USA, Japan and the Middle East, the work at Bognor Regis[28] and Sea Palling[29] indicates that the effect of these structures on the beach morphology is not currently fully understood for locations with the large tidal range and strong long-store drift typical of much of the UK coastline. Further research is being carried out to establish design guidelines for UK schemes.

Since 1995, shoreline management practices in England and Wales have been guided by Shoreline Management Plans (SMPs) to provide a more comprehensive and integrated approach to managing the cost[24]. The primary aim of the SMP is to provide the framework for the development of sustainable coastal defence policy for a particular stretch of coastline. SMPs are currently non-statutory and are the product of collaboration in coastal groups between maritime local authorities, statutory agencies and other organisations with coastal responsibilities. SMPs have been produced for the entire English and Welsh coastlines and include environmental and other non-market considerations in order to achieve environmentally sustainable solutions. As well as taking account of local economic and development planning needs, the guidance offered in SMPs is based on processes occurring in coastal cells along the relevant section of coast. A recent review of the East Anglian SMPs[30], however, has revealed that there is still a substantial lack of knowledge regarding these processes and the way in which they interact with sea defence measures. Although the coastal cells on which these plans are based are assumed to be discrete natural units within which sand and shingle-sized sediment is retained, detailed information on sediment transport pathways, particularly of fine sediments, within or between the cells, is often lacking. To provide an adequate assessment of the risk of coastal flooding, and thus the risk of flooding to human health, it is necessary to qualify and, if possible, quantify the uncertainty introduced by this lack of information.

The three main options for shoreline management identified in the SMPs, are 'managed retreat', 'accommodation', and 'hold the line'. These options are currently being reassessed for the second round of plans.

Assessment of past, present, and possible future adaptation strategies

As mentioned above, coastal defence and management policy and responsibilities are changing and such changes need to be incorporated in any coastal flood risk assessment. O'Riordan and Ward[6] presented arguments in favour of a more participatory and mediated approach to consultation and decision-making. In their opinion, a more integrated approach to shoreline management will facilitate a workable consensus amongst the stakeholders and create an outcome which will be continually reassessed.

Traditionally, there was a widespread perception that we have a duty to prevent land loss. This perception is slowly changing because of increased agricultural productivity per hectare and a lessened need for domestic agricultural self-sufficiency[24]. These factors might in future be acknowledged in the implementation of local responses to flood defence and coastal protection of agricultural land, including the managed realignment of the coastline. Such changes in perception would, in turn, have important effects on the risk of coastal flooding. At present the managed abandonment of coastal areas, which are untenable in the long-term, is controversial because there is no financial mechanism for the reimbursement of property holders and landowners whose assets are sacrificed for the wider benefit of the community. Long-term adaptive policies that encourage managed retreat will have to be formulated. The Select Committee recommended that, in future, The Environment Agency should have powers to deter inappropriate development in flood plain land or require developers to set aside sufficient funds for the provision of flood defence works before planning permission is granted.

4.6.7 Vulnerability

Population at risk

The popularity of coastal districts has resulted in the steady increase in their populations at a time when the population of the country as a whole is relatively static. In 1995 the population of England and Wales was 51.8 million and it is projected to grow by 5% over the 40 year period to 2031. The number of people living within 10 km of the coast in England and Wales is about 16.9 million, or about a third of the population. Roughly 11.5 million people are estimated to live within 1 km of an estuary in Great Britain. East Anglia as a whole, and its coastal districts in particular, have been growing in population continuously since the 1951 census at a rate much faster than the national population. Table 4.14 shows the population changes between 1951 and 1991 in the seven most populous coastal districts in East Anglia (excluding the one manufacturing city, Ipswich), and the UK as a whole, confirming this trend over most of the coastal region.

Table 4.14 Population changes 1951 to 1991: UK and coastal districts

District	1951	1961	1971	1981	1991	% increase 1951-1991
UK ($\times 10^6$)	48.9	51.3	54.0	54.1	54.8	12
Great Yarmouth ($\times 10^3$)	68.9	72.6	75.7	80.8	87.7	27.2
North Norfolk	77.3	73.8	74.2	82.0	90.4	16.9
Broadland	55.3	65.9	86.5	98.3	106.2	92
Suffolk coastal	74.5	82.9	89.1	95.2	107.8	44.7
Waveney	74.6	77.8	90.6	99.2	106.6	42.8
Colchester	85.5	93.8	118.1	133.7	142.4	66.5
Maldon	28.6	31.0	40.5	47.7	52.7	84.2

It can be seen that in many parts of East Anglia the increase in population in coastal areas has been substantial. It is not evident that this has been strongly guided by considerations of flood risk and the insurance industry (D Crichton, *pers comm*) has observed, for example, that development goes ahead in about a third of cases where the Environment Agency has objected.

Building vulnerability

The vulnerability of buildings and their occupants to flood depends primarily on the height of the flood water in relation to the floor level of the house. Flood damage is worse if the water is fast flowing and if the flood water is sea water. Vulnerability estimates have been made for the UK building stock[31].

An important consideration affecting the likely number of casualties is that occupants of single-storey houses and mobile homes are much more likely to suffer loss and injury or death because they cannot escape or move their property to upper floors. Buildings built on piers to elevate them above expected flood water would be safer for the expected flood, but may be more vulnerable than conventionally founded buildings if higher flood waters occur. Census data unfortunately provide little information on building types. Estimates have been made by Cambridge Architectural Research Ltd based on regional data available on the distribution of building types in an English house condition survey (1991). This suggests that a proportion of more vulnerable building types - namely bungalows and mobile homes - in these coastal districts may be substantially greater than the average in the population as a whole. Regionally, East Anglia has 16.6% of bungalows in its urban dwelling stock compared with 6.9% for the south-east. It is not clear whether this proportion is changing with time or how far it applies to rural buildings also. In the East Coast floods in 1953, 65 deaths occurred when most of the bungalows between Hunstanton and King's Lynn were swept away[2].

Sea coast defences

Although sea defences have been improved since 1953, sea-level rise and the expected greater frequency and severity of wind storms resulting from climate change will ensure that a high risk of catastrophic flooding remains in the coastal zone. In addition, many of the sea defences established after 1953 are now reaching the end of their design lives. Concern about the present flood and coastal defence infrastructure has been expressed by the House of Commons Select Committee on Agriculture in its Sixth Report (1998), which states[25]:

> *"... Flood and coastal defence policy cannot be sustained in the long-term if it continues to be founded on the practice of substantial human intervention in the natural processes of flooding and erosion. Indeed, it is of great concern to us that the legacy of flooding and erosional problems arising from this practice - and the likely increase in future of climatological and other environmental pressures on the UK's ageing flood and coastal defence infrastructure - might combine to present flood and coastal defence authorities with insuperable difficulties."*

Many of the ageing defences are being replace using alternative, 'soft', engineering schemes (for example, beach re-charge or managed re-alignment). Very little is known about how these changes in coastal management affect natural processes in the coastal zone and thus how they affect the characteristics of possible future extreme flooding events.

The Environment Agency[3] designs coastal defences to protect against a storm with a specified risk of recurrence, which is cost-effective and commensurate with current land use. Generally, there is greater protection for urban areas than rural areas (Table 4.15).

Table 4.15 Indicative standards of protection against tidal flooding for grant-aided schemes[32]

Current land use	Return period (years)	Annual probability of failure
High density urban containing significant amount of both residential and non-residential property	100–300	0.3%–1%
Medium-density urban. Lower density than above, may also include some agricultural land	50–200	0.5%–2%
Low-density or rural communities with limited number of properties at risk. Highly productive agricultural land	10–100	1%–10%
General arable farming with isolated properties. Medium productivity agricultural land	2.5–20	5%–40%
Predominantly extensive grass with very few properties at risk. Low productivity agricultural land	<5	>20%

It can be seen from Table 4.15 that maximum protection is afforded by defences anticipated to resist a flood with a return period of 300 years although provision is made for the consideration of higher standards where appropriate. The 1953 flood was estimated to be a 1 in 500 year event (as can be best determined) and it would be important to ascertain what would happen to these defences in a return 1953 event. In 1976 very similar sea levels recurred but there was no flood. The defences held, confirming the engineers' belief in the security provided by the defences. Decision-making processes, including cost-benefit analysis, may lead to the establishment of standards that may be more or less demanding than the indicative standards of protection shown in Table 4.5. Risks to life are not routinely included in the assessment on the grounds that flood warning systems should provide protection. In the Netherlands, where 60% of the national wealth depends on defences against inundation, risks to life are taken into account.

A special example in the UK is the Thames Barrier, owned and maintained by the Environment Agency, which was completed in 1982 at a cost of £600 million. It costs £4 million a year to operate and protects over a million housing equivalents. It was designed to contain a 1 in 1000-year flood event. The barrier has been closed 30 times in the 15 years from 1982 to 1997. The barrier is closed whenever sea levels are forecast to rise to within 450 mm of defences in central London. With current projections of sea-level rise, forecasts show that there will be ten barrier closures per year by the early part of this century and with current operating rules this could increase to 325 barrier closures per year by 2100[3] . Estimated probabilities of flooding in east London from a failure of the Thames Barrier are regarded as 'tolerable' when the risks of between 100 and 1000 casualties is less than 1 in 1000[33]. Individual risk for people living in the likely area of inundation is less than 1 in a million. The consequences to human health of a 1 in 1000-year flood overwhelming coastal defences do not appear to have been calculated.

Infrastructure

Studies of flood and storm surge casualties in other countries indicate that the failure of power, the performance of the transportation infrastructure, and the maintenance of relief and rescue facilities are critical to minimising casualties and dealing with injuries. For the most at-risk coastal locations, detailed studies are needed of the infrastructure (roads, railways, airports, power transmission, telecommunications) and its propensity to be damaged, of the risk to emergency services (fire brigade, ambulance, A & E departments in hospitals, police) and their location and viability, and the existence of places of safety within each local community. It is not generally appreciated that the east coast floods in 1953 occurred against a backdrop of post-war Britain, when there were 500,000 servicemen available for rescue work, together with military logistic tools such as landing craft, which were immediately put into the disaster response and would have undoubtedly made a large impact on the rescue capability of that time. None of this would be available in the present day and it is not evident that the emergency services have drawn up emergency plans for responding to a catastrophic coastal flood. Current initiatives by the Environment Agency are encouraging the development of such emergency plans by all potentially affected local authorities.

Forecasts and warnings

Coastal high water levels are predicted by a model used by the Met Office in Bracknell, which has been constantly updated since it was first devised following the floods in 1953. The predictions for East Anglia are normally very good and well validated to within 10-20 mm. The model was devised and is updated by the Proudman Oceanographic Laboratory. The Environment Agency has for the last three years been the central government body responsible for issuing warnings based upon its use. The Agency goes into flood warning mode from September to May, when wide-scale forecasting is performed every 6 hours. The model can also be used to model synthetic sea levels for exceedence levels for sea coast defences. The model does not take into account changes in sea level and increases in storminess caused by climate change. Local models exist, for example for the Thames Barrier, which include river flows. Commensurate with developments in forecasts and warnings would be the designation of risk zones for populations depending upon their susceptibility to flooding - the hazard maps on which such zones could be drawn by the Environment Agency will soon be available to the public.

Community preparedness

The extent to which most communities at risk are aware of the flooding hazard (through for example, warning sources such as radio or TV), and are knowledgeable about evacuation measures is limited. The Environment Agency launched a new awareness campaign in October 1999. A special study would be needed for the risk assessment on the details of operation of the warning system, including lead times and criteria for evacuation of areas at risk. Details of flood warning plans for each area are available from the Environment Agency.

4.6.8 Human health consequences of floods

Floods and health

The impact of a coastal flooding event will depend upon the behaviour of the flow of water, its velocity and depth. In addition, wintry weather will greatly increase the risk of deaths from exposure. After the East Coast floods there was a reported increase in mortality in the flooded community in the three months and the year after the flood[1,2]. In the Netherlands flood of 1 February 1953, resulting from the breach of a polder, extensive areas of the country were affected and 1795 people died, mainly by drowning. Six medical problems were identified after the flood:

- ❑ identifying and recovering corpses;
- ❑ evacuating the sick and old;
- ❑ providing physicians with routine supplies;
- ❑ setting up emergency hospitals to take care of the evacuated;
- ❑ restoring hygienic services (food, water, sanitation); and
- ❑ taking measures to fight epidemics.

It was explicitly stated that the injured, as a group, did not represent a medical problem. The age and sex specific mortality of those killed in the flood was estimated and a three- to four-fold greater risk of death in the elderly was found[34,35].

In the Bristol, England, flood on 10/11 July 1968, 13 cm of rain fell on the city of Bristol between 5 am and 5 pm. About 3000 houses, shops and other buildings were flooded. The peak of the rainfall coincided with a high spring tide, which blocked the outflow into the river Avon. The water level reached no higher than the ceilings of the ground floor and subsided in most cases after about 10 hours. One man was drowned in the flood. Of great interest is the effect this event appears to have had on subsequent mortality and morbidity[34,35]. In the 12-month period after the flood the surgery attendance of the flooded population for whom records were available increased by 53% (males 81%, females 25%), although the total number of people attending did not change substantially - the non-flooded group showed a slight fall in attendance. The difference between the attendance of flooded and non-flooded men was statistically significant, as was the difference in attendance within the flooded group for the period before and after the flood. The increase in attendance by women was not significant. Hospital referrals from the flooded group more than doubled during the year after the flood. This was again accounted for mainly by men. Hospital admissions showed the same trend. The reasons for illness were non-specific and no diagnosis suggested any direct physical relationship with the flood.

Mortality rates were also calculated for all homes in the city and in the county of Bristol which had been flooded, as well as those which had not been flooded. Surprisingly, mortality in the flooded group increased by 50%, mainly in the three-month period after the flood. The most pronounced rise was in the age group 45-64, for both male and female deaths, otherwise the increases were predominantly amongst those over 65, especially women over age 75. For the rest of non-flooded Bristol deaths fell by 1%. Again no specific cause of death could be linked to the flooding and the increase was provisionally explained in terms of the psychological effects of the flooding. A similar pattern to mortality was observed in Canvey Island after the floods in 1953[2,3]. Remarkably, this type of analysis does not appear to have been repeated in subsequent flood events.

On a world scale, floods present a major natural hazard[34,36]. For example, in flood-prone Bangladesh, approximately 15 000 people are killed each year on average due to flood disasters. Among all natural disasters in the USA, floods are the main cause of death. Two thirds of the 6000 disastrous events on record in the 1990s relate to floods and flood-generating storms. In the USA, with more than 20 000 cities and communities subject to flash flooding alone, the average annual loss of life due to floods has been estimated at between 48 and 146 deaths. Notable floods occur in the People's Republic of China where more than 40 million inhabitants are estimated to be affected yearly by flood. Malilay[37] has reviewed the literature, which shows continuing differential levels of mortality associated with individual flood events in various areas of the world, and more investigation is needed of the factors that contribute to flood-related deaths, illnesses and injuries. Surprisingly little information has been gathered that provides the level of insight given by the studies of the East Coast flood in 1953 and the Bristol flood in 1968. In most events, however, the spectre of major epidemics of infectious diseases due to disruption of water purification and waste-water disposal systems does not appear to be realised through increases in endemic diseases such as malaria and cholera in tropical areas. Large numbers of casualties with multiple injuries also do not seem to be a major problem. Releases of toxic substances in floods from hazardous chemical sites is a potential hazard. The mental health effects of flood disasters have been studied, but more work on the long-term impacts on morbidity and mortality are warranted.

In summary, the main anticipated impact on humans of an East Coast flood would be deaths by drowning, followed by deaths from exposure, which would occur in the phase of the disaster striking. Some deaths would arise subsequently from delays in search and rescue, which would be inevitable with a large part of the country under water. Large numbers of injured requiring rapid transfer do not appear to be an issue for the emergency services, though this may be a false impression created by the delays in rescue in severe flooding events when access to survivors in the first few hours after the event is impossible (so trauma victims die from lack of urgent attention). Clearly, the time of day would be very important in terms of both the size of impact and access to survivors (flooding at night is much more hazardous). Further increases in mortality and morbidity amongst survivors would occur in those who require regular primary care treatment, such as access to insulin in diabetes sufferers, and other key maintenance medication in the chronic sick. For this sub-group of the population, including the elderly, expeditious removal from flooded areas to safe havens would be important. Provision of food and potable water and first aid to those large numbers of people trapped in the flooded area, but otherwise unharmed, would be an immediate need in the post-impact phase. Acute and longer-term mental health issues amongst survivors would need to be addressed, as after other major disasters. The long-term impacts on morbidity and mortality as revealed by the Bristol flood study and the reporting after the East Coast floods in 1953 show that illness and deaths may rise in non-specific ways. A 'culling' effect may be happening here, i.e. a hastening of death in those predisposed to die by underlying illness.

Risk scenarios

Hazard maps for coastal flooding are being used to produce risk maps delineating the population at risk. Refined versions of risks maps should utilise the hazard areas of flood impact, and should include zones of graduated risk of death and injury.

$$\text{Risk} = \text{hazard (probability of event)} \times \text{value} \times \text{vulnerability}$$

‘Value’ in this equation could be the number of people at risk, with ‘vulnerability’ as the proportion of the population at risk, or most exposed, for a variety of reasons, to the flood impact (Section 4.6.7). Establishing risk requires first of all an understanding of the most foreseeable flood scenarios. Some work on this is now in progress in the Environment Agency, with the aim of providing a standardised approach across the country. The worst scenario would be a flood in the absence of any coastal defences and the Agency has performed a mapping exercise based on how far the water would travel until the sea level equated with the land level. These so-called Indicative Flood Plain Maps have now been generally released. The maps will be essential for estimating the total population at risk for disaster planning purposes. For assessing the risk in a reasonably foreseeable flooding event a study of a dam break analogue with modelling of the consequent gravity current of water would be needed.

A reasonably foreseeable scenario for East Coast floods would be the breach of a section of the coastal defences, or possibly a small number of breaches, during a storm/tide event comparable to 1953. A breach could be for example, 50 m or 100 m wide, taking three days or 10 days respectively to repair. From the Humber to the Wash and around the Norfolk and Suffolk coasts the population is dependent upon a wall of sea defences of variable strength: a failure in an extreme weather event could lead to even a small breach which could have devastating consequences. The development of a flood scenario under these circumstances is possibly politically difficult for the Environment Agency and here research by independent workers would be invaluable in order to increase our understanding of the impacts such an event would have on settlements and human health.

4.6.9 Mitigation measures

A key factor in any analysis of risk is the extent to which society may take steps to protect itself against the impact of climate change. The implications of these for risk also need to be studied in depth. Specific areas for mitigation strategies are described below.

Forecasts and warnings

Forecasts and warnings of flood hazard to the population have been the responsibility of the Environment Agency for the last three years. The Storm Tide Forecasting Service (Met Office) predicts height of tides, taking account of surge activity, and the Environment Agency determines, in accordance with pre-set criteria, the threshold of a combination of tide, wind speed and wind direction which if exceeded would trigger a six-hour warning before high water. Warnings go out through various routes and emergency services are put on alert. Flood wardens alert those in the areas they are designated to cover. The warning service is tailored to particular circumstances and the degree of risk - warning systems range from individual telephone alerts to general radio announcements. Only certain high-risk areas with relatively frequent flooding have siren warning systems. Many thousands of other people live in areas where they are probably quite unaware that they could be impacted by a major coastal flood. The current indicative flood plan areas are based on combinations of historical records, computer modelling and expert judgement.

The decision to evacuate settlements would be taken by the Police Technical Group, responsible for major incident planning in conjunction with county and borough councils. The understanding of the population for disaster planning, and the feasibility of the measures to evacuate people from areas of risk, needs to be further evaluated.

Engineering measures

The sea defences are a combination of hard (concrete) and soft (e.g. sand dunes) 'barriers' (see above). The Environment Agency has compiled a directory of sea defences and it is possible that some parts may fall short of the indicative criteria laid down for them. Strengthening of the weakened parts of the defences is an ongoing process. Predicting sudden failure does not appear easy and so predictions may not be routinely performed. Repairs of the sea defences do take into account sea-level rise. The engineering issues involved in raising defences to combat rising sea levels needs to be further explored in terms of overall safety and risk, as well as cost. DEFRA provides funds for approved capital works which, nevertheless, are a local responsibility.

Further work is needed on whether hardening of houses in some way in those areas most at risk would be beneficial. Bungalows and trailers or caravans would be most at risk in a flood, as mentioned above.

Land use planning

Already, local planning departments give consent to about a third of the developments against the advice of the Environment Agency. The population increase in coastal districts over the last five decades has been between 50-100% and the trend seems likely to continue. This demographic change would be a key factor in any risk assessment. In the future the insurance industry might play a key part by refusing to provide cover to developments not recommended by the Environment Agency.

Community preparedness

Providing adequate public information on the flood risk is overdue. The Environment Agency ran a public awareness campaign in October 1999 and this was repeated in 2000 and may help to improve matters, but to date planning for flood emergency has been low key. For example, the health sector has not been drawn into a comprehensive disaster planning process. Emergency planning needs to be at the national, regional and local level with agreement on the worst reasonably foreseeable scenarios, as well as others which can be prepared for. The Environment Agency is required to operate a programme of flooding incident exercises with other operating authorities. Undoubtedly much more work on the vulnerability of housing and the delineation of flood risk areas has been undertaken in the private sector, e.g. by insurance companies, than is available to researchers outside the industry.

Probabilities of extreme flooding events

Natural hazards such as sea surges are subject to non-linear behaviour, but a recent study of extreme event statistics has concluded that the forecasting is still best done by a combination of probability statistics and numerical modelling based on the monitoring of past events (Julian Hunt, *pers comm*). The Health and Safety Executive has used the Thames Barrier example in its publications on quantified risk assessment and tolerability of risk[33]. Individual and societal risks have been estimated using the annual probability of it being overcome by a tidal surge (1:1000), as defined by its designed failure rate, and the population at risk of inundation should it fail. We may use the indicative criterion for the sea defences in the same way, but they are not, for probability purposes, a single structure. Thus, the probability of inundation *anywhere* along the sea defences will depend upon how well-correlated the impacts of a single surge event will be (i.e., whether all or only parts of the coast will be affected by the same event), and so it is likely that the annual risk of a group of people being drowned as a result of a breach somewhere along the defences will be potentially higher than 1:200. An important additional consideration is the weakened state of the present defences as described above, which may add to the risk. A key question in any discussion of probability is what would happen in a very large event (greater than 1:1000 for the Thames Barrier, or the 1:1000 event breaching the sea defences), when the loss of life could possibly be very large indeed. An increase in storminess would make failure more likely, especially if the types of storms change, by increasing wave and surge heights and damage to defences in an extreme event. The 1 in 200 criterion (at best) seems inadequate, especially when the Thames Barrier is engineered to a 1 in 1000 year event, and further review of this figure and its basis is needed for risk assessment purposes. These considerations do not appear to have been well debated in the public domain, but are essential for exploring the human consequences of floods.

The potential for mitigation in such a flooding event is high through further development of the warning system and community preparedness. Timely evacuation would be the key measure to reduce risk, but it is not evident that a detailed risk assessment and an analysis of risk reduction measures has been undertaken. The Environment Agency is doing important work on disaster planning, but this is not yet in the public domain.

4.6.10 Risk assessment: Summary of the direct and indirect impacts on human health to be considered

A risk assessment would need to be based on a 1953-type flood model. It would need to incorporate mitigation measures and use scenario modelling of a sea surge and a flow of water following a sudden breach of the sea defences. One or more study areas could be chosen to evaluate the impact of flooding in different types of urban areas. The probability of such an extreme event along the East Coast is stated to be 1 in 100 to 1 in 200 years, but this return period could decrease by an order of magnitude with the prospect of rising sea level and increased storminess. The following impacts would need to be evaluated further.

- ❏ Impact phase. Death by drowning and exposure. Potentially hundreds to several thousands of people in the event of a breach, or several breaches, of the sea defence wall.
- ❏ Immediate post impact phase. Deaths of injured or sick and aged individuals unable to obtain first aid, or primary care or treatment in hospital during the 'golden hours'. Perhaps as many as 10% of the overall mortality figure.
- ❏ Recovery phase. Subsequent increase in morbidity (hospital referrals and hospital admissions) and non-specific mortality in the flooded group in the months after.
- ❏ Recovery phase and subsequent mental health sequelae. Mental health problems are likely to be significant in survivors of a major event, but only a small proportion are likely to be severely affected by post-traumatic stress disorder or anxiety/depression as a result of the incident. Non-specific psychological syndromes may appear, but are unpredictable.
- ❏ Other causes of ill health. The risk of infections arising from floods in the UK appears to be quite low. Other hazards include the threat of toxic substances entering the flood water and adding to the health impact. Multiple disasters, e.g. floods causing train derailment, plane crashes at airports, chemical releases from factories in the line of the flood, will need to be considered as part of an overall risk assessment.

4.6.11 Conclusions and recommendations

Coastal and river flooding present some of the most serious natural hazards that the UK faces. This chapter has focused on East Coast flooding risk, which is undoubtedly the most hazardous extreme type of flooding event. The effects of global warming are likely to make the return time of such an event shorter and its impact more destructive.

Any estimate of the impact of an extreme East Coast event on human health will depend upon a risk assessment being performed which will take into account the hazard (sea surge, waves and tide), the probability of forcing events and their return times, the vulnerability of sea defences and the efficacy of mitigation measures, as discussed above. The Environment Agency and the insurance industry have already done much work on these issues, but this does not appear to be in the public domain.

The social, structural, infrastructural, economic and human vulnerability to a catastrophic East Coast flood needs to be evaluated by an interdisciplinary modelling study of a sea defence failure and the flow of flood water into one or more representative urban areas, work which is still at the research stage.

This preliminary work on human consequences of coastal flooding has highlighted a serious natural hazard to a substantial proportion of the UK population, even in the absence of climate change effects. There is a need to review urgently the adequacy of the existing disaster reduction measures and bring the risk issues involved into the public domain.

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APPENDIX 1

Casualties in storms affecting the East Coast 1953 to 1990 (Greave, 1956)

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31 Jan - 1 Feb 1953 Storm Surge

Location: Lincolnshire to Kent

Time: Evening, night

Observations: 307 drowned. 100 died in East Anglia

132 died when ship sank in Irish Sea

16 drowned at Sutton

20 drowned at Skegness

At South Beach, Heacham, where 40 holiday bungalows had been built, water surged over bank and swept away homes. 9 occupants died. 32 died at Hunstanton

At Snettisham, 25 people died. Some drowned when bungalows flooded

King's Lynn, ground floors flooded, 15 drowned

58 died at Canvey Island, Essex

1 drowned at Cley

1 drowned in kitchen at Wiveton

1 swept through kitchen window, drowned, at Salthouse

At Sea Palling waves burst through dunes, engulfed buildings, swept sand up village street where it lay in drifts

People swept to their deaths. 7 drowned in Sea Palling: 1 while attempting to reach rescue boat, 1 of exposure to gale and freezing spray while standing on roof of bungalow, some survived by climbing on to roofs

At Great Yarmouth sea attacked from front, Breydon waters from rear, 9 died. At Southdown 6 people, mainly elderly women living alone, drowned. Another 3 died of shock. 1 found entangled in iron bedstead

No loss of life or serious injury at Lowestoft due to new sea wall

In Southwold all 5 deaths occurred in bungalows in Ferry Road. From below South Green, Southwold to Pleasure Pier end not a single bungalow survived. 30 dwellings swept into sea

No-one died in Aldeburgh during surge but 1 died few days later as he helped Army repair breaches to sea and river walls

At west end of Felixstowe on Landguard Peninsula by estuary of River Orwell, post-war pre-fabs facing inland. All inhabitants fought for lives when wall lining estuary smashed and surge engulfed houses. Some drowned in beds when water quickly reached eaves. 28 people who had clung to roofs were washed away and drowned. In total 40 people died in Felixstowe

In Essex, 8 died at Harwich. 37 drowned at Jaywick when sea flooded housing estate. Whole of Canvey Island under water, 58 died.

Riverine (Fluvial) Flooding

4.6.13 Context to fluvial and inland flooding

Towards the end of 2000 the UK experienced the most extensive and widespread inland flooding in over 50 years. Following a wet spring and early summer, autumn 2000 was the wettest on record for over 270 years.[1] The combination of saturated catchments and exceptional rainfall produced record or near record river levels in many river systems. Although 280,000 homes were protected from flooding by flood defences, over 10,000 homes and businesses were flooded in more than 700 locations. In several locations properties were flooded up to three times in the autumn, and for some up to five times in the last year. Around 11,000 people were advised to evacuate their properties, and hundreds were left with uninhabitable homes.[1]

Despite improvements in flood forecasting, flood warnings, and public awareness-raising, particularly since Easter 1998, large numbers of people are likely to be at risk of experiencing a flood event in the future. Climate change could make extreme floods such as those in 2000, and those of Easter 1998, a more frequent occurrence due to the projected wetter winters and more intense summer storms (see Section 1.2). An estimated 1.85 million homes, 185,000 commercial properties and approximately five million people are now considered to be at risk from flooding in England and Wales.[1] There will inevitably be future occasions when conditions are so severe that flood defences are overwhelmed, moreover, according to the Environment Agency, it will not be possible to protect everyone from all floods in the future.

Another complicating factor contributing to inland flooding is poor surface water drainage, particularly in urban areas. Urban land area is estimated to have increased by 50% between 1930 and 1990.[1] Continued development in the floodplain leads to increased runoff and less land available for infiltration by rainwater. Moreover, flooding from overflowing sewers, which is not always related to fluvial flooding, is also an area of potential concern. The implications of the above on people's health and well-being, and on health service provision, therefore need to be considered.

4.6.14 Existing research on the health effects of flooding

The human health consequences of floods, particularly relating to coastal flooding, are discussed in Section 4.6.8. Health consequences from river or inland flooding would in many respects be the same e.g. those caused by the shock, disruption and inconvenience of the flood, as well as worry about future flooding. As outlined above, there has been no large-scale research in the UK on the health effects from flooding to date. Bennet's 1970 study[2], which demonstrated some significant effects, was the last systematic examination, although this only related to one town and one particular flood event. Research carried out in the 1980s further highlighted the seriousness of the so-called 'intangible' impacts of flooding on people's lives and wellbeing.[3 4 5 6 7]

Several small-scale qualitative studies have been carried out since the flooding of Easter 1998 in eight communities in England and Wales affected by inland flooding.[8 9 10]* Three of these were communities flooded at Easter 1998, two were communities flooded in June 2000, and three were communities flooded in autumn 2000. The studies, which covered communities with varying socio-economic backgrounds and who experienced flood events of varying characteristics and impacts, have revealed some important consequences on people's health from river flooding. Although the results from these studies cannot be said to be representative of flooded populations generally, due to the small samples involved (a total of 116 people), the same or very similar problems were reported in all eight communities which indicates a wider applicability of the findings.

*** Some of this research is yet to be published.**

What is not clear from the earlier studies is how long the various health effects reported following flooding were likely to continue. No longitudinal studies on the health effects of natural disasters could be found for the UK. Those studies that have been undertaken in the US and Europe have largely focused on the psychological impacts such as post-traumatic stress disorder and associated impairment to physical health.[11-14]

4.6.15 Factors contributing to consequences of flooding on human health

Results from the qualitative research reveal that the adverse human health consequences of flooding are complex and may be far-reaching. The World Health Organization defines good health as 'a state of complete physical, mental and social well-being, and not merely the absence of disease and infirmity'.[15] Hazards such as floods can therefore be regarded as potentially multi-strike stressors and health effects may result from a combination of some or all of the following factors:

- characteristics of the flood event (depth, velocity, duration, timing, etc.)
- type of property e.g. single storey, two storey, etc.
- the amount and type of property damage and losses
- whether flood warnings were received and acted upon
- previous flood experience and awareness of risk
- any coping strategies developed following previous flooding
- having to leave home and live in temporary accommodation
- the clean-up and recovery process and associated household disruption
- frustration and anxiety dealing with insurance companies, loss adjusters, builders and contractors
- a loss in the level of confidence in the authorities perceived to be responsible for providing flood protection and warnings
- financial worries (especially for those not insured)
- a loss of the sense of security in the home
- an undermining of people's place-identity and their sense of self (e.g. through loss of memorabilia)
- disruption of community life

Additional components affecting the stress and health impacts of flooding may include socio-economic and cultural factors.

4.6.16 Time-related consequences of flooding on human health

There appears to be a time dimension to the health impacts resulting from flooding. Health effects can be categorised as those resulting at the time of the flood or immediately after, those which develop in the days or early weeks following the flood, and those longer-term effects which may appear and/or last for months or even years after the flood. A common perception is that once the floodwaters have receded the problem is over. For many flood victims, this is when most of their problems begin.

4.6.17 Physical health effects during or immediately after flooding

The effects on human health during or immediately after flooding reported by people flooded in 1998 and 2000 are summarised in Table 4.16. These largely involve risk to life from fast-flowing floodwaters, general sprains from over exertion, consequences of being exposed to cold and damp environments or from coming into contact with contaminated floodwaters.

Table 4.16 Physical health effects reported *during, or immediately after*, Easter 1998 and summer and autumn 2000 floods

Injuries from being knocked over by floodwaters or thrown against hard objects, or from being struck by moving objects
Injuries from over-exertion during the flood e.g. sprains
Hypothermia
Fear of electric shocks (although none were reported)
Cold, coughs, flu
Headaches
Sore throats or throat infections
Skin irritations e.g. rashes
Shock

Severe coastal flooding can generally pose a more serious risk to life and threat of injury than fluvial flooding. However, people flooded by a high velocity river flood in North East England in 2000 spoke of fearing for their lives from drowning or being swept away by the floodwaters. Several people had to swim to save themselves or others, and some were knocked over by the force of the waters when trying to wade through them. In the USA the main cause of death from flooding is of people attempting to drive or wade through fast-flowing floodwaters, and several people have also been killed in this way in the UK in recent years. As little as 30-40 cm of water can be enough to sweep even a strong and fit person off their feet. Even trying to wade through relatively calm waters, when deep, can be enough to disorient a person, and can pose the danger of injury from obstacles hidden beneath the waters or from dislodged man-hole covers. There is therefore a need to increase public awareness of the dangers of trying to navigate through floodwaters.

4.6.18 Physical health effects during weeks or months following flooding

The physical health problems reported by flood victims in the weeks and early months following flooding are listed in Table 4.17. They largely comprise problems arising as a consequence of living in damp or dusty conditions, or those probably arising from the stress of the recovery period and increased levels of anxiety about a repeat flood event, such as high blood pressure. Many people reported suffering from diarrhoea and upset stomachs following the floods, while others spoke of other types of infections. The close proximity of people living in cramped conditions in their homes following the flood also meant that some problems were inevitably passed from person to person within the household. Conflicting information and advice on health issues given by different authorities after flooding was another area causing anger and concern. There is evidence that people would welcome clear guidelines on the kinds of health effects that may (and may not) result from people and property coming into contact with contaminated floodwaters, and how these effects can best be avoided or dealt with.

Table 4.17 Physical health effects reported *in the weeks or months after* Easter 1998 and summer and autumn 2000 floods

Gastro-intestinal illnesses
Cardiac problems
Respiratory problems e.g. asthma, chest infections, pleurisy
Lacerations, abrasions and contusions
Sprains and strains
Skin irritations e.g. rashes, dermatitis etc.
High blood pressure
Kidney or other infections
Stiffness in joints
Muscle cramps
Insect or animal bites
Erratic blood sugar levels (diabetics)
Weight loss or gain
Allergies e.g. to mould spores

As Section 4.4.2 suggests, there is no evidence to suggest significant public health problems arising from flooding in recent years. Clean water and good sanitation systems in developed countries minimise the risk of communicable diseases, although many flood victims speak of experiencing gastro-intestinal illnesses, minor infections, and skin irritations. Enhanced surveillance systems and follow-up after floods are needed, particularly in light of the potential effect of climate on water-related disease due to increased flooding and associated increased risk of pathogens breaching water treatment and sanitation safeguards (see Section 4.4.2).

Pre-existing health conditions also appeared to lead to increased susceptibility to health problems among some people who had experienced flooding, particularly the very elderly. Along with a number of anecdotal accounts of elderly people dying following flooding, there is some quantitative evidence that death can be *hastened* by the experience of flooding, rather than somehow being *caused* by it. Following the 1968 flooding in Bristol, Bennet[2] reported morbidity and mortality rates for the 12 months after the flood had increased significantly in the homes of people who were flooded.

4.6.19 Psychological health effects during weeks or months following flooding

For the majority of those included in the qualitative studies the psychological effects of being flooded were much more significant than the physical effects (Table 4.18). Anxiety during heavy rainfall had resulted in many people fearing a repeat flood event. In these cases rainfall can act as a 'trigger' for increased stress levels, being a factor directly related to the initial flood event. This can lead to people adjusting their normal behaviour, for example by moving possessions to upper floors of properties, staying up at night to observe river levels, purchasing furniture that might not be damaged from any future flooding etc. The stress and disruption from cleaning properties and dealing with insurance claims and builders repairing flood damage was for many people said to be the most stressful aspect of the flood. Disruption to normal family life can also be significant, and many people spoke of this 'lost time' in the months following the flood which they could never be compensated for.

Table 4.18 Psychological health effects reported *in the weeks or months after* Easter 1998 and summer and autumn 2000 floods

Anxiety e.g. during heavy rainfall
Panic attacks
Increased stress levels
Mild, moderate, and severe depression
Lethargy/lack of energy
Feelings of isolation
Sleeping problems
Nightmares
Flashbacks to flood
Increased use of alcohol or prescription (or other) drugs
Anger/tantrums
Mood swings/bad moods
Increased tensions in relationships e.g. more arguing
Difficulty concentrating on everyday tasks
Thoughts of suicide

It is expected that people who experience a traumatic event will have a severe reaction to it, particularly in the first few days. For people who display symptoms beyond this period there are three possible diagnoses: Adjustment Disorder, Acute Stress Disorder, and Post Traumatic Stress Disorder. The three can be differentiated by looking at the type of stressor, and the range and duration of symptoms.[16] Flooding, in common with other traumatic life events, is associated with increased rates of the most common mental disorders: anxiety and depression (*pers. comm.*, 2000). Many people in the qualitative studies were displaying symptoms of impaired mental health such as these, as well as those related to Adjustment Disorder (*pers. comm.*, 2001). These symptoms included: avoidance of talking or thinking about the flooding, flash-backs, sleep disorders, and depression.

The nature of a trauma (e.g. flood event) may impact upon the severity of symptoms. Research suggests a complex relationship between the experience of a traumatic event and subsequent mental disorders. It could be suggested that the greater the damage, losses, and inconvenience from a flood event, the greater the stresses suffered by flood victims are likely to be. Evacuation and loss of personal possessions may also have significant psychological implications upon people, often undermining their sense of place-attachment and self identity, as well as reducing the security previously felt in the home as a place of refuge.[17]

4.6.20 Long-term health consequences of flooding

Follow-up qualitative research at between one year and eighteen months after the UK floods within three of the eight communities studied revealed continuing psychological health effects among most of those interviewed.[9] Physical health effects were still being reported by a minority of people, but for most these were largely said to have been restricted to the first few weeks following the flooding. Some people were continuing to experience chest infections and coughs and colds more frequently than before the flood. However for the majority of the flooded populations in the study it was the psychological effects which were still causing them distress. Therefore, although physical health consequences from flooding may be significant for some people within flooded populations, these appear to be largely short-lived and do not pose serious threats to public health. However, the psychological effects of being flooded are likely to be more significant and much longer-lasting. There was also the suggestion that the full health impacts of the floods have yet to reveal themselves. It is often only after people's homes have been put back in order that the full realisation of what has happened to them is appreciated.[9,10] This further indicates that the effects of flooding on people's health and general well-being can continue for many months, or even years, after the actual flood event.

4.6.21 Whose health is most at risk?

It can be suggested that to some extent everyone living or working in flood risk areas are vulnerable to the impacts of flooding. However, research literature indicates that certain groups within communities (e.g. the elderly, disabled, children, women, ethnic minorities, and those on low incomes) may be more vulnerable to the effects of disasters than others.[8-10, 19-23] 'Vulnerability' can be determined by the characteristics of a person or group in terms of their limited capacity to anticipate, cope with, resist, and recover from the impact of a natural hazard.[24] Consequently, these groups may suffer greater effects from a flood and may need special consideration by the authorities during the response and recovery periods. Two of these groups are discussed here.

4.6.22 Children

It has been suggested that children are often among those who are the most affected by a disaster.[20] However, there has been little research on the impacts of natural disasters on children, and little evaluation of disaster-related interventions with children has been published.[25] Many of the parents who took part in the qualitative studies felt that their children's health had been seriously affected by the flooding.[10] Fear for children's health and safety had led many parents to evacuate their children to relatives. This sometimes resulted in families being split up for long periods, which both children and parents found distressing. An important impact on children was the disruption to their familiar routines. This also meant having to miss out on regular activities because they were temporarily living elsewhere, or because the activity was cancelled due to the flooding. Many parents reported that their children were anxious of a repeat flood event and became agitated during heavy rainfall. The loss of treasured possessions and even pets had deeply affected some of the children and a number of mothers reported behavioural problems with their children since the flooding. These included problems sleeping, nightmares, and tantrums. These behavioural changes were also noted in children following the 1990 North Wales floods in Towyn.[26,27]

A number of other issues were raised by parents, these included: the lack of advice for parents on how to deal with children after a disaster such as flooding, and the sort of impacts they might face; the lack of support and childcare facilities where parents (especially single parents) could leave their children while they dealt with the clean up and recovery process; the lack of psychological or emotional support for children. Crèches and playgroups were set up in Towyn, following the 1990 flooding, which many parents found extremely helpful.[27]

4.6.23 Women

Disasters can also impact upon men and women in quite distinct and different ways.[8-10,18,19,28] Women, even when in full or part-time employment, are traditionally responsible for the management of the household and may suffer more inconvenience when this is disrupted. Moreover, women's paid and unpaid care-giving responsibilities position them to emotionally and materially sustain their families throughout the flood and recovery process. Men and women may also express their distress in different ways; however, socio-economic or ethnic differences may be as important, or even more important, than gender differences. In the majority of the households represented in the qualitative studies, it was the women's health that was said to have been most affected by the flooding. Men admitted feeling upset at not being able to do more during the flood event itself, as well as afterwards when working full-time and leaving their wives to cope with much of the recovery process.

4.6.24 Conclusions/recommendations

Although the risk to life and health would potentially be greater from a major coastal flood, inland flood events are already affecting many households and communities every year, and are likely to increase in the future. There are a number of actions that can be taken to mitigate the adverse impacts of flooding. For example, the Environment Agency has been improving its flood forecasting and warning systems, and increasing public awareness-raising of flood risks through annual campaigns and 'Flood Awareness' weeks. There is now regular use of flood warnings on television and radio weather reports and promotion of the Environment Agency's Floodline information service.

Mediating factors between stress and health may include flood warning, coping strategies and social support; however, where flooding is unexpected, sudden and without warning, these may be weakly developed or non-existent. Self-help measures to reduce the damage to property and the stress caused by flooding are also being encouraged, thereby alleviating some of the negative consequences on people's health. These measures include flood-proofing of properties, development of a family Flood Plan along the lines of those widely used in the USA, and other community preparedness developments. Where feasible and cost-effective, flood alleviation schemes may also be considered, along with development control legislation to restrict new building in the floodplain. As suggested in Section 3.5, the UK is likely to need to adapt to increased risk of flood events in the future and to develop national coping strategies rather than those purely at the local or individual household levels.

Much more research is needed on trying to understand the complex health consequences which may result following flooding. Disease surveillance needs to be increased during floods, and information disseminated rapidly to dispel false rumours of public health epidemics. The longer-term psychological impacts on people's health and social well-being particularly require more investigation, along with the issue of social support during the recovery period. Evidence (discussed in Section 4.1) that socio-economic deprivation may be an important determinant of excess winter deaths due to cold, may also hold true for the health effects of flooding. The social and community dimensions of flooding, which can have significant impacts on households and individuals, are other factors often neglected in post-flood studies. Community activity often breaks down following serious flooding, and it can be many months before normal functioning is achieved. Moreover, some flood victims have spoken of a long-lasting deterioration in community life.

A final issue is that of the impacts on the health service from increased flooding in the future. Evidence from the USA following Hurricane Floyd in 1999 shows that health systems can also be badly affected by flood events, particularly if facilities are themselves located in floodplains, or when affected by disruptions to electricity, water supply, and transportation systems (*pers. comm*, 2000). The UK medical community also needs to be prepared to address these concerns and both the short and the long term health needs of people who have been affected by flooding.

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4.7 Air Pollution and Climate Change

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Summary

- Over the timescales considered in this report (see Section 1.2) there will be a reduction in episodes of cold still winter weather typically associated with winter air pollution episodes. There will also be a reduction in the emissions of particles, oxides of nitrogen (NO_X) and sulphur dioxide (SO_2) resulting in a considerable decrease in mean annual and episodic winter ambient concentrations of particles, nitrogen dioxide (NO_2) and SO_2, the latter showing the largest fall.

- A considerable reduction is likely in the adverse health effects associated with winter ambient concentrations of particles, NO_2 and SO_2, largely due to the reduction in mean levels rather than the reduction in episodes. These reductions in adverse health effects cannot be quantified but a 50% decrease seems to be a reasonable estimate.

- Key trends in summer pollution will be an increase in episodes of hot sunny summer days; an increase in background concentrations of ozone (as part of a north west European phenomenon); a reduction in the emissions of ozone precursors including NO_2 and a reduction in concentrations of particles.

- The overall effect of these summertime trends is likely to be a small net increase in ozone episodes. If a threshold of effect is assumed, the increase in health effects due to ozone will be relatively small. If no threshold is assumed then the increase in mean concentrations of ozone will be much more influential and the increase in premature deaths is predicted to be 10%, 20% and 40% for the years 2020, 2050 and 2080 respectively, over a 1996 baseline. These effects will be countered to some extent by the fall in concentrations of particles and NO_2.

4.7.1 Introduction

Outdoor air pollution, whatever its cause, has long been regarded as a potential danger to health. Harmful effects of air pollution on health were however recognised only late in the first half of the 20th century, following a succession of intense episodes in Europe and North America which were associated with obvious increases in mortality and morbidity. These episodes mostly occurred in the winter during cold stagnant weather, which tends to prevent the dispersion of local emissions from domestic and industrial sources. The association of winter air pollution episodes with stagnant weather conditions was obvious and the belief that increases in mortality during fogs could be entirely attributed to the cold and fog delayed the recognition that air pollution itself was also harmful.[3,4] In London and most other cities where episodes have occurred in the past, winter episodes have become less frequent and less intense. This can largely be attributed to a reduction of emissions of sulphur dioxide and smoke from domestic open coal fires and industrial and power generation sources. Nowadays, in urban areas motor vehicles are typically the main source of primary air pollutants, which include NO_X, carbonaceous particles, carbon monoxide and various organic compounds. When cold stagnant weather conditions prevail, it is these pollutants that fail to disperse and this is one reason why winter episodes, such as that which occurred in 1991, are characterised by high concentrations of NO_2, CO and volatile organic compounds.[5]

Potentially harmful air pollutants may also be created by chemical reactions in the atmosphere. For example, ozone is elevated in hot sunny weather, when ultraviolet light interacts with NO_2 and volatile organic compounds from traffic and industrial sources.[6, 7] The ozone episodes which result from these processes have been recognised since the 1950s, most notoriously in Los Angeles and Mexico City, and may be a relatively new phenomenon. In hot sunny weather, ozone episodes sometimes occur over south east England, the longest and most intense example occurring in 1976. The intensity of ozone episodes in the UK seems to have diminished in recent years, possibly because of a reduction in precursor pollutants.[7] Unlike winter episodes, ozone episodes tend to affect whole regions and precursors from other countries may be carried by weather systems.

There has been much progress during the last century towards controlling air pollution problems, and almost all of the worst pollution sources have been brought under control. However, some new sources, particularly motor traffic, are still growing in some countries and we cannot be complacent about air pollution in the twenty-first century. Furthermore, important components of UK air pollution are transported in air from continental Europe, over which we have less control as far as emissions are concerned.

In this section we will be concentrating on the national-scale implications of the impact of climate change on air quality. We will not be dealing with point source local air pollution incidents following accidental or other releases of air pollutants. The question of biomass burning, while important elsewhere in the globe, notably in south east Asia, does not seem directly relevant to the UK and will not be discussed further.

Our assessment of the likely future impacts of air pollution on human health in the UK will be based on a synthesis of three different strands of information. First, we shall estimate trends in the primary emissions of suspended particles, and of the primary pollutant precursors for ozone. Secondly, we shall examine the likely effect of climate change on the mean levels of pollutants and the frequency and intensity of wintertime and summertime air pollution episodes. Thirdly, we shall use the above information to estimate the direction and in some instances the scale of the health effects of climate-related changes in air pollution.

These estimates will be for the UK for the years 2020, 2050 and 2080 where possible, and will be expressed as a change relative to a baseline year in the 1990s. The evidence linking air pollution with health effects is more extensive for short-term effects, and this will be the thrust of our quantitative analysis. The most convincing evidence of health effects of air pollution concerns particles and ozone, and we shall concentrate on these. We shall however touch on the likely trends in NO_2 and SO_2, the other main gaseous pollutants which may affect health. Estimating the effects on chronic disease will be more speculative because there is less information about the time relationships. Assumptions about trends in the sensitivity or vulnerability of future populations will also need to be made on inadequate evidence.

4.7.2 Ambient air pollution: Sources and health effects

A large number of chemical substances are found in the ambient air, many of them resulting directly or indirectly from human activity, predominantly the burning of fossil fuel. The pollutants that are of most concern to human health are listed in Table 4.19. Detailed reviews are widely available and only the most essential points will be summarised here.[8-18]

Table 4.19 Main ambient pollutants of potential health significance

Gases	Nitrogen dioxide
	Sulpur dioxide
	Ozone
	Carbon monoxide
Inhalable particles	Primary combustion sources (mainly fine)
	Secondary (mainly fine)
	Other sources (mainly coarse)
Toxic chemicals	Benzene
	Butadiene
	Polycyclic aromatic hydrocarbons
Biological particles	Pollens
	Mould spores

Knowledge about the adverse health effects of air pollutants may be divided broadly into that from experimental laboratory studies and that from real-world observational studies in the occupational, domestic and ambient environments. The results of experimental studies with animals are difficult to extrapolate to humans, not only because of species differences but because higher levels of exposure are often used in animal work. Studies using human volunteers are useful for demonstrating the possibility of adverse health effects and understanding pathophysiological mechanisms. Nevertheless the results of these human volunteer studies cannot be translated directly into exposure-response relationships that can be applied to the ambient situation. Occupational studies may be useful for understanding the effects of certain pollutants but usually involve higher exposures than encountered in the outside world. Direct evidence of effects of air pollution on public health should, ideally, be obtained from epidemiological studies of free-living populations. A lot of such evidence has now accumulated, especially on short-term effects of day to day variations in pollution, but is difficult to interpret. In particular, there are problems relating to estimation of population exposure, quantification of health outcomes and confounding of associations by other factors (e.g. social class, weather), which may be related both to pollution and health effects. In addition, since ambient pollution is almost always a mixture of pollutants, it is difficult to identify the specific individual contribution of pollutants.

Most epidemiological studies of short-term effects have used time-series techniques to examine associations between daily indicators of health effects (mortality, hosptial utilisation, symptoms, lung function), and individual air pollutants. These techniques can detect associations at much lower than 'episode' levels, and they control for confounding factors, and distinguish, to some extent, between the effects of individual pollutants.

The clear associations between past major air pollution episodes and increased mortality and morbidity still provide some of the most convincing evidence that air pollution may be harmful. This is in spite of the fact that it is not entirely possible to separate the effects of air pollution *per se* from those of the associated cold or hot weather, or to separate the individual effects of the various pollutants in the mixture. One of our aims is to predict the future incidence of weather patterns associated with air pollution episodes. We shall, therefore, briefly review the evidence concerning the health effects of winter and summer episodes, and then summarise what is known about the individual pollutants.

Winter episodes

Winter air pollution episodes tend to occur during still weather in which locally emitted pollutants accumulate, possibly to very high levels. Earlier in the century, when the source of pollution in UK cities such as London was primarily domestic coal burning, the pollution mixture mainly comprised carbonaceous particles and SO_2, and formed an acidic aerosol. Major episodes of this type in the past were associated with obvious increases in mortality and morbidity, the best known example being the 1952 London fog, though there have been many others. In 1952 an estimated 4000 people died during the four days of the fog, and several more thousands in the subsequent weeks.[19] Many other episodes have been associated with increases in mortality, though not to the extent observed in 1952.[2] The last reported episode of this type was in London in 1975. The disappearance of these traditional episodes was a result of emission control measures including the Clean Air Act. Stagnant winter weather still occurs however, and more recently, in 1991, London experienced an air pollution episode during which concentrations of NO_2 and particles increased by about five-fold over the seasonal mean for four successive days.[5] This was at a time when NO_X emissions were at a historic high and such an event is therefore unlikely to occur again, even if the weather conditions were to recur. It was estimated that, after allowing for the effects of the cold weather, mortality and hospital admissions increased by about 10%, but it is not possible to be certain whether particles or associated gases were responsible.[19] It is likely that episodes of lesser intensity or duration would not be associated with health effects detectable by episode analysis.

Summer episodes

Summer episodes are characterised by elevated ozone and often particle concentrations, and are also associated with increased mortality and morbidity. The largest episode to occur in the UK was in 1976, when high hourly concentrations occurred daily for about a fortnight. Mortality increased by 9.7% in England and Wales, and by 15.4% in London.[21] An episode analysis of hospital data from the Oxford Region, which was similarly affected by heat and high ozone levels, found evidence of a 34% increase in respiratory hospital admissions. (Anderson *et al.*, unpublished data). It is difficult to identify confidently the contribution of air pollution to these adverse health effects[22], but for Greater London it was estimated that ozone was responsible for nearly half of the increase (6.7%).[21] These results give the probable outer limits of the effects of future air pollution episodes of similar intensity that might occur in hot spells.

Particles

In the UK, there has been a marked fall in primary emissions and ambient concentrations of particles since the 1950s. This is due to a reduction in emissions from domestic and industrial sources. Over recent years however the absolute and relative contribution of particles from traffic has increased, because the greater volume of traffic has more than compensated for the reduced emissions from individual vehicles. Emissions of particles from road traffic sources in UK cities also peaked in the early 1990s.

Particles comprise a complex and variable physicochemical mixture. The most important are those with an aerodymamic diameter of less than 10 μm (PM_{10}), since these have the potential to enter the airways within the lung. Within the PM_{10} fraction, it is the fine particle fraction $PM_{2.5}$, that penetrates as far as the air exchanging tissues (alveoli). In the UK, the ratio of coarse to fine particles is about 1:2. The $PM_{2.5}$ fraction mainly comprises particles of anthropogenic origin and it is these that are relevant to the climate change question. The composition of $PM_{2.5}$ varies from place to place and over short and long time scales. In the UK at present, about half of $PM_{2.5}$ is composed of primary particles from combustion sources, and the other half of secondary particles of which sulphate is the most important.[13; 23]

Secondary particles are created by various chemical processes in the atmosphere. An important example is the oxidation of SO_2 to sulphate and of NO_2 to nitrate. These may exist as acidic particles (e.g. sulphuric acid) or, where neutralised, (e.g. by ammonia from farms), as salts of ammonia). The coarse fraction ($PM_{2.5-10}$) is mainly comprised of dust from crustal sources (e.g. re-suspended road dust, construction dust), but in coastal areas includes sea salt. Fine particles have a low settling velocity and drift over wide areas; they also penetrate indoors quite easily. By contrast, coarse particles are more localised and tend to settle relatively quickly.

The effects of particles on health have been extensively reviewed.[3,4,14,16] Because of technical difficulties, laboratory evidence about the effects of ambient particles is relatively sparse and this has retarded the understanding of pathophysiological mechanisms. The most abundant evidence is from epidemiological time-series studies which relate air pollution to various health effects on a daily basis. To date, associations have been reported with daily mortality, health care utilisation, symptoms, lung function and various other markers. These associations have also been observed in most but not all UK studies.[26-34] The main effects appear to be on respiratory and cardiac conditions. The causality of these associations is a matter for interpretation, as discussed above, but the conclusion of the Committee on the Medical Effects of Air Pollution report on particles[16] was that it would be imprudent not to regard these associations as causal.

Ozone

Ozone is a highly reactive oxidant gas which occurs naturally in the troposphere as a result of atmospheric processes involving sunlight and the methane and NO_X emissions from human activities, particularly agriculture, together with natural emissions from biomass burning, soils, wetlands, swamps and marshes.[16] Background levels vary seasonally and from region to region but have approximately doubled since measurements began last century. The ozone that occurs over and above background levels is a secondary pollutant, created by a complex process in which ultraviolet light acts on NO_2 and volatile organic compounds, both of which are primary anthropogenic emissions. Ozone tends to be lower in urban areas because concentrations combine with nitric oxide from combustion sources to form NO_2. Ozone and its precursors may be carried long distances and it should be regarded as a regional pollutant. It is important in the production of secondary sulphate and nitrate particles. Future levels of ozone will be influenced not only by weather factors but by the availability of precursor pollutants.

The health effects of ozone have been reviewed.[8; 17; 35; 36] Human exposure experiments have shown that ozone has detectable but reversible toxic effects on the lung at concentrations near to ambient background. Epidemiological studies in various parts of the world have observed short-term associations between ozone and daily mortality, hospital utilisation, respiratory symptoms and lung function. In the UK, ozone has been associated with daily mortality and hospital admissions for respiratory disease,[28; 30] but not with changes in children's lung function.[34] There is limited evidence from high-exposure environments that ozone may be associated with an increased incidence of chronic lung disease.[37] There is some evidence that individuals with reactive airways, a characteristic of asthma, may be more sensitive to the effects of ozone.

Nitrogen dioxide[10]

Oxides of nitrogen (NO_X) are created by the oxidization of nitrogen in high-temperature combustion processes. The most potentially toxic is NO_2, and health effects have been observed in humans exposed to high concentrations in occupational settings. However, most human chamber studies have not identified toxic effects at ambient levels. In contrast, epidemiological studies, including some from UK cities have frequently found associations with short-term health effects, but these are often interpreted as indicating an association with traffic pollution in general, of which NO_2 is a marker. Associations with chronic respiratory disease have also been reported, but again it is generally thought that these may represent the effects of some co-pollutant.[38]

Sulphur dioxide[9]

SO_2 is produced from fossil fuels that contain sulphur, especially coal, but also some diesel fuels. SO_2 is a precursor of sulphate, a species of fine particle that can be transported over long distances. In the absence of neutralising agents such as ammonia, it can lead to the formation of sulphuric acid aerosol. Concentrations in the UK are currently very low by historical standards. It is a respiratory irritant and asthmatics are especially sensitive. Human chamber studies have failed to demonstrate effects at current ambient concentrations, but epidemiological studies continue to observe associations with daily mortality and morbidity.[31; 33; 40] The causal significance of these relationships is unclear and it is generally considered that the SO_2 may represent a marker for some other more toxic pollutant.

Other toxic chemicals

These include potentially carcinogenic chemicals such as benzene, butadiene and polycyclic aromatic hydrocarbons (PAH). There is no direct evidence that these compounds produce cancer at the current low ambient concentrations but mechanistic considerations make it prudent to assume no threshold of effect.[41-43]

4.7.3 Exposure response relationships to be used in estimating health effects

Whatever the uncertainties, enough is understood about the health effects of air pollution to be fairly sure that a reduction could be beneficial and that an increase could be harmful. Health impact assessment requires, amongst other things, choosing an appropriate exposure-response relationship. If this is not based on local studies, the appropriateness of using relationships obtained in different environments must be considered carefully. It may be appropriate to use a summary estimate derived from a meta analysis of several studies. We have attempted a quantification of the health impact of climate change-associated air pollution only in the case of ozone because this is the pollutant for which the best predictions can be made over a long timescale. Based on the Quantification report[35], which has considered these issues already, we have used a coefficient of +3% and +3.5% for a 50 $\mu g/m^3$ 8-hour mean ozone increment, for deaths and respiratory hospital admissions respectively. These are rounded estimates based on a meta analysis of European studies.[44; 45]

Individuals probably vary in their threshold and intensity of response to air pollutants and are exposed to a larger range of concentrations than are indicated by fixed site background monitoring stations. This would suggest that a threshold approach is probably not appropriate at the population level. There is some discussion about whether there is a threshold for the health effects of ozone because some studies have observed a threshold[30] and because background levels of ozone are close to those that have been found to have toxic effects in human experimental studies. Following the Quantification approach, we have estimated the health impacts with and without a threshold assumption at 50 ppb. It is reasonable to assume that the most accurate estimate of the health impact of ozone is somewhere in the wide range between the threshold and no threshold estimates. It is generally considered that there is no threshold for the effects of particles[35; 46] and we have followed this assumption. For NO_2 and SO_2, it is also assumed that there is no threshold of effect. The evidence for a direct causal effect of NO_2 is regarded as the weakest of the four candidate pollutants. For these three pollutants, particles, NO_2 and SO_2, we have not attempted a quantitative analysis.

4.7.4 Meteorological factors and future air pollution episodes

Wintertime air pollution episodes

To address the occurrence of the meteorological conditions which drive wintertime air pollution episodes, we have examined the daily meteorological parameters produced by the Hadley Centre Climate Model (HadCM3) for each day through to December 2099. This is a coupled ocean-atmosphere global climate model, driven by the increasing concentrations of greenhouse gases and aerosols as described by the IPCC IS92a (business as usual) scenario. The output has been taken for a single grid point in the British Isles, [52.5°N, 0°W], which corresponds with the location of central England. Figure 4.27 presents the time-series of minimum annual temperatures for a height of 1.5 metres above the surface for each year of the next century. Figure 4.28 presents the minimum annual windspeed for 10 metres above the surface over the same period.

Whilst Figures 4.27 and 4.28 are useful in setting the scene and introducing the climate model output, they do not necessarily describe the meteorological parameters that drive the occurrence of wintertime air pollution events. This is because the days with minimum windspeed and minimum temperatures may occur on different days throughout the year. It is the simultaneous occurrence of low windspeed and freezing conditions that is associated with poor air quality.

Figure 4.27

Annual minimum and maximum temperatures for central England through to year 2099 from the Hadley Centre Climate Model

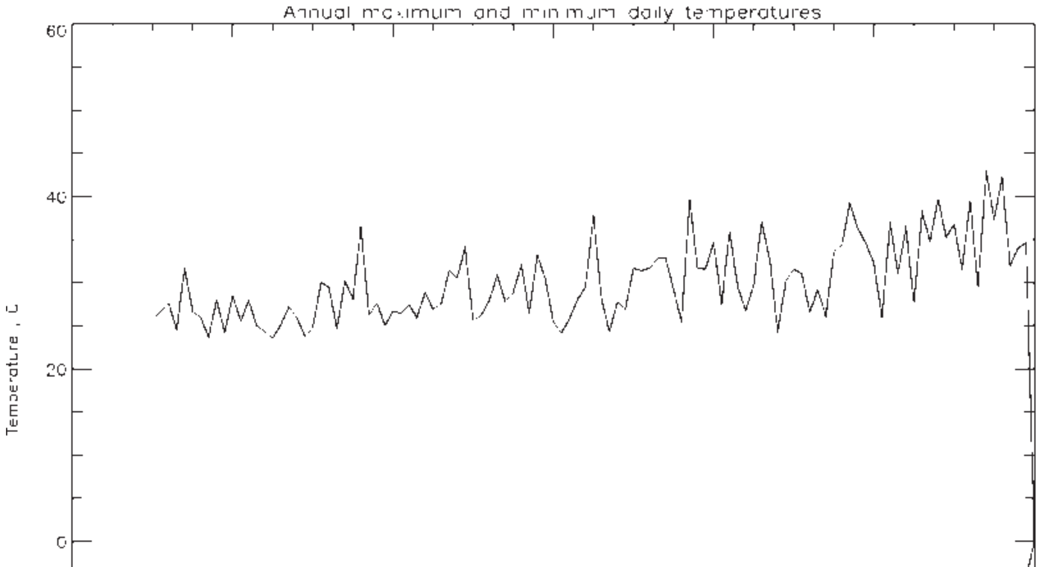


Figure 4.28

Annual minimum wind speed for central England through to the year 2099 from the Hadley Centre Climate Model

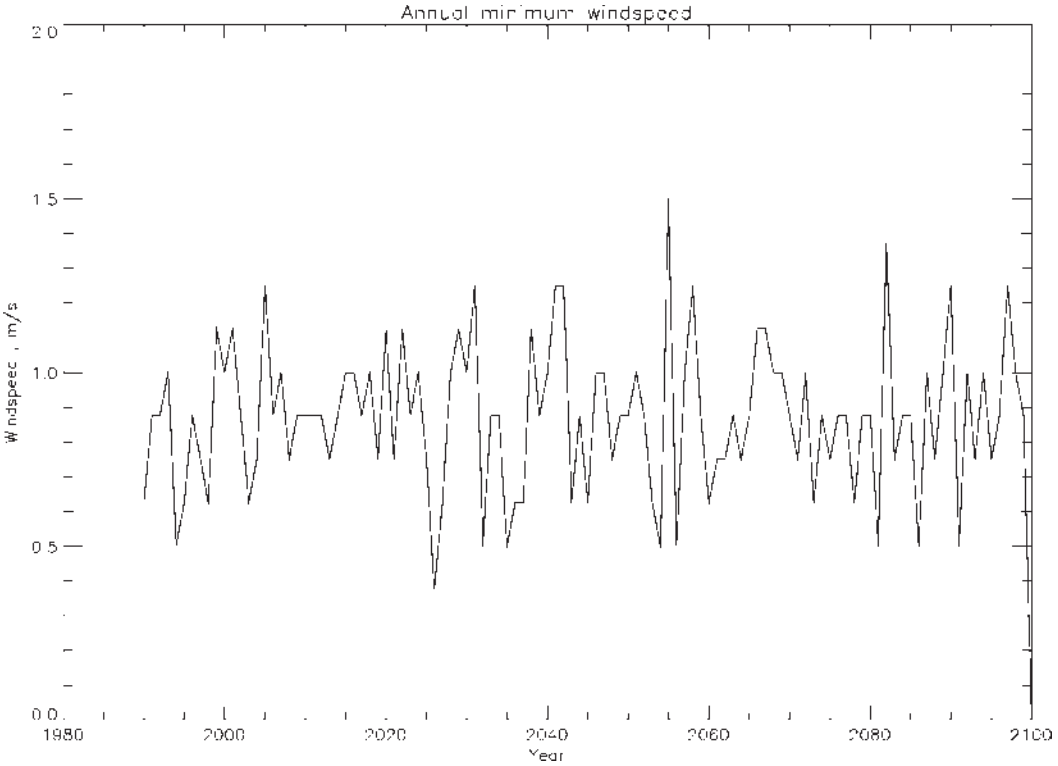


Table 4.20 presents predictions of the number of days in each decade into the future when low windspeeds and low temperatures combine together to produce poor dispersion conditions. There are isolated days with low windspeeds and below freezing temperatures during the decades up to 2030-2040 but their frequency is reduced in the decades from 2050 onwards through to the end of the century. The number of days with temperatures just below zero and low windspeeds also declines dramatically through the next century.

Table 4.20 The number of days with at least one hour in which the windspeed is less than 2 m s^{-1} and the minimum temperature is in the range shown for each decade up to 2100

Decade	**Number of days in the range from -15°C to -10°C**	**Number of days in the range from -10°C to -5°C**	**Number of days in the range from -5°C to 0°C**
1990 - 1999	0	1	32
2000 - 2009	0	2	17
2010 - 2019	0	1	38
2020 - 2029	1	3	43
2030 - 2039	1	3	11
2040 - 2049	0	2	30
2050 - 2059	0	1	20
2060 - 2069	0	1	30
2070 - 2079	0	0	26
2080 - 2089	0	1	24
2090 - 2099	0	0	17

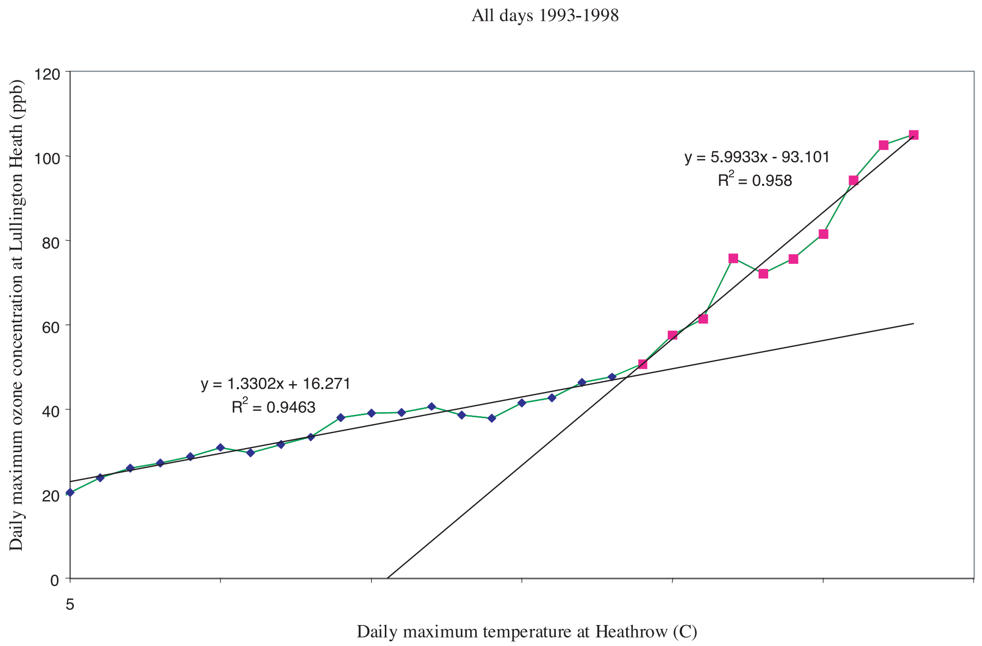
In summary then, conditions of low windspeeds and below freezing temperatures appear to occur with a frequency of about once per decade throughout much of the first half of the present century. During the second half of the present century, such conditions appear much less frequently as winters become generally warmer and windier. The meteorological conditions which drive wintertime air pollution episodes should follow on from these simple trends through the next century.

Summertime pollution episodes

From time to time during warm, sunny anticyclonic conditions during summertime, elevated ozone concentrations occur over the British Isles as hazy, regionally-polluted air masses drift in from continental Europe. Elevated ozone concentrations tend only to be recorded when daily temperatures exceed 25°C and when winds are light and from the east. The influence of high temperature on photochemical ozone formation is illustrated in Figure 4.29.

Figure 4.29

Relationship between daily maximum temperatures at Heathrow and daily maximum ozone concentrations at Lullington Health, West Sussex



To address the occurrence of the meteorological conditions that drive these summertime air pollution episodes, we have again examined the daily meteorological parameters produced by the Hadley Centre Climate Model (HadCM3). Figures 4.27 and 4.28 show the maximum annual temperatures and minimum annual windspeeds for each year through to 2099. A strong increase in summertime maximum temperatures is clearly apparent in Figure 4.27 taking peak temperatures above 40°C towards the end of the next century. However, it is the simultaneous occurrence of daily maximum temperatures above 25°C and low windspeed conditions which favour the occurrence of summertime air pollution episodes and so the joint distribution of elevated temperatures and low windspeed conditions has been investigated.

Table 4.21 presents predictions of the number of days with low windspeeds and peak daily temperatures for each of the decades through to 2090-2099. There are an increasing number of days with low windspeeds and daily temperatures above the threshold for elevated ozone levels. Table 4.21 also shows that an increasing number of low windspeed days have temperatures in excess of 30°C. Towards the end of the century days are recorded with peak temperatures above 35°C and approaching 40°C.

Table 4.21. The number of days with at least one hour in which the windspeed is less than 2 m s^{-1} and the maximum temperature is in the range shown for each decade up to 2100.

Decade	Number of days in the range from 25°C to 30°C	Number of days in the range from 30°C to 35°C	Number of days in the range from 35°C to 40°C
1990 - 1999	1	0	0
2000 - 2009	1	0	0
2010 - 2019	3	0	0
2020 - 2029	3	0	0
2030 - 2039	5	0	0
2040 - 2049	8	1	0
2050 - 2059	9	2	0
2060 - 2069	8	2	0
2070 - 2079	6	1	1
2080 - 2089	14	2	0
2090 - 2099	15	5	2

In summary then, conditions of low windspeeds and maximum daily temperatures above 25°C appear to occur with an increasing frequency throughout much of the first half of the present century. During the second half of the present century, such conditions appear much more frequently as summers become generally warmer and peak temperatures approach 40°C. The meteorological conditions which drive summertime air pollution episodes should follow on from these simple trends through the next century.

4.7.5 Climate change and global ozone baseline levels

It is firmly recognised that the summertime European regional scale photochemical ozone episodes sit on top of an ozone baseline which is itself global in scale. The evidence is that emissions of nitrogen oxides, methane and carbon monoxide from human activities have increased northern hemisphere ozone baseline levels since pre-industrial times. Ozone monitoring carried out at the Montsouris Observatory near Paris during the second half of the 19th century shows ozone levels which are about one half to one third of present-day ozone levels. Computer modelling studies have shown that this apparent increase in northern hemisphere baseline ozone levels from pre-industrial times through to the present day could have been caused by increasing emissions of methane, CO and nitrogen oxides from human activities. Furthermore, these computer modelling studies suggest that this ozone increase should continue into the future.

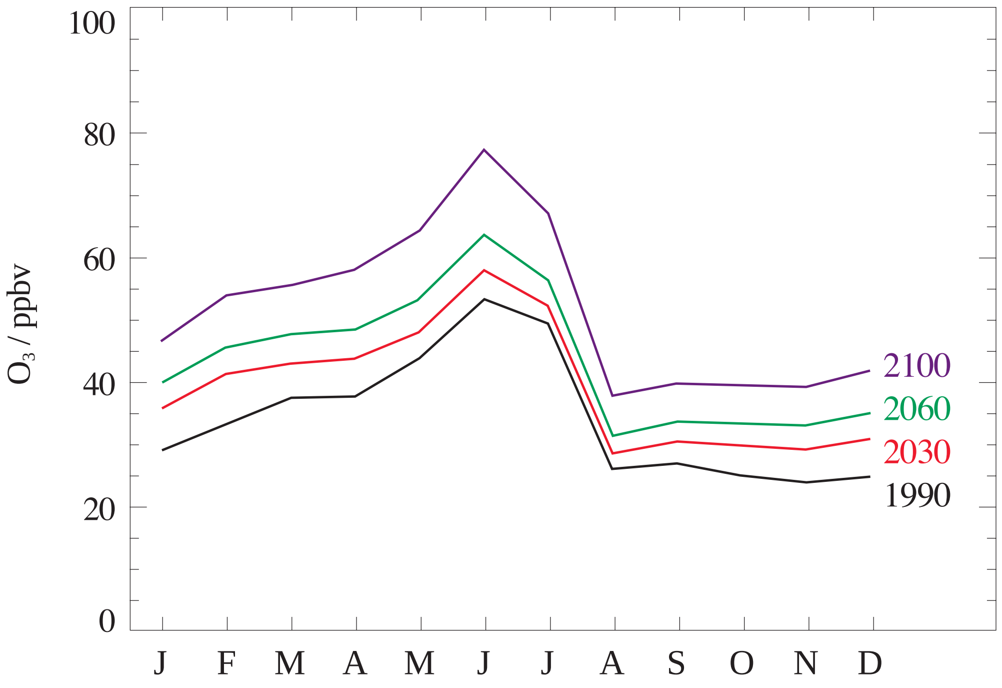
The global three-dimensional Lagrangian chemistry model STOCHEM has therefore been used to calculate the influence of the projected increases in emissions of methane, CO and nitrogen oxides from human activities through to the year 2100 on the global distribution of ozone. The emissions presented in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios have been used and specifically the A2 variant*. The surface ozone distributions for the present day are given in Figure 4.30, with those for 2030 in Figure 4.31, for 2060 in Figure 4.32 and 2100 in Figure 4.33≠.

In the context of the IPCC A2 scenario case, it is readily apparent that surface ozone concentrations are expected to rise steadily throughout the next century. In the 1990 maps, the 60 ppb ozone contour has only a limited global spatial coverage, extending over much of central Europe, China, Brazil and South Africa and the eastern North America during summertime. In 2030, all of these areas of exceedences of 60 ppb have apparently grown in spatial extent, particularly in Europe and North America. By 2060, most of the populated continental areas lie within the 60 ppb contours. In 2100, the 60 ppb ozone contour covers much of the northern hemisphere and most of the populated areas of the southern hemisphere continents.

With this background then, it is not surprising that ozone baselines are expected to increase within the British Isles. We have focused on the global ozone model output to understand the seasonal cycles of ozone at one particular location in central England. Figure 4.34 presents the seasonal cycles in ozone for this location in each of the years 1990, 2030, 2060 and 2100. Because of the spatial resolution of the global model, this seasonal cycle represents that of the northern hemisphere baseline with only a slight influence from European regional scale photochemical episodes.

Figure 4.34

Seasonal cycles in ozone for Central England in each of the years, 1990, 2030, 2060, 2100



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* The IPCC developed long-term emission scenarios for future greenhouse gas emissions for use in the analysis of possible climate change, its impacts and mitigation options. Each scenario represents a quantitative interpretation of one of four narrative storylines — variants A1, A2 B1, B2 — that were developed to represent different directions for future demographic, social and environmental change, economic development and technological progress.

≠ Figs 4.30 – 4.33 are located at the end of this section.

Annual mean ozone concentrations at the central England location increase from 34.3 ppb in 1990, to 39.2 ppb in 2030, 43.5 ppb in 2060 through to 51.8 ppb in 2100. The percentage increases in baseline ozone, relative to the 1990 case, are 14% in 2030, 27% in 2060 and 51% in 2100.

European regional scale summertime photochemical episodes will sit on top of this baseline and are assessed separately.

4.7.6 Estimation of changes in health effects of air pollution associated with climate change

Method

The approach that we have adopted for the estimation of changes in health effects of air pollution associated with climate change is consistent with the approach adopted in the report published by the Department of Health's Committee on the Medical Effects of Air Pollutants (Quantification of the Effects of Air Pollution on Health in the United Kingdom).[35] The results of this type of calculation are a refinement of the crude estimates that might be produced by assuming that all the population is exposed to some national average concentration of pollutants. A method that is equivalent to assessing the population weighted mean concentrations of air pollutants across the country is required because both the concentrations of air pollutants and the population density are variable across the country.

The method adopted by COMEAP[35] to assess the likely heath impact of current air pollutant concentrations can be summarised as follows.

1. The country has been divided into grid squares and the annual average concentration of pollutants and resident population has been estimated for each square. The former has been derived from the national mapping of the UK pollutant concentrations and the latter from census data.
2. A baseline level of the given health-related and pollution affected events e.g., daily deaths, hospital admissions for the treatment of respiratory diseases has been assigned to each grid square.
3. By combining the data from (1) and (2) and applying a coefficient linking pollutant concentrations with the relevant effects the estimated health impact of each pollutant can be calculated for each grid square.
4. Summing the results obtained in (3) gives the relevant totals for the UK.

This method can be used to provide an estimate of the impact of current air pollutant concentrations on health in the UK. This can be combined with information on the likely impact of climate change on future air pollutant concentrations in order to assess their associated health effects.

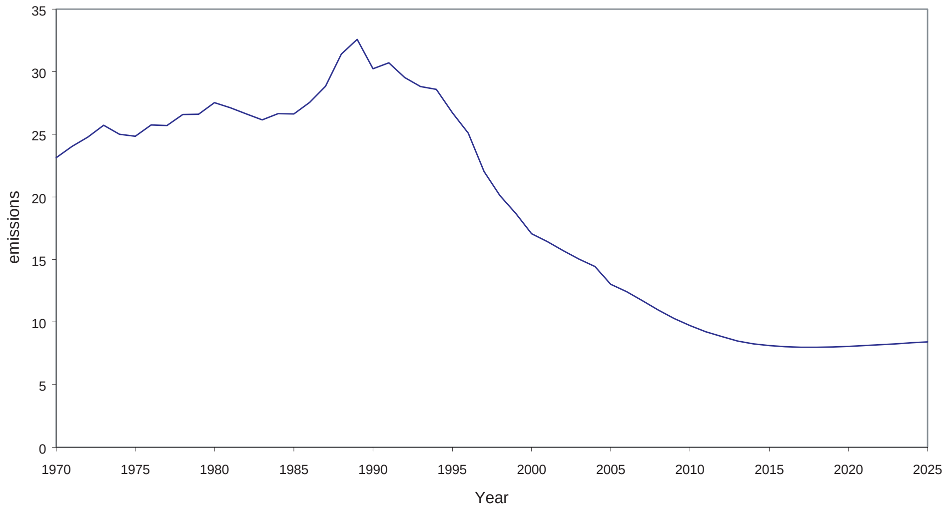
Wintertime PM_{10} episodes

The analysis presented above shows that the meteorological conditions leading to wintertime poor dispersion episodes will become less frequent than at present, particularly during the second half of the present century. Emissions of primary PM_{10} in urban areas of the UK are also expected to decline considerably from current levels over the next century due to the continuing tightening of both fuel and vehicle emissions legislation. Figure 4.35, for example shows the anticipated fall in UK urban traffic PM_{10} emissions up to 2025 from peak levels in the early 1990s.[47] Taken together this indicates that both the frequency of wintertime episodes and concentrations of PM_{10} during these episodes are likely to decrease in the next century.

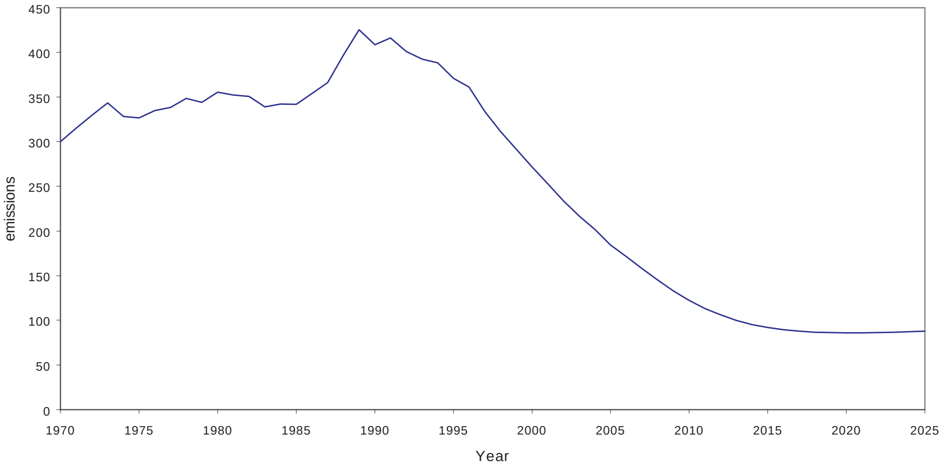
Figure 4.35

Trends in UK urban traffic PM_{10} emissions up to 2025.

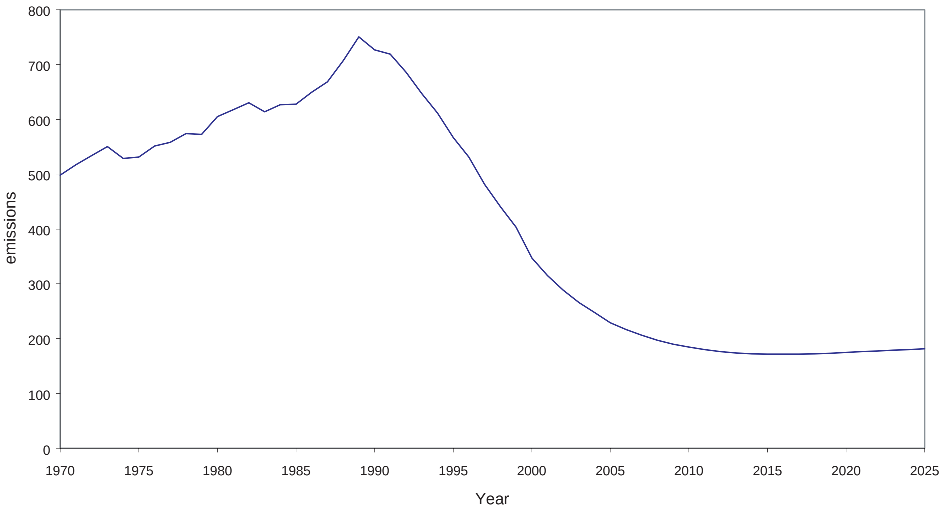
UK Urban PM10 emissions from road transport (ktonnes)



UK Urban NOx emissions from road transport (ktonnes)



UK Urban VOC emissions from road transport (ktonnes)



PM_{10} mean concentrations

The estimates of the health impacts of particles of the type carried out by COMEAP[35] were calculated on the assumption of a linear dose-response function with no threshold. Quantifiable health effects can therefore be considered to depend on annual mean PM_{10} concentration. The most recently published analysis[48-50] estimated that there were a total of 7060 additional or brought forward deaths in urban areas of the UK during 1995 that were attributable to PM_{10}.

Current urban PM_{10} annual means in UK consist of roughly equal thirds of primary, secondary and coarse particles[23] and a decline in both primary PM_{10} emissions and emissions leading to formation of secondary particles are expected over the next 10 to 20 years. The number of deaths brought forward is anticipated to decline to 6170 per year by 2005, due to the reduction in primary emissions from traffic and other sources, with a decline in UK secondary particle concentrations of about 30% between 1996 and 2010.[51] Climate change is likely to lead to better, rather than worse dispersion of primary PM_{10} emissions and the health impacts of annual mean PM_{10} concentrations can be expected to continue to decline in the next century.

Summertime ozone episodes

The analysis presented above shows that the conditions of low windspeed and peak daily temperatures over 25°C appear to occur with an increasing frequency throughout much of the first half of the next century. During the second half of the present century, such conditions appear much more frequently as summers become generally warmer and peak temperatures approach 40°C. Projections of UK urban traffic emissions of NO_X and volatile organic compounds, which are the precursors of photochemical ozone episodes, show similar declines to that shown for PM_{10} and these trends are expected to be mirrored across much of NW Europe.

Estimates of the health impacts of ozone that assume a 50 ppb threshold for effect focus attention on ozone episodes.[35; 52] The most recently published analysis[48-50] estimated that 720 deaths were brought forward during summer 1995 due to ozone episodes. This number is expected to reduce to 235 deaths per year by 2010 due to emissions reductions, which are expected to lead to a decline in peak ozone concentration in 2010 by about 20% of 1995 values. The implied reduction in deaths brought forward is considerably greater than 20% because the reduction takes account of some episode days below 50 ppb.

Taken together, the influence of climate change on increasing the frequency and severity of the meteorological conditions that lead to summertime ozone episodes is likely to be reduced by changes in European emissions of ozone episode precursor species. In the absence of detailed modelling studies, we conclude that the impact of climate change on the health effects of ozone episodes in the next century will be small.

Ozone mean concentrations

Estimates of the health impacts of ozone that assume no threshold for effect focus attention on mean ozone concentrations.[35; 52] The most recently published analysis[48-50] estimated that 12,240 deaths were brought forward during summer 1995 due to mean ozone concentrations for a no threshold health impact calculation.

There are expected to be several influences which will change mean ozone concentration in the present century:

- ❑ Urban ozone concentrations are likely to rise and more closely resemble rural values as urban traffic emissions of NO_X decline.

- ❑ Peak ozone concentrations are expected to fall as precursor emissions are reduced, as indicated above.
- ❑ The most important influence is likely to be that hemispheric ozone background concentrations are expected to increase considerably as indicated above.

A typical annual mean ozone concentration for the rural monitoring site at Sibton in Suffolk during the period from 1990 to 1995 was 26 ppb, which is considerably lower than the estimates of baseline mean ozone concentrations for the UK in 1990 from the global model output. This is because of the influence of both local and regional emissions, which are superimposed on the baseline ozone concentration.

Mean ozone concentrations were higher at sites more remote from emission sources and a typical annual mean ozone concentration at the Strath Vaich monitoring site in North Scotland was 34 ppb, which is in excellent agreement with the model output.

This good agreement between estimated baseline ozone concentrations and measurements enables us to use the model results to carry out a simple extrapolation of the estimates of health effects due to mean ozone forward to the present century. The results of this extrapolation are listed in Table 4.22a and b. Results for years other than those for which we have modelled ozone concentrations have been interpolated.

Table 4.22a Estimated numbers of respiratory hospital admissions (additional or brought forward) and deaths brought forward due to ozone (numbers have been rounded to the nearest 10)

Year	Baseline ozone (ppb)	Respiratory hospital admissions	Deaths brought forward
1990	34.3	10450	12240
2030	39.2	11950	13990
2060	43.5	13250	15520
2100	51.8	15790	18490

Table 4.22b Estimated numbers of respiratory hospital admissions (additional or brought forward) and deaths brought forward due to ozone (numbers have been interpolated and rounded to the nearest 10).

Year	Respiratory hospital admissions	Deaths brought forward
1990	10450	12240
2030	11570	13550
2060	12820	15010
2100	14520	17000

Mean ozone concentration is expected to be the most important issue for the impact of climate change on air pollution and its associated health effects.

Episodes of elevated NO_2 and SO_2 concentrations

Our analysis has not extended to providing quantitative estimates for these pollutants but we can make some qualitative remarks. Very little NO_2 is thought to be emitted directly into the atmosphere as a result of high temperature combustion processes; the bulk of NO_X emissions is in the form of NO, with subsequent chemical reaction to form NO_2. The dominant mechanism is oxidation by ozone:

$NO + O_3 = NO_2 + O_2$.

An additional oxidation mechanism contributes to NO_2 formation at very high NO concentrations (above about 1000 ppb) because the rate of this reaction depends on the square of the NO concentration:

$NO + NO + O_2 = NO_2 + NO_2$

The 'classic' example of winter episodes of elevated NO_2 concentrations is provided by December 1991 in London.[5] This type of episode is therefore expected to become increasing rare as UK NO_X emissions decline from their peak in the early 1990s.

Episodes of elevated NO_2 concentration in the summer occur when photochemical ozone episodes happen at the same time as relatively poor dispersion of NO_X emissions. The magnitude of summer NO_2 episodes is expected to decline over the next 10 years as a result of both reductions in NO_X emissions in urban areas of the UK and the expected decline in peak ozone concentrations resulting from reductions in European emissions of ozone precursors. Taken together with a small increase in the incidence of summertime ozone episodes it is reasonable to assume that there will be a decline in summer NO_2 episodes during the next century but it will be less dramatic than the decline in winter episodes.

Wintertime episodes of elevated SO_2 concentrations tend to be confined to areas of the UK with significant use of coal as a domestic fuel. This use of coal is likely to continue to decline with the use of cleaner fuels and this, together with less frequent episode meteorological conditions is expected to lead to a steep decline in this type of episode.

Episodes of SO_2 pollution during the summer are generally associated with plumes from individual major industrial plant and have not been considered here. The current trend towards tighter regulation, cleaner fuels and cleaner technology in industries such as power generation is however likely to lead to a reduction in the frequency and severity of this type of episode.

Mean concentrations of NO_2 and SO_2

Mean NO_2 concentrations in many urban areas will not decline as steeply as the expected decline in NO_X emissions since current annual mean NO_2 concentrations are often limited by the availability of oxidant (ozone), in addition to the availability of NO_X. The anticipated increase in baseline ozone will, over the next century, therefore tend to lead to more complete oxidation, and limit the decline in mean NO_2 concentrations.

Mean SO_2 concentrations are expected to decline as domestic coal use reduces and cleaner fuels and technology are used in industrial plant. Climate change is likely to lead to better, rather than worse dispersion of SO_2 emissions and the health impacts of annual mean SO_2 concentrations can be expected to continue to decline in the next century.

4.7.7 Conclusions

Summary of effects on health of changes in levels of air pollution caused by climate change and reductions in pollutant emissions

The predicted health effects are summarised in Table 4.23. There will be a reduction in episodes of cold still weather typically associated with winter air pollution episodes. There will be a reduction in the emissions of particles, SO_2 and NO_X. From this we predict a) a reduction in episodic winter pollution and b) a reduction in mean levels of these pollutants. Since there is no threshold assumption for the effects of these pollutants on health, the effects of the fall in the mean ambient concentrations is likely to be greater than that of the reduction in winter episodes. This cannot be quantified due to inadequate predictions of ambient levels and some uncertainties about the health effects of low-level SO_2 and NO_2. However, there is little doubt that the health impact of particles and SO_2 will be substantially reduced. Relatively, the reductions in NO_2 and hence of adverse health effects due to this pollutant will be less because of the increased levels of ozone.

Table 4.23 Summary of predicted climate change associated pollution effects on health

Pollutant	Year 2020	Year 2050	Year 2080
Particles	Large decrease	Large decrease	Large decrease
Ozone (no threshold)	Large increase (by about 10%)	Large increase (by about 20%)	Large increase (by about 40%)
Ozone (threshold)	Small increase	Small increase	Small increase
Nitrogen dioxide	Small decrease	Small decrease	Small decrease
Sulphur dioxide	Large decrease	Large decrease	Large decrease

There will be an increase in episodes of hot sunny days with low wind speeds, typically associated with summer ozone episodes. This is against increasing background concentrations of ozone and reducing emissions of precursor pollutants. From this it is estimated that in the short-term (2010) the days with ozone over 50 ppb will decrease, due to a reduction in precursor pollutants. Deaths brought forward by ozone exposure over 50 ppb will fall by two thirds of the 1995 values. In the longer-term, quantification is not possible but we predict a small (i.e. no more than 10%) increase in the health effects of ozone episodes.

If no threshold assumption is made for the health effects of ozone, the effects of an increase in mean background levels will far outweigh those of episodes. We estimate, using 1990 as a base-line, an increase of approximately 10%, 20% and 40% for deaths brought forward in the years of 2020, 2050 and 2080 respectively. Similar effects on hospital admissions for respiratory disease can also be expected.

It is unlikely that concentrations of particles, SO_2 or NO_2 will be higher during summer episodes and more likely that they will be lower than at present.

Uncertainties

Uncertainties surround all three of the cornerstones of this analysis, i.e. emission scenarios, climate models and health impact assessment. Uncertainties in the climate model have been dealt with elsewhere in this report. Concerning the health effects, we have an imperfect understanding of quantitative relationships between air pollutants and health, and of the scope of possible health effects, especially those which are chronic or the consequence of long-term exposure. We know little about the short- or long-term adaptation that may take place in the population. Because ozone is an oxidant, it may be possible to mitigate its effects by increasing the antioxidant status of the population by, for example, dietary means. Trends in the baseline prevalence of diseases that may be affected by air pollution will also influence the health impact of climate change. For example, if cardiorespiratory diseases continue to decline, so shall the population-attributable risk associated with air pollution. On the other hand, if competing environmental causes of disease (e.g. smoking, acute infections) were to fall, the relative importance of remaining factors such as air pollution would increase. For the purpose of this exercise, the estimated health impacts must therefore be regarded as incomplete and subject to many uncertainties.

There is also considerable uncertainty in the emissions scenarios for the air pollutants that we have discussed. Inventories of current emissions of pollutants to the atmosphere can be verified to a certain extent by the application of dispersal models and subsequent comparison with measured concentrations. Emission projections for future years are based on our understanding of the influences that will affect future emissions. These include forecasts of economic activity and emission factors which relate emissions to the level of activity. Projections can be made on the basis of the impact of current and planned national and international legislation on both activity and emission factors. Reasonably reliable estimates can be made for the next ten to 20 years but the uncertainty of emission projections increases as we look further into the future.

Research

Since ozone is likely to be the main problem, there is a need to understand its effects, both short and long-term, as well as we can. We also need to study ways of mitigating its effects. There are populations currently exposed to the levels of ozone that are higher than predicted for Britain in the future. In Mexico City during 1991-1992, the median 8-hour moving average was 102 ppb, with a maximum of 212 ppb.[53] Studies of health effects in such populations should be considered.

There is also a need for research into the global, regional and UK-scale modelling of the combined effects of climate change and changes in the emissions of the precursors of both baseline and episode ozone concentrations in the next century.

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Figure 4.30

The surface ozone distributions for the present day. Source: Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (A2 variant)

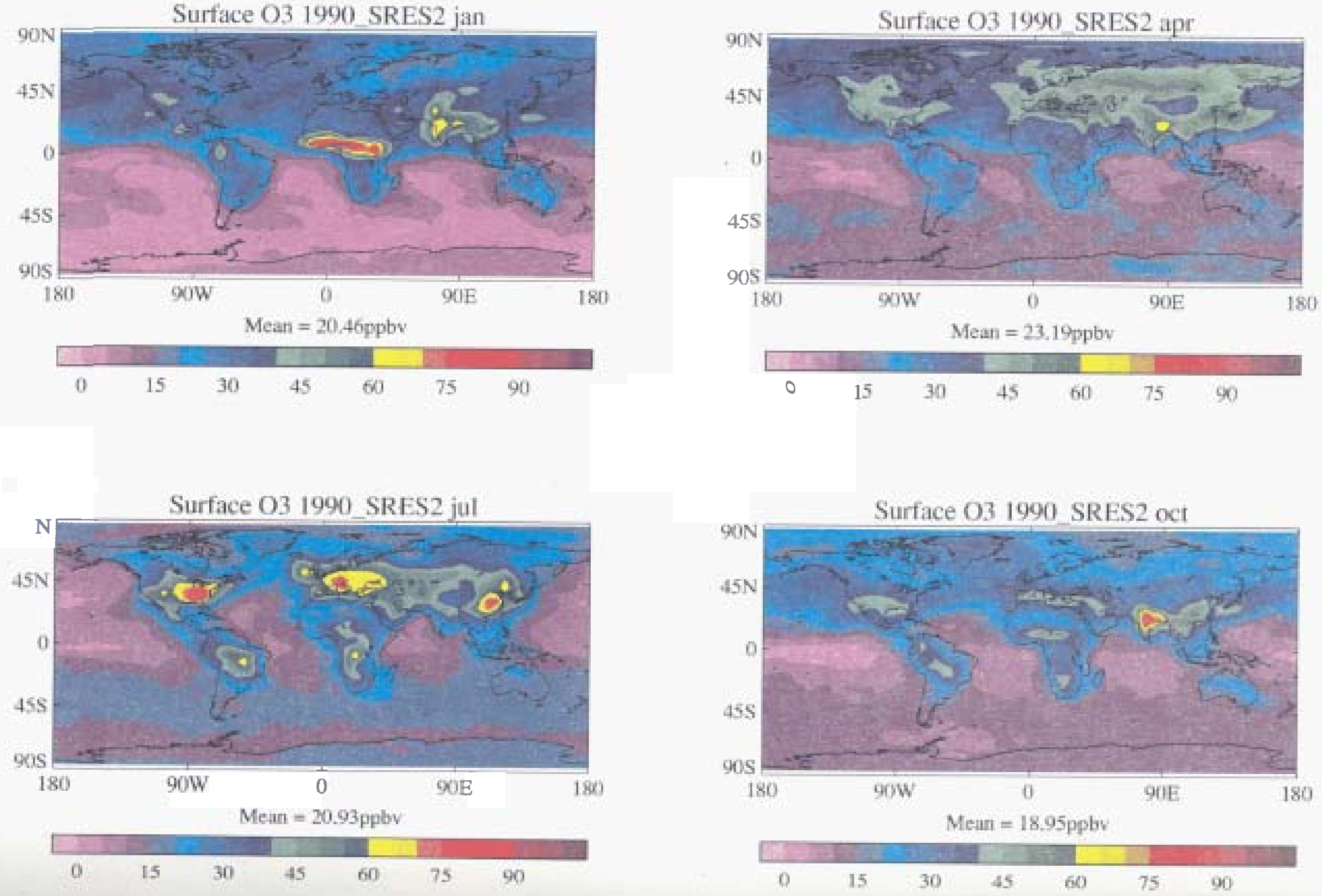


Figure 4.31

The surface ozone distributions for 2030. Source: Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (A2 variant)

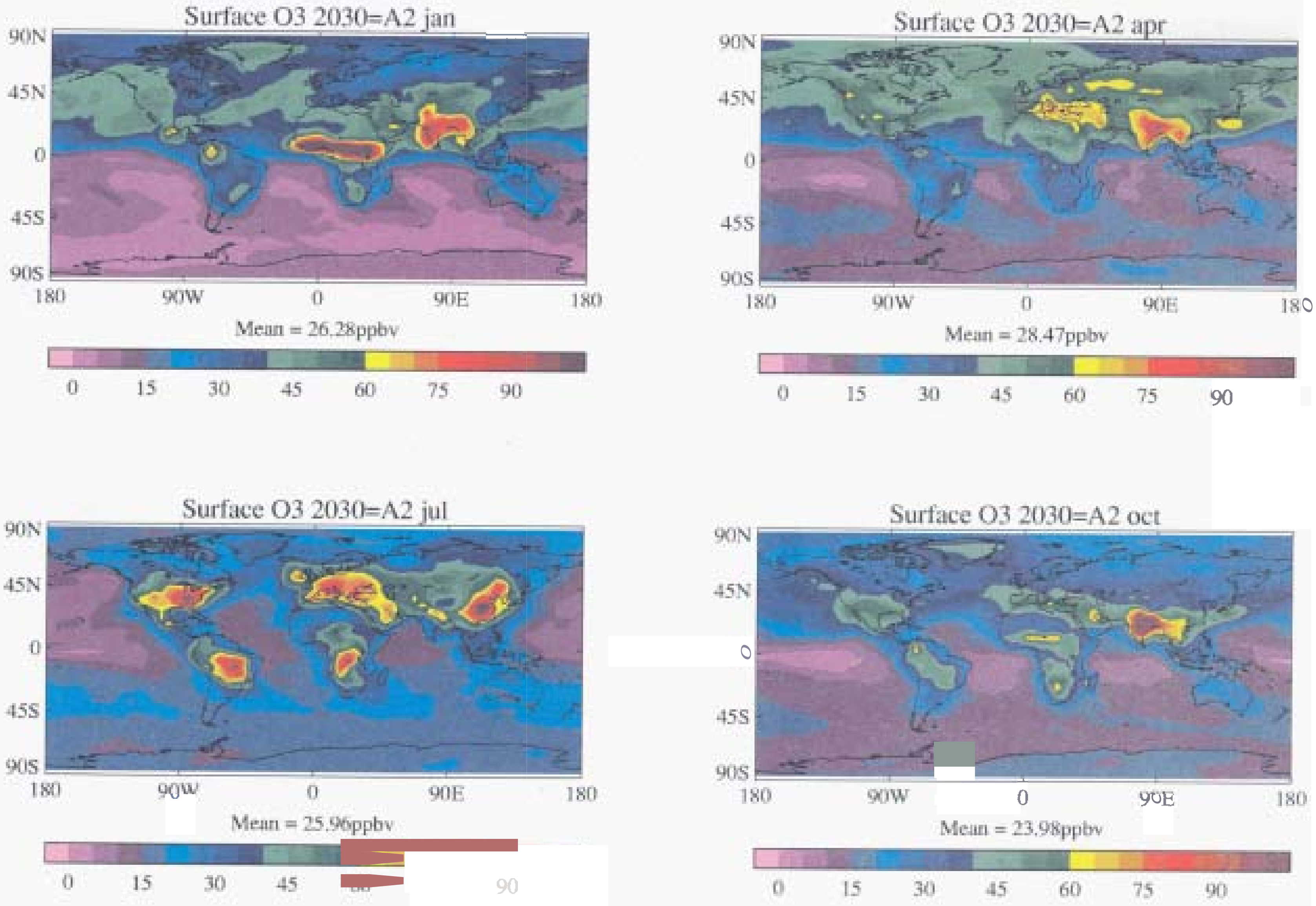
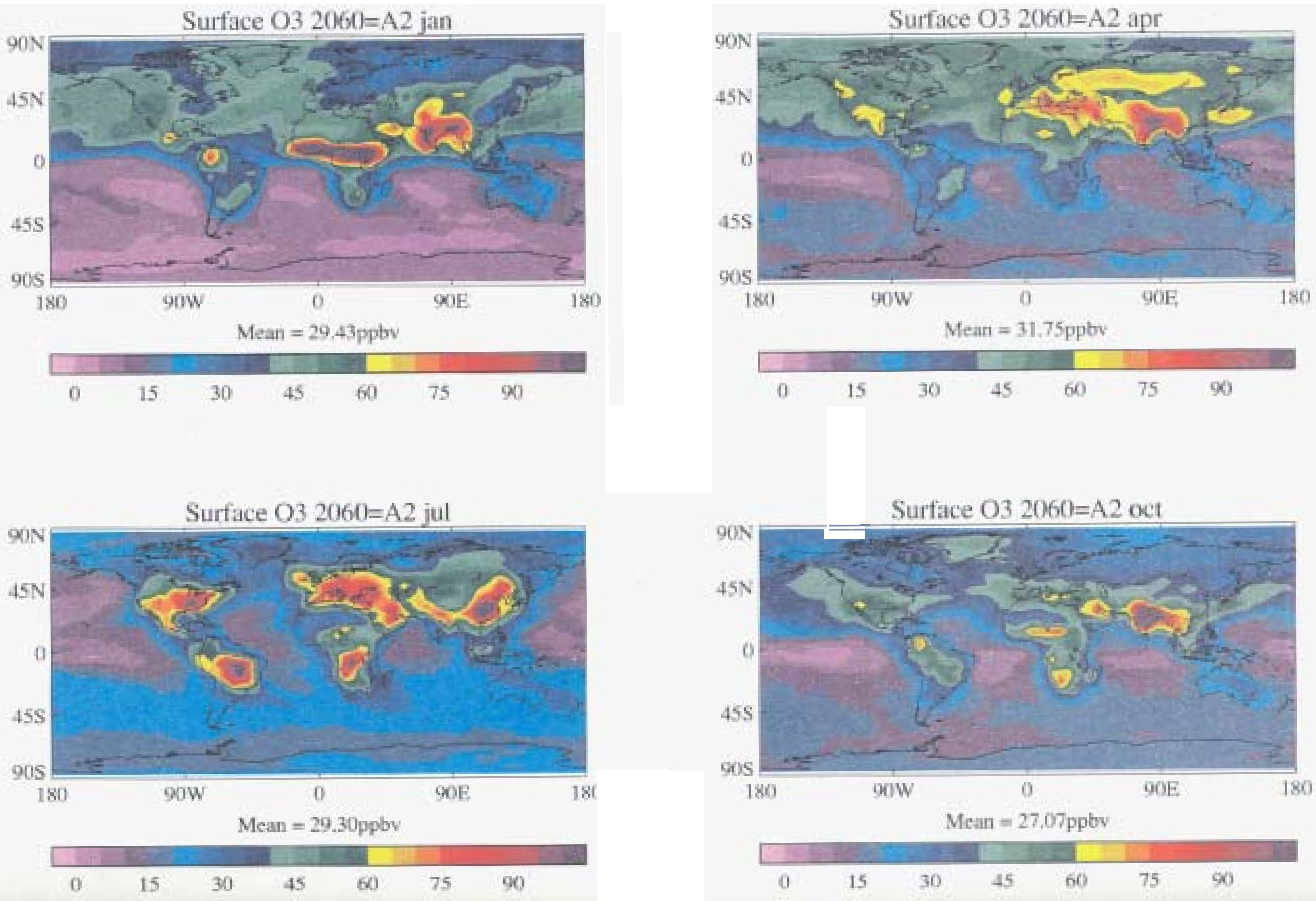


Figure 4.32

The surface ozone distributions for 2060. Source: Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (A2 variant)



Surface O3 2060=A2 jan

Mean = 29.43ppbv

Surface O3 2060=A2 apr

Mean = 31.75ppbv

Surface O3 2060=A2 jul

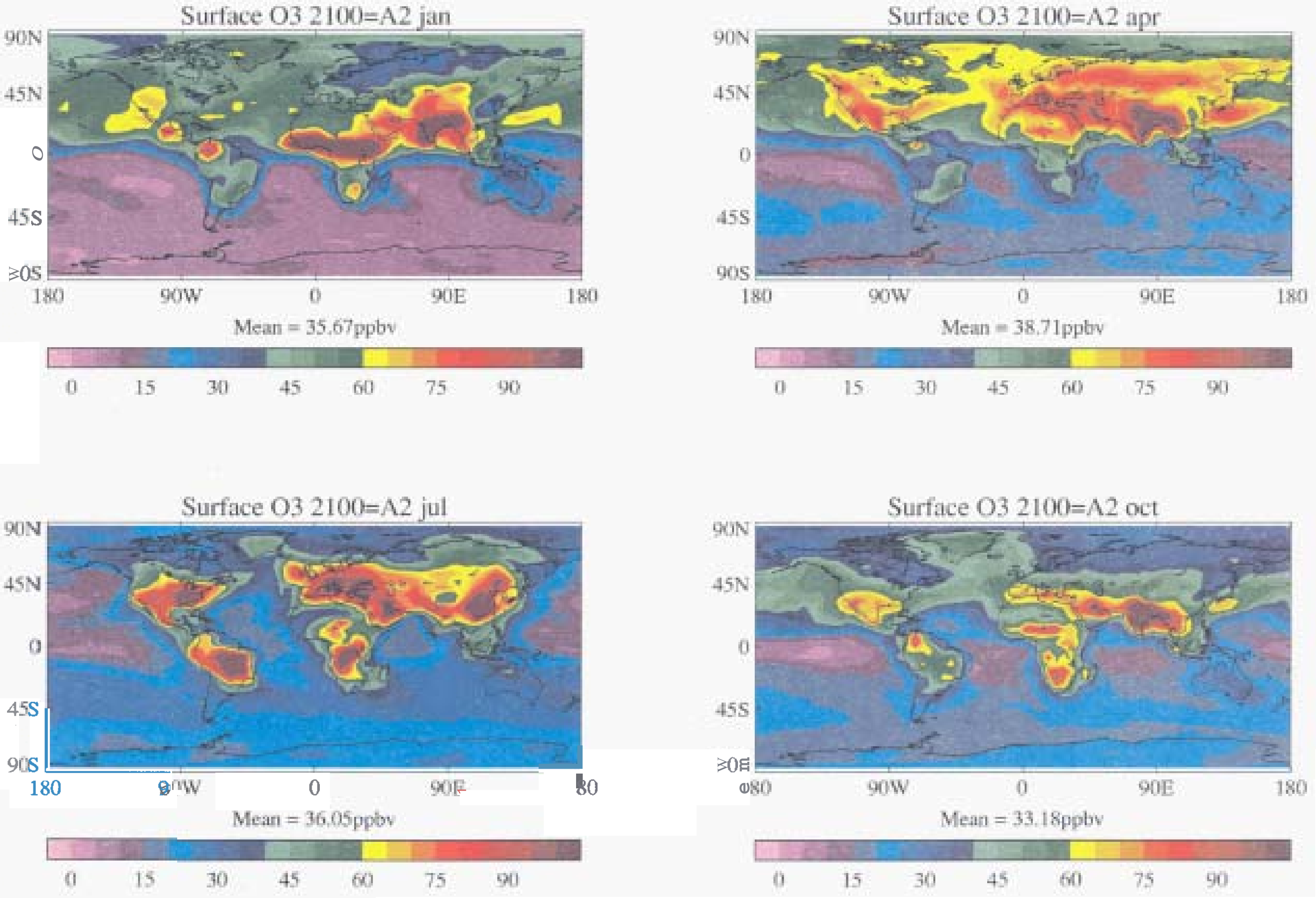
Mean = 29.30ppbv

Surface O3 2060=A2 oct

Mean = 27.07ppbv

Figure 4.33

The surface ozone distributions for 2100. Source: Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (A2 variant)



4.8 UV Radiation

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Summary

❏ Climate change producing warmer weather, and reductions in the capacity of the ozone layer to reduce UV penetration to the earth's surface are likely to lead to increased exposure to UV radiation in the UK.

❏ Quantitative estimates of the effects of increased exposure to UV radiation are based on expected reductions in emissions of chemicals that damage the ozone layer set out in the Montreal Protocol and the subsequent Copenhagen Amendments.

❏ Achievements of reductions in emissions as set out in the Copenhagen Amendments will limit the likely effects of increased exposure to UV radiation in the UK. However, by 2050, some 5000 extra cases of skin cancer and some 2000 more cases of cataract than seen today may be expected each year.

❏ Measures to reduce personal exposure to UV radiation are effective. Thus campaigns to maintain public awareness of the need for such measures are required.

4.8.1 Introduction

The ozone layer in the stratosphere efficiently absorbs most (but not all) of the biologically active UV-B radiation (280-315 nm.) received at the edge of the Earth's atmosphere from the Sun. Levels of UV-B radiation at the Earth's surface are therefore substantially lower than they would be without this protective ozone layer. This is important for human well-being because exposure to ultraviolet radiation (principally UV-B radiation) has a number of effects on health including sunburn, skin cancer, immune suppression and damage to the eye. The discovery of a substantial loss of stratospheric ozone over Antarctica was a cause for concern. This was heightened when evidence emerged that ozone losses (albeit smaller than over Antarctica) were also taking place in the Arctic and over heavily populated mid-latitudes in both the northern and southern hemispheres. This damage to the ozone layer therefore threatened to increase human exposure to UV-B radiation and the health effects associated with it. It is now known that this damage is the result of the release into the atmosphere of certain chlorine and bromine containing chemicals (mostly CFCs, HCFCs and halons) and a series of increasingly stringent international agreements has sought to control their production and use and thereby limit further damage to the ozone layer.

Trends in stratospheric ozone depletion, the resulting changes in ultraviolet radiation and the health and other impacts that these might produce have been the subjects of extensive reviews by the United Nations Environment Programme (UNEP), the most recent of which was published by UNEP in 1998[1]. Other useful reviews of trends in stratospheric ozone and the science of ozone depletion can be found in the report of the Stratospheric Ozone Review Group (SORG)[2]. The report of the UV-B Impacts and Measurements Review Group focused on the climatology of biologically damaging UV-B radiation in the UK, the potential increases as a result of stratospheric ozone depletion and the impacts that these might have, including effects on human health[3] and this has been updated together with the SORG report[2].

Here we summarise some of the main findings of these previous reports with a particular emphasis on health risks from changes in population exposure to solar ultraviolet radiation in the UK. However, most previous reports have focused only on changes in UV dose to the population resulting from stratospheric ozone depletion. Here we also consider the changes that might result from greenhouse gas-related climate change and from changes in behaviour. Consideration is also given to recent claims that there may be some health benefits from exposure to sunlight.

4.8.2 Ozone depletion and UV change

Since the discovery of the ozone hole over Antarctica in the 1980s an intensive monitoring programme from both ground stations and satellites has shown that large-scale losses (typically ~50% compared to values for the 1970s) of ozone occur each year in the Austral Spring. It is now known that the distinctive conditions of the Antarctic stratosphere, particularly the extremely low temperatures and strong polar vortex, are conducive to ozone depletion. However, it is now clear that ozone depletion is not confined to the Antarctic and substantial ozone depletion, averaging ~15% are also occurring in springtime over the Arctic. Of particular concern is the recognition that ozone losses are also occurring over heavily populated mid-latitudes. For northern hemisphere mid-latitudes losses have been ~6% for winter/spring and ~3% for summer/autumn[1]. To date, long-term trends in UV in the UK have not been detected, as high-quality data records do not cover a sufficient period to distinguish trends from natural variability related to factors such as clouds and aerosols[2]. However, there is clear evidence that ozone levels and UV are inversely correlated and it is probable that UV levels in the UK have increased. Using satellite based ozone measurements for the period 1979-1992 and a radiative transfer model it has been estimated that at 55°N. (i.e. the latitude of northern England) increases in UV have been ~4% (erythemal action spectrum) and ~7% (DNA damage action spectrum) per decade[4]. If it is assumed that other factors have remained constant this would suggest that since the 1970s ozone depletion may have been responsible for an increase in ambient UV levels in the UK of between approximately 5 and 10% depending on which action spectrum is used. It should be recognised that, within such longer-term trends, shorter episodes of much greater ozone depletion and UV increase have been observed within the UK, as in the period 30 April to 2 May 1997 when erythemally-weighted ultraviolet radiation levels over southern England were almost 50% higher than normal[5].

4.8.3 Future ozone and UV trends

Atmospheric concentrations of several of the chemicals that cause ozone depletion have peaked in the late 1990s and others are expected to peak in the early years of the 21st century. Ozone depletion is predicted to reach its peak about 15 years later than the peak halogen loadings because of coupling between stratospheric climate change (particularly stratospheric cooling) and ozone chemistry[2]. The maximum amount of depletion and its timing are uncertain due to the complexity of this interaction. Following this peak there should be a slow recovery of stratospheric ozone but it is not expected to recover to its 1980 value (when the ozone hole became evident in the observational record) before about 2050. There is therefore likely to be about a 50-year period of elevated UV levels. However, the future abundance of ozone will be influenced by changes in other atmospheric gases, and by interactions with the climate system. Other factors that could influence the recovery include non-compliance with the Montreal Protocol and its amendments, and future volcanic eruptions. This means that the ozone recovery may not be a simple, slow return to earlier values and may take longer than predicted.

4.8.4 Health effects of UV exposure

If there are no changes in behaviour, increases in UV radiation in the environment will lead to increases in the doses received by the population and any health effects associated with such exposures. Any assessment of the health risks posed by increases in UV levels requires information on the relationship between doses and different health end-points. There is a considerable body of research evidence on the health effects of exposure to ultraviolet radiation[6,7]. For a few health effects this is sufficient to allow a quantitative risk assessment to be undertaken. For others there are important gaps in knowledge that preclude reliable quantification of risk.

Sunburn

Perhaps the most obvious effect of exposure to ultraviolet radiation from the sun is sunburn (erythema). Following exposure there is usually a latent period of 2 to 4 hours with the maximum intensity of erythema being reached between 8 and 24 hours after exposure[3]. Severity varies greatly depending on the intensity of exposure, but if this is high enough the skin can become painful and blistering can occur with the effects taking several days to resolve. Since it is UV-B radiation that is most effective at causing erythema it might be expected that increases in UV-B as a result of stratospheric ozone depletion would increase risk. However, change in risk could be complicated by factors relating to protective adaptation of the skin. A general response to UV-B exposure is thickening of the skin and in many individuals (depending on skin type) the development of a tan provides some protection. This adaptive protection develops over time with UV-B exposure and will typically be lowest at the end of the winter or early spring following the long period (at mid or high latitudes) of low UV-B levels. Springtime episodes of substantial ozone depletion and UV-B increases might therefore carry a particular risk of erythema. This underlines the value of UV warning systems which can alert the public to increases in risk. However, de Gruijl (1997)[7] has argued that since expected ozone depletions are greatest in winter and spring the seasonal modulation of UV-B exposure and loss of protective adaptation may not be so great and this could reduce the harmful effects of spring/early summer exposures. The effect could be less sunburn not more. Such complications mean that a reliable quantitative assessment of changes in the risks of erythema is not yet possible.

Skin cancers

The three commonest types of skin cancer are basal cell carcinoma (BCC), squamous cell carcinoma (SSC) and malignant melanoma (MM). BCC and SSC are often considered together as non-melanoma skin cancers (NMSC). These are very common cancers with figures for the UK for 1989 showing ~30,000 cases of BCC and ~6000 of SCC[3], although because of under-recording these are probably substantial underestimates of the true number. Malignant melanoma is rarer (~4000 cases in the UK in 1989), but it is more aggressive than NMSC and causes more deaths. In common with most other developed countries with predominantly fair-skinned populations the incidence of both NMSC and MM has been increasing in the UK for several decades.

There is strong evidence that exposure to solar ultraviolet radiation is a major aetiological factor for both NMSC and for MM. However, the different types of skin cancer show important differences in the relationship between solar exposure and risk[6]. SCC demonstrates the simplest pattern with risk being related to cumulative lifetime exposure to ultraviolet radiation (predominantly UV-B). It was once thought that BCC risk also showed this dependence on cumulative lifetime exposure, but more recent research suggests a more complicated picture.

Kricker *et al.*, 1995[8] have presented evidence that there may be a plateau in BCC risk at high doses and it has been suggested that exposure during childhood may be particularly hazardous[6]. For MM the picture is even more complicated, with the largest risks being associated with intermittent, intense exposure to unacclimatised skin, as is the case with many outdoor recreational activities and sun-seeking holidays. There is also evidence that exposures in childhood are particularly important. A further complication is that results from animal models suggest that exposure to UV-A as well as UV-B may be important[6]. Since UV-A levels are not strongly influenced by ozone this would mean that ozone depletion would have little influence on that part of the overall risk of MM that was attributable to UV-A rather than UV-B.

Eye damage

Exposure to sunlight is associated with a variety of eye disorders[9] the most significant of which, from a public health perspective, is cataract, which is the leading cause of blindness in the World. This is characterised by a gradual loss in the transparency of the lens, the end result of which is frequently blindness, unless the affected lens is removed by surgery. Several epidemiological studies have shown an association between cortical cataract incidence and UV levels, including studies based on individual UV exposure estimates[10]. However, there is some uncertainty about which part of the solar spectrum is producing the cataract, with evidence that UV-A as well as UV-B may be significant[7]. These doubts about the action spectrum make it difficult to estimate the effects on cataract incidence that might result from ozone depletion which would affect UV-B levels but have little influence on UV-A. Also other factors, such as diet, play a role in the aetiology of cataract and there is a potential for these to act as confounders in epidemiological studies of cataract and UV.

Immune suppression

There is experimental evidence from both animal and human studies that exposure to UV-B radiation can cause suppression of the immune response both locally and systemically[6]. Human infectious diseases that in animal models have shown an effect of UV-B exposure include herpes, tuberculosis, leprosy, trichinella, candidiasis, leishmaniasis, listeriosis and Lyme disease. Experimental studies have also shown that UV-B can activate viruses such as herpes, HIV and human papilloma virus. Such evidence on immune suppression and virus activation has raised concerns that UV exposure could adversely affect the course of some infectious diseases in humans as well as the effectiveness of some vaccinations. However, epidemiological evidence on this issue remains sparse and insufficient to support firm conclusions on the potential impact on human health[6,7]. Perhaps the clearest picture is for the common cold sore (herpes labialis) where it has been shown[11] that UV-B exposure can reactivate latent infections and that application of sunscreen cream can prevent such reactivation. However, suggestions that sunlight exposure could exacerbate HIV infection were not supported in a recent US study[12].

As well as its possible effects on infections, UV-B induced immune suppression may also be important for some cancers. It has been shown that renal transplant patients who receive immunosuppressive drugs to prevent graft rejection are at greatly increased risk of squamous cell skin cancer[13]. Immune impairment, whether by drugs or as a result of diseases such as AIDS, is also the most firmly established cause of non-Hodgkin's lymphoma (NHL)[14]. This has led to the hypothesis that the large increases in incidence of NHL that have occurred in most developed countries may be the result of increased population exposure to sunlight acting as an immunosuppressant[15].

This has been supported by evidence that the incidence of NHL shows a positive association with UV-B levels both within England and Wales[16] and internationally[17]. However, studies from the USA do not show the same association[18,19] and the issue remains controversial.

Possible beneficial effects of exposure to sunlight

It has been pointed out that in addition to having a number of well-established harmful effects there may also be some health benefits from exposure to sunlight[20]. One of the clearest beneficial effects is the production of vitamin D_3 from precursors in the skin on exposure to UV-B radiation,[21] deficiencies of which can increase the risks of rickets in childhood and of osteomalacia and fractures in adults, particularly the elderly[22]. It has also been suggested that vitamin D may reduce the risks of some cancers, including colon, prostate and breast cancers[23] although the epidemiological evidence in support of this is weak and controversial[7]. It has also been reported that vitamin D may protect against acute myocardial infarction[20]. There is also evidence that exposure to UV-B radiation can reduce blood pressure, possibly by means of its effects on serum vitamin D levels[24].

It has also been hypothesised that exposure to sunlight may protect against multiple sclerosis[25]. Noting the strong latitudinal gradient of multiple sclerosis some workers have suggested that this may reflect differential ultraviolet radiation-induced suppression of autoimmune activity.

4.8.5 Quantitative estimates of the health risks associated with stratospheric ozone depletion

There are too many uncertainties in our current knowledge of the effects of UV-B to allow reliable quantitative estimates of all the potential health impact of changes in exposure as a result of stratospheric ozone depletion. For reasons that have been discussed above this is true for sunburn and for the human health effects that might be related to UV-induced immune suppression, and it is also the case for the possible health benefits of UV exposure. However, the literature does include some quantitative risk estimates for skin cancers and for cataract, albeit with important qualifications about their reliability.

Skin cancer risk estimates

Quantitative assessment of the skin cancer risks associated with a given or predicted level of ozone depletion involves two main stages. The first is the estimation of the resulting changes in biologically effective UV dose received by the population, which is sometimes referred to as the radiation amplification factor (RAF). The second involves the use of dose-response models to estimate the change in cancer incidence (or mortality) that can be expected from the change in UV dose, and this is often called the biological amplification factor (BAF). The overall increase in incidence per percentage ozone depletion is then represented by the amplification factor (AF) $AF = RAF \times BAF$.

In the UNEP 1998 assessment the AF for SCC is estimated to be 3.0 and that for BCC 1.7. There is greater confidence in the AF for SCC than for BCC because of the relatively straightforward relationship between risk and cumulative lifetime UV dose. For malignant melanoma the uncertainties are even greater, particularly because of the uncertainties about the role of UV-A as well as UV-B in the development of melanoma. If this is strongly UV-A dependent then ozone depletion might have little impact on melanoma risk, since UV-A levels (unlike UV-B) are not greatly affected by ozone. Accordingly, in the UNEP 1998 assessment the RAF for melanoma is estimated as being in the range of 0.1 to 1.2.

The most sophisticated attempt to estimate the effects of ozone depletion on skin cancer incidence is a study by Slaper *et al*. (1996),[26] the results of which are reported in the UNEP 1998 assessment. The model that is used integrates dynamic aspects of the full source-risk chain, from the production and emission of ozone depleting substances, through their atmospheric residence time, their effects on ozone, the increases in carcinogenic UV radiation and finally the increases in skin cancer incidence. This is done for a number of scenarios including one involving no restriction of ozone-depleting substances and comparing this with a scenario based on compliance with the Montreal Protocol and its Copenhagen amendments. Results are presented for all skin cancers combined, although the model does take into account differences in response for the main types of skin cancer. They are given for the USA and for north west Europe which includes, and should be broadly representative of, the UK. The baseline incidence of skin cancer (all types) is taken to be 1100 per million per year; Table 4.24 shows the model estimates of the increases in incidence rates associated with different scenarios for ozone depletion. The 'no restrictions' scenario assumed a continuous 3% increase in the production of ozone-destroying substances. In the 'Montreal Protocol' scenario it is assumed that the production of the five most important ozone depleting chemicals is reduced to 50% by the end of 1999, as agreed upon in 1987. In the 'Copenhagen Amendments' scenario the production of 21 ozone depleting chemicals is reduced to zero by the end of 1995. The model assumes full global compliance with these restrictions and unchanged human behaviour with respect to sun exposure.

Table 4.24 Model estimates of excess cases of skin cancer per million per year for north west Europe[26]

Year	Scenario		
	No restrictions	**Montreal Protocol**	**Copenhagen Amendments**
2000	17	17	14
2030	121	103	58
2050	348	231	89
2070	1017	414	77
2100	3468	1051	23

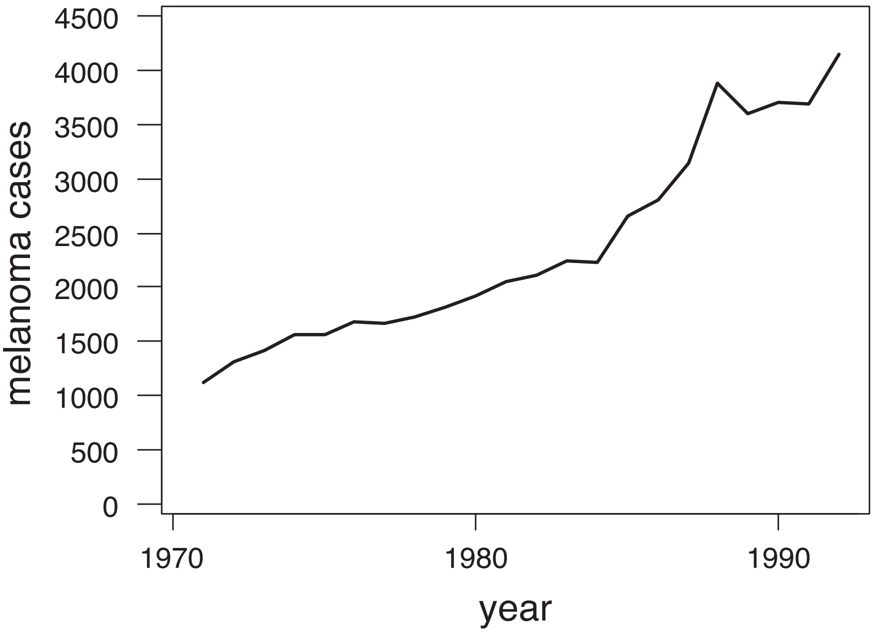
The results suggest that if the production of ozone depleting chemicals had been allowed to increase without restriction this would result in a very large increase in the incidence of skin cancer. The Montreal Protocol controls would have limited the scale of this rise, but the increase would still have been substantial. Under the more stringent restrictions of the Copenhagen Amendments the increase is much smaller, peaking at an increase of ~90 skin cancer cases per million per year in 2050, after which there is a gradual fall as a consequence of the recovery of the ozone layer. For the UK with a population of ~60 million this would imply ~5000 additional cases of skin cancer per year at the time of the peak impact in 2050, which represents a relative increase in risk of ~8%. To put this in perspective, Figure 4.36 shows that the registered incidence of melanoma in England and Wales has been increasing at ~6% per year over the period 1971-1992, while non-melanoma skin cancers have shown a rise of ~4% per year. Against the background of such large changes over time in skin cancer incidence as a result of factors such as changes in behaviour it seems unlikely that increases related to ozone depletion would be detectable epidemiologically. However, it should be emphasised that the risk estimates for ozone depletion produced by Slaper *et al.* (1996)[26] should be regarded as conservative estimates of impacts. They assume full compliance with the restrictions on ozone-depleting chemicals, which may not be achieved. Also they may not adequately represent the effects of other factors, such as changes in stratospheric temperatures, which could influence the future pattern of ozone depletion. Nor do they take into account any changes in behaviour, nor the ageing of the population.

Cataract risk estimates

In the light of the uncertainties about the role of UV-B radiation in the development of cataracts the UMIRG 1996 report on the potential effects of ozone depletion in the UK did not feel justified in making quantitative estimates of the effects on cataract. However, others have made quantitative estimates, albeit with strong qualifications about the uncertainties that are involved. Reviewing the experimental and epidemiological data, de Gruijl (1997)[7] suggests that a rough estimate would be that cataracts could ultimately increase by ~0.5% for every lasting 1% decrease in ozone. The 1998 UNEP assessment presents the results of risk estimates for the US population produced by its Environmental Protection Agency. This is based on an integrated risk model based on different scenarios for ozone depletion, similar to the approach taken by Slaper *et al.* (1996)[26] for skin cancer. This concludes that without restrictions on ozone depleting chemicals and even with the controls under the original Montreal Protocol there would have been a very large increase in cataract incidence. However, assuming compliance with subsequent more stringent controls, such as the Copenhagen Amendments, there would be more modest increases peaking at ~30 excess cases per million per year near the middle of the 21st Century. If it is assumed that these results are broadly applicable to the UK population this would imply ~2000 excess cases per year.

Figure 4.36

Malignant melanoma registrations in England and Wales 1971–1992



4.8.6 Climate change, sunlight exposure and health

The prospects of increased solar UV-B radiation as a result of stratospheric ozone depletion has attracted a great deal of attention. However, what has frequently been overlooked is that greenhouse-gas induced climate change may also independently influence population exposure to sunlight and hence the risks associated with it. One of the reasons is that clouds have a substantial effect on the amount of UV-B reaching the surface. The 2050 Medium-High climate change scenario for the UK[27] shows decreases in summer cloud cover of about 4% for south-eastern England and consequent increases in incident short-wave radiation, although elsewhere the changes are smaller and for Scotland cloud cover increases slightly. Where summer cloud cover decreases an increase in UV-B can be expected, with a decrease in cloud cover of 4% likely to be associated with ~2% increase in ambient UV-B levels[28]. However, changes in climate such as increases in sunshine, reductions in precipitation and higher temperatures would all be likely to favour patterns of behaviour involving more outdoor activity, lighter clothing and greater exposure to the sun. At the moment summers in Britain are often too dull and cold to encourage an outdoor lifestyle but a move to sunnier and warmer conditions could have a substantial effect. Casual observation suggests that in warm sunny summers such as 1995 the British spend a much longer time outdoors: they are more likely to eat their lunch outdoors (at the time of peak levels of UV-B); there is greater participation in outdoor leisure activities, including sunbathing at the beach; and they are likely to wear clothing that exposes more of the body. Unfortunately there is very little empirical evidence on the possible links between climate, outdoor activity and UV exposure in the UK, which would allow a quantification of the risks that might be involved. The only relevant data are from a study by Diffey *et al.* (1996),[29] which reports the results of a survey of primary and secondary schoolchildren which recorded time spent outdoors and UV exposure using personal film badges. This showed that children in southern England spent a longer time outdoors at weekends and received substantially more UV exposure than those in northern England. Furthermore, the differences in UV exposure between areas were much greater than the differences in ambient UV levels, suggesting that other factors such as climate may be important influences on behaviour and UV-B doses received by the population. Although such evidence from current geographical variations in UV-B provides only indirect evidence it is consistent with the possibility that climate change could lead to a marked change in patterns of behaviour that might increase population exposure to sunlight and the health risks associated with it. It is therefore possible that future doses of solar UV-B for the UK population may be affected more by greenhouse gas-related climate change than by stratospheric ozone depletion. However, any conclusion must remain tentative until we have further research evidence on the links between climate and weather, patterns of behaviour and the UV-B doses received by the population.

Behavioural influences on exposure to sunlight and associated health risks

The health effects of solar UV radiation depend on the doses received by the population and these depend on:

1. the UV flux in the environment;
2. patterns of behaviour which bring about exposure to UV in the environment; and
3. any deliberate actions taken by the population to mitigate the effects of such exposure.

It has been stressed above that both stratospheric ozone depletion and greenhouse gas-related climate change may increase UV-B levels in the UK, although such changes are not expected to be large. We have also commented on the possibility that climate change could encourage changes in behaviour that lead to greater exposure to sunlight. However, such factors will not be the only influence on UV dose since this is also profoundly affected by changing patterns of human behaviour that are taking place for a variety of other reasons. It is likely that the large increase in skin cancer in the UK (and elsewhere) in the past half century has been the result of changes in lifestyles and behaviour rather than any changes in UV flux, which altered little over this period. One important factor has probably been the growth of holiday travel to foreign destinations, which is still continuing. Furthermore, in recent years the most rapid increases in foreign holiday travel have been to low-latitude destinations where UV levels are typically high. For example, holiday visits to the USA (where Florida is the most popular destination) increased 15-fold in the 20 years up to 1997. It therefore seems likely that changing patterns of holidaymaking will continue to be an important factor, tending to increase the overall UV doses received by the UK population and any associated health risks. Closer to home, recent results from the General Household Survey[30] confirm that the long-term growth in outdoor leisure activities has continued in the 1990s with consequential increases in sunlight exposure. Future trends remain uncertain but a continuation of such increases would add to the UV doses experienced by the population and the risks associated with them. What is less clear is whether the effects of such trends may have begun to be mitigated by a deliberate move to more cautious patterns of behaviour in the sun. Social survey-based data (Office of National Statistics, 1997) have appeared which show that most people are aware of the importance of measures such as staying in the shade, avoidance of the sun, the use of suncream and the wearing of a wide-brimmed hat. Notwithstanding this widespread knowledge of how to avoid risk, substantial numbers of respondents still reported getting sunburnt in the last 12 months and positive attitudes towards having a suntan were common. This suggests that for many people knowledge of risks and how to avoid them is not being fully reflected in changes in behaviour. Nor do we yet have sufficient information on whether there are any significant trends over time in attitudes or behaviour. Hints that such changes might be underway come from the divergence in trends in melanoma incidence and mortality by sex, where the upward trend for females is slower than that for males. Interestingly, survey evidence[31] shows that women's knowledge of the importance of sun-avoidance measures is greater than men's and they are less likely to have experienced recent sunburn.

The evidence that behavioural factors profoundly affect solar UV exposure and associated health risks suggests that changes towards a more cautious pattern of behaviour could mitigate the effects of increases in UV-B levels in the environment.

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5 Secondary impacts of mitigation

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5.1 Introduction

Section 4 described the potential nature and scale of direct effects of climate change on health in the UK. This section describes some of the potential indirect effects arising from measures taken to combat climate change.

The principal measures proposed by UK government focus on the reduction of greenhouse gases, mainly carbon dioxide, through the reduction of energy use. This reduction in energy use is expected to come about through alternative or more efficient energy conversion, reducing energy loss and by reducing the primary demand for energy. The consequences of many of these measures for the health of UK residents are likely to be neutral; from some, however, a positive health outcome can be expected whilst for others the health outcome will depend on how the measure is implemented. There is, therefore, considerable uncertainty about the scale of the potential benefits. In this section we have therefore focused on the nature of the impacts of the measures proposed and on the areas in which further analysis might support the assessment of different options.

Further measures, beyond action on energy, are also under active consideration to control some of the secondary greenhouse gases. These may also impact on health, but the outcomes are even more uncertain.

5.2 UK Policy on reducing Greenhouse Gases

The Kyoto Protocol agreed in December 1997 contained a target for the UK of 12.5% reduction of greenhouse gas emissions from their 1990 level by sometime within the period 2008-2012. However, the Government has as an aim of policy a CO_2 emission reduction of 20% by 2010. Proposals for measures which would enable the UK to meet these targets are presented in a document entitled *Climate Change: Draft UK Programme* published for consultation in March 2000[1]. *This report was completed before the draft climate change consultation document was published by DETR. The draft will be studied and this report updated before final publication.*

For each of six economic sectors, the DETR consultation paper sets out current measures required to meet the Kyoto target and the further measures which might be needed to achieve more demanding aims of policy. The current measures emerge in part from the broader UK policy framework, including:

- ❏ the sustainable development strategy set out in *Opportunities for Change*[2];
- ❏ the integrated transport strategy contained in the White Paper *A New Deal for Transport*[3]; and
- ❏ the energy strategy contained in the White Paper *Conclusions of the Review of Energy Sources for Power Generation*[4].

The climate change programme also takes account of fiscal measures including the road fuel duty escalator, the landfill tax and the reductions in VAT on domestic fuel and power and on insulation products. The current estimate of potential saving in the six sectors is given in Table 5.1.

Table 5.1 Estimated potential reductions of greenhouse gases in the UK

Year	**1990 Baseline**	**2010 Projection (assuming current policy) Savings in MtC**	**Further measures (lower cost measures) Savings in MtC**	**Further possible measures (higher cost measures) Savings in MtC**
Energy sector	72	13	0	5
Business	87	12	3	7
Transport	39	–3	4	2
Domestic	47	6	3	4
Agriculture, forests and land use	26	4	0.5	0
Public	9.7	0.3	0.5	0.6
Total	**280.7**	**32.3**	**11**	**18.6**
Change from 1990 (greenhouse gases)		12%	15%	22%
Change from 1990 (carbon dioxide)		–3%	–9%	–20%

MtC = Mega tonnes Carbon

The potential health impacts of the measures to achieve these savings are described in the sections below.

5.3 Energy Supply Industry

The main measures to be taken within the energy supply industry (ESI) include policies to address market distortions, the implementation of Integrated Pollution Prevention and Control (IPPC) and the further review of ESI fuels. These are expected to lead to greater plant efficiency, increased use of combined heat and power and, in the longer run, of renewable energy sources. The UK waste strategy is also expected to lead to a greater use of incineration with heat and energy recovery, further displacing conventional power station fuels (Section 5.8).

The most likely outcome is a further reduction in the use of coal and heavy oil, with coal demand falling to below 50 million tonnes in 2010 compared with some 70 million tonnes in 1997. Less efficient and well-governed plant will be replaced to an accelerated timetable as IPPC measures take effect.

These changes in fuel mix and the plant inventory will have an impact on emissions of air pollutants from the ESI. Emissions of sulphur dioxide (SO_2) and oxides of nitrogen (NO_X) are controlled at a national level through the Government's plan for meeting agreements under the UNECE Long Range Transboundary Air Pollution Convention[5]. Emissions of fine particles are controlled at present under European legislation and will be controlled in future under provisions of IPPC. The measures to be taken to achieve UK targets for CO_2 will add to these pressures. All three major pollutants are subject to air quality standards, set on the advice of the government's Expert Panel on Air Quality Standards, because of their health impacts[6].

The added health benefits due to pressure on emissions from the climate change strategy remain to be calculated.

5.4 Business (including manufacturing and commercial sectors)

Pressure on carbon emissions from the business sectors will, as in the case of the ESI, tend to accelerate the shift from primary to secondary energy and from coal and oil to gas as primary energy sources. This is expected to reduce air pollution emissions from the sector, with a matching contribution to national aims for protecting health against the impacts of air pollution.

5.5 Transport

Transport is the one UK sector in which CO_2 emissions are rising, by an expected 5% above 1990 levels by 2000. This rise is due mainly to the continual growth in road transport, in particular in private cars.

The measures envisaged to reduce CO_2 emissions include action to improve fuel efficiency and to manage the demand for motor transport.

Measures to improve fuel efficiency are likely to include fuel switching, from petrol and diesel to alternative fuels such as gas and electricity, with an associated beneficial local impact on emissions of regulated pollutants. The impact of regulated pollutants, in particular NO_X and fine particles on health is recognised in the UK National Air Quality Strategy and the increased pressure for reductions in their levels from the UK Climate Change Strategy will act to accelerate health benefits.

It is well established that speed is linked to road accidents. Fuel consumption is also linked to speed. Reduction of speed limits and general traffic calming offer highly cost-effective opportunities to reduce greenhouse gas emissions. They will also have the effect of reducing road traffic accidents.

Measures to reduce demand for motor transport include reducing the need to travel, by better planning and promoting walking, cycling and public transport.

Recent reports by the British Medical Association[7] and the Health Education Authority[8] described the damaging effects of motor vehicles and the health benefits of strategies for reducing vehicle use. Damage to health is a result of road accidents (more than 3000 deaths annually in the UK), air pollution and community severance. However, there is also strong evidence[9] that the benefits of exercise from walking and cycling, which reduce cardiovascular disease, can greatly outweigh these risks. In a study of London, for example,[10] it was calculated that a 10% shift from cars to cycling and walking might save 100 deaths and 1000 hospital admissions in London each year.

5.6 Domestic Sector

Measures to address carbon emissions from the domestic sector are focused largely on improved efficiency of energy conversion in heating and domestic appliances and on reducing energy losses, for example though improvements in home insulation.

The Government plans to increase funding for the Home Energy Efficiency Scheme, the Energy Saving Trust and the Energy Efficiency Best Practice Programme. It will make more money available for local authorities to tackle the backlog of repairs. For the future, further scope for improvement for example through the building regulations and the wider use of community heating has been identified and the contribution such measures would make to reduction of greenhouse gases is being assessed.

Many of these measures are aimed primarily at fuel poverty and the general need to conserve energy in the domestic sector. They receive a powerful boost, however, from the contribution they make to the Government's climate change policy as they are seen as cost effective compared to other measures, for example in the transport sector. As a result, schemes for improving domestic energy efficiency, which might not otherwise be implemented, are under active consideration.

The effect of improved domestic energy efficiency and home insulation should be to produce a more consistent indoor climate at a more affordable cost than at present. Estimates of the impact this will have on health are not available at present. It is estimated, however (Section 4.1) that winter deaths could be reduced by 2-3% with changes of 2-2.5°C increase in winter temperatures. Changes of this magnitude are not expected until 2050, but exposure of vulnerable communities, the poor and old, to indoor cold would be reduced by domestic sector measures at an earlier stage.

However, there are dangers if domestic sector measures lead to changes in ventilation regimes that would reduce indoor air quality. Furthermore, these measures are focused at present on the provision of affordable warmth to alleviate winter distress. Their impact on the provision of a cool summer indoor environment has not been assessed.

5.7 Agriculture, Forestry and Land Use

Agriculture both absorbs and emits greenhouse gases. For example, using fertilizers causes significant emissions but agricultural soils can act as a sink by sequestering carbon. It is assumed that crop cycles are broadly neutral but that new schemes, for example reforestation, will act to provide a carbon sink. It is also assumed that the agricultural sector can contribute through the development of biomass energy to offset fossil fuel use.

The effects on health of planned mitigation measures is likely to be small. The effects of policy, endogenous change in agriculture and the impact of climate change on agricultural production may be more significant.

If a lower-energy agriculture leads to reduced production of livestock (and feeds) with increased consumption of fresh fruit and vegetables this will also have health benefits through reduction in cardiovascular disease[11].

5.8 Public Sector

The principal measure proposed for the public sector is the general improvement of energy efficiency in public estate, including schools, hospitals and government buildings. This will impact on the comfort of these places in winter and will provide an improved working environment for public servants.

However, the public sector is also responsible for waste disposal; 85% of waste goes to landfill. This in turn produces some 40-50% of the national emission of methane, a powerful secondary greenhouse gas[1].

Measures to reduce methane emissions at a national level are highly dependent on what can be achieved from the reduction of landfill gas. There has, therefore, been considerable progress in control through landfill gas capture and energy recovery. This also has the effect that land fill sites are likely to become less hazardous when the land is reclaimed for housing.

A European Community Directive on landfill will reduce the amount of municipal solid waste diverted to landfill, with more expected to go to incineration with heat and energy recovery. The use of conventional ESI fuels could be reduced by up to 5 million tonnes of coal equivalent by 2020 and, since incinerators will be required to achieve the highest environmental standards, this can be expected to produce further reductions in regulated pollutants from the ESI.

5.9 Conclusion

Measures taken to reduce greenhouse gas emissions are themselves likely to have an impact on health. This will be through improved indoor climate, improved external air and exercise integrated into ordinary daily activities of travel.

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6 Recommendations for further work

It has become clear during preparation of this report that a great deal is unknown about the likely effects of climate change on health in the UK. Whilst we also recognise that climate change is not a process that occurs rapidly, and that it will be some years before a marked effect on health in the UK occurs, we are concerned that this timescale may inhibit action which should be taken now, to improve understanding of likely effects and develop means for mitigation of the more severe effects.

We recommend, therefore, that the national programme of work in this area that has already begun be continued and expanded as the evidence that shows that effects are likely becomes increasingly clear. As we have pointed out in several places in this report, the work of the UK Climate Impacts Programme is of critical importance. Funding for this programme and by Research Councils is essential. This will ensure that future studies of the likely impact of change in health are even better based than the present study.

In drawing up a list of specific recommendations for further work and research we have tried to structure our recommendations. We recommend work in the following areas:

1. *On the extent of climate change likely to occur in the UK during the coming century*
    - ❑ Improved modelling of the likely climate change in the UK is needed.
    - ❑ Modelling should include finer resolution spatial analysis of likely changes.
    - ❑ Modelling should also provide better predictions of the likely changes in the risk of extreme weather events such as severe winter gales.
    - ❑ There is a clear need for better understanding of non-linear or rapid changes in the climate of the UK.
2. *On the impact of climate change on a wide range of factors that have a direct or indirect effect on health*
    - ❑ The links between climate change and events such as severe winter gales and storm surges should be explored. The likelihood of increased maximum windspeed during severe storms is of critical importance.
    - ❑ Better modelling of building damage by high winds is needed.
    - ❑ The effect of climate change on the distribution of daily temperature extremes should be explored.
    - ❑ The effect of changes in daily temperature on bacterial and algal growth in water for drinking and recreation should be explored.
    - ❑ The association between temperature and food poisoning should be explored.
    - ❑ Work is needed on the impact of climate change on arthropod and other vectors of disease in the UK and elsewhere.
    - ❑ Improved modelling of the interaction between climate change and changing levels and patterns of emissions of air pollutants and their precursors is needed.
    - ❑ Improved modelling of links between climate change, depletion of the ozone layer and ground level exposure to UV radiation is needed.

3. *On the linkages between the factors discussed above and effects on health*
    - Better assessment of populations most at risk from exposure to changes in temperature, especially extremes of temperature, is needed.
    - A better understanding of both the association between ambient temperature and disease and of the underlying mechanisms of this association are needed.
    - Improved reporting and investigation of food poisoning are needed.
    - Improved reporting of and investigation of outbreaks of water-borne diseases are needed.
    - Improved reporting of vector-borne diseases is needed. Increased occurrence of rare diseases may require focused research. A GP-based system for reporting such diseases is recommended.
    - Refinement of the exposure-response relationships for air pollutants, especially for ozone, is needed.
4. *On means of mitigating the effects of such factors on health and on the extent of adaptation that is likely to occur*
    - Improved systems for forecasting severe gales and floods are urgently required.
    - The development of programmes to raise community-awareness of the effects of extreme weather conditions and associated events such as floods, should be pursued urgently.
    - A better understanding of people's adaptation to changing temperature patterns is needed.
    - Research into the effects of dietary factors such as the intake of antioxidants on the effects of exposure to ozone is needed.
    - Studies of effective means of advising people to modify their behaviour, for example by use of hats and sunscreen ointments are needed.
    - Development and exercising of plans for coping with disasters such as widespread flooding should be advanced.
    - The provision of coastal defences against storm surges should be reviewed and the risk analysis associated with such work should be made publicly available.

Annex

Members of the Expert Group on Climate Change and Health in the UK

Three workshops (18 February 1999; 25 June 1999; 5 November 1999) were held at the MRC Institute for Environment and Health to discuss the potential health impacts of climate change in the UK. Individuals listed below participated at one or more of these meetings.

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