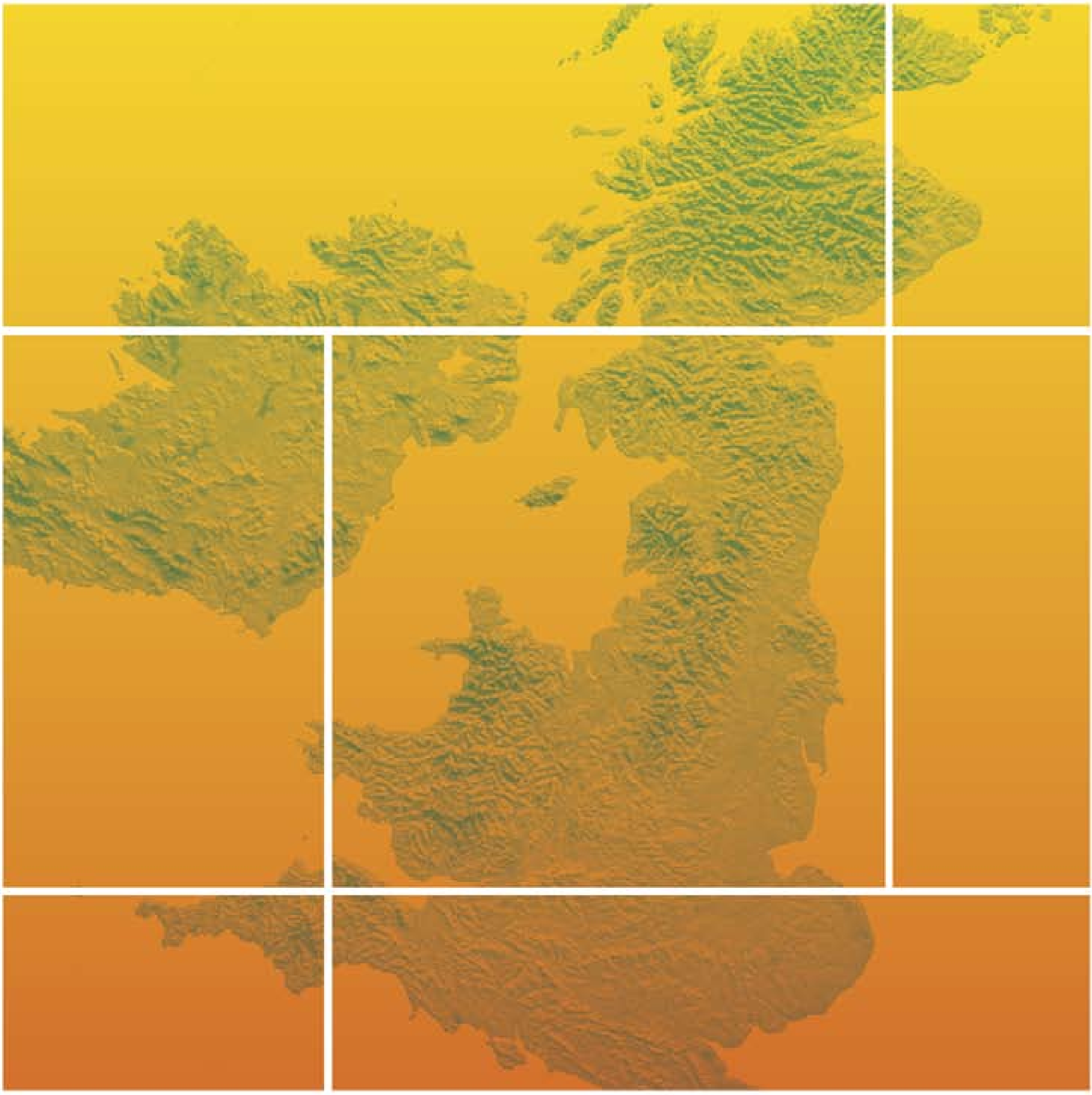
Health Protection Agency

Health Effects of Climate Change in the UK 2008

An update of the Department of Health report 2001/2002

Edited by Sari Kovats



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Health Effects of Climate Change in the UK 2008

Edited by Sari Kovats

Preface I

Climate change will have consequences for the health of UK citizens. In 2002 the Department of Health published a report on the '*Health Effects of Climate Change in the UK*'. This report was amongst the first of its kind in that it sought to provide quantitative estimates of the possible impacts of climate change on health. The report was well received and widely quoted.

Now, six years later, I am pleased to welcome an update to the original report, published jointly by the Department of Health and the Health Protection Agency. Independent scientific experts were commissioned by the Department of Health to focus on areas that had changed since the original report was written. The briefer new report is therefore to be read in conjunction with the previous report. This report was first published in draft for wider comment on 4th May 2007. Valuable comments have since been received which have been acknowledged in the appendix. Apart from updating the report, the messages remain the same.

Since the work of this expert panel, other key reports on climate change have been published, most recently that of the Intergovernmental Panel on Climate Change (IPCC). Our report supports the IPCC findings but concentrates solely on the impacts of climate change on human health rather than including the factors which affect climate change itself.

One of the effects of climate change already encountered in this country is the increased frequency of heatwaves. The devastating heatwave across Europe in 2003 led to the Department of Health first launching its *National Heatwave Plan* in 2004, in which a 'Heat-Health Watch' system operates in England during the summer months, with advice from the Met Office, with four levels of response and appropriate advice.

Key areas for the NHS in adapting to climate change include: adapting the health and social care infrastructure (hospitals, nursing homes) to be more resilient to the effects of heat, gales and floods; development of local 'Heatwave', 'Gale' and 'Flood' plans for coping with disasters; and increasing awareness of how people can adapt to changes in climate.

Actions are also being taken across the UK Government and the NHS to reduce emissions contributing to climate change. The UK's Climate Change Bill is the first legislation of its kind in the world, establishing a long-term legal framework to underpin the UK's contribution to tackling climate change, by putting in place a clear and credible emissions reduction pathway to a statutory goal of a 60% reduction in carbon dioxide emissions by 2050.

From the Government's climate change programme, the Department of Health is leading in setting mandatory targets for energy/carbon efficiency for the public sector and is working with the Carbon Trust on the NHS Carbon Management Programme. Work is continuing across the NHS at a regional and local level to mitigate to the projected impacts of climate change. The NHS is working towards mandatory energy and carbon efficiency targets (from 2000 to 2010) with advice and guidance from the Department of Health on energy/carbon management for existing operational estate and for new capital build developments. However, whilst the energy performance of the NHS is improving, with over 70% meeting the mandatory targets of 55–65 gigajoules/100m^3, due to the expanding size of the healthcare estate, the growing levels of service provision and use of medical and other technologies, energy use is increasing.

In January 2007 the then Minister of State for Health Andy Burnham announced a £100M Energy and Sustainability Capital Fund for 07-March 09 to assist the NHS to meet the overarching target of 15% energy or 0.15 million tonnes carbon efficiency saving between 2000 to 2010, particularly by 'spend to save' initiatives.

DH is continuing to work with the Sustainable Development Commission on the ‘NHS as a Corporate Citizen’ self-assessment model already taken up by over 200 NHS bodies which includes action to make operations more sustainable. Sustainable Operations on the Government Estate (formerly known as the Sustainable Development in Government programme) requires reporting on sustainable developments in government and addressing operational targets on energy use, water and waste.

Climate change poses great challenges and it is important to plan ahead for the health consequences. Let’s not forget we also have a societal role to play in the mitigation of climate change by supporting sustainable development programmes – through consumer choice, reducing our carbon footprints and recycling waste.

Dawn Primarolo

Dawn Primarolo

Preface II

Climate change is perhaps the most significant environmental problem which mankind will face in the coming century. Efforts to reduce the extent of climate change are of course important, but it is likely that we will have to deal with at least some impacts on health. Preparing for climate change is now one of the top four shared priorities for UK action set out in 2005 in *Securing the future: Delivering UK sustainable development strategy.*

As a response to the need to estimate possible impacts of climate change on health, this new report, jointly published by the Department of Health and the Health Protection Agency, is a timely update of earlier work published by the Department of Health in 2002 (*Health Effects of Climate Change in the UK*).

The new report should be read in conjunction with the original report as it focuses on areas where things have changed rather than covering, again, the whole field. A new approach has been taken in some sections and recent research findings have been included in many chapters.

The report was written by Dr. R.L. Maynard and a group of UK experts and we are grateful to them for their input to this incisive report and for the time they devoted to it.

The report was edited by Sari Kovats. Her contribution has been most important – indeed the report would not have been completed without her input.

Sir William Stewart
Chairman
Health Protection Agency

Reference

HM Government (2005) *Securing the future: Delivering UK sustainable development strategy*. The Stationery Office.
www.sustainable-development.gov.uk/publications/pdf/strategy/SecFut_complete.pdf

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Executive summary

The Department of Health report *Health Effects of Climate Change in the UK*, published in 2002, was among the first of its kind in that it focused on the quantitative aspects of possible impacts of climate change on health. The report was well received both in the UK and abroad. The present report provides an update on the findings of the first report but is not a second edition. Much that was included in the original report remains of value and detailed accounts of some approaches to quantification of effects have not been repeated here. In this second report a different approach has been taken in some of the major areas of concern. Preparation for climate change is now one of the top four shared priorities for UK action set out in 2005 in *Securing the future: Delivering UK sustainable development strategy*.

A small group of experts was asked to consider the original report and to advise on whether updating was needed. The group included chapter authors from the group that wrote the original report and experts who had not been involved before. For some chapters revision was recommended; for others, substantial rewriting was undertaken.

An important feature of the report is the updating of the climate change scenarios provided in Chapter 2. These reflect state-of-the-art work: the UK is among world leaders in this area of prediction of climate change. It is now perhaps even clearer than it was in 2002 that the climate of the UK is changing. The latest models used in this report predict an increase of mean annual temperature in the UK of between 2.5 and 3 degrees centigrade by the end of the century. Periods of very cold weather will become less common, but periods of very hot weather (heatwaves) will become more common. Application of the epidemiological concept of ‘attributable risk’ to meteorological data allows us to assess the extent to which human influence on climate has contributed to the risk of a specific weather event. Using this approach, a significant role for human influence can already be identified in, for example, the European summer heatwave of 2003 which contributed to over 14,000 premature deaths in France. Changes in wind and rainfall are less certain but periods of sudden heavy rain seem likely to become more common despite a possible reduction in annual rainfall in some areas. Flooding is an increasing risk.

We know rather little of the total effects on health of flooding. These were discussed in some detail in the original report and that discussion has not been repeated here. The predicted risk of severe coastal flooding remains low, but this will increase as sea levels rise. The need for upgraded coastal defences in East Anglia is stressed.

As regards vector-borne diseases the picture is perhaps more encouraging. Reappraisal of the evidence suggests that outbreaks of malaria in the UK are likely to remain rare, though Health Authorities need to remain alert to the possibility of outbreaks of malaria in other European countries and to the possibility that more effective vectors (different species of mosquito) may arrive in the UK. Rapid response to outbreaks of malaria will reduce the chances of the disease becoming endemic in the UK. Tick-borne diseases are likely to become more common in the UK, but this will be more likely to be due to changes in land use and leisure activities than to climate change. The likelihood that tick-borne encephalitis will become established in the UK is very low.

Warmer summers are likely to be associated with an increase in foodborne diseases but the picture has not changed significantly since the original report was published.

A fresh look at the effects of climate change on supplies of drinking water has been taken. Three problems have been identified: increased rainfall (over short periods) leading to increased numbers of bacteria in surface water; increased water temperature leading to an increase in algal blooms in reservoirs; and a decrease in the efficiency of chemical coagulation: a major method of removal of microbes from drinking water.

A new approach to the direct effects of high temperatures on health has been taken in this report. This chapter (Chapter 6) should be read in conjunction with that in the original report: both contain important and complementary material. Summers in the

UK have become warmer, but no change in heat-related deaths occurred during the period 1971–2003. This suggests that the UK population is capable of adapting to warmer conditions. But heatwaves still present a serious risk. Predicting severe heatwaves and their effects is difficult, but there is a 1 in 40 chance that by 2012 South-East England will have experienced a severe heatwave that will cause perhaps 3,000 immediate heat-related deaths. In terms of conventional thinking about risks to health a risk of 1 in 40 is high. Winter deaths will continue to decline as the climate warms.

The air pollution climate of the UK will continue to change. Though concentrations of a number of important pollutants are likely to decline over the next half-century, the concentration of ozone is likely to increase. This will increase attributable deaths and hospital admissions. The increases are likely to be significant: with the least constraining assumptions (no threshold of effect assumed) up to about 1,500 extra deaths and hospital admissions per annum might be expected.

Further work has confirmed the effects of increased exposure to ultra-violet light. Skin cancers are expected to increase.

In each chapter of the report summaries of the main points are made and a number of recommendations for mitigating the effects of climate change on health are put forward. These can be summarised as:

- the need for greater emphasis to be placed on climate change and its impacts and the need for governments to focus on this problem
- measures individuals can take to mitigate the effects of climate change on their health. Keeping cool in hot weather is important. The easy-to-remember advice “keep cool, keep clean, keep covered” remains sensible
- the need for further research in many of the areas touched on in this report.

Contents

1 Climate change in the UK: the evidence

(See also Chapter 3 in 2001/2002 report)

Tom Holt, Climatic Research Unit, University of East Anglia
Clare Goodess, Climatic Research Unit, University of East Anglia
David Viner, Natural England

Summary

- Mean annual Central England temperatures have continued to rise and are now over 2°C higher than in the coldest period of the 'Little Ice Age' in about 1690. Half of this increase occurred in the last 40 years, which has also seen a rapid rise in the number of hot days. These changes are consistent with anthropogenic warming.
- Total summer rainfall in England and Wales has decreased by about 50mm over the last 250 years, while autumn and winter rainfall have both increased by about 50mm.
- Assuming a medium-high emissions scenario, the increase in mean temperature over the UK by the end of the century is projected to be about 2.0°C (±0.2°C) in winter and about 4.0°C (±0.3°C) in summer.
- The duration of the annual longest cold spell (a period of days with the lowest daily temperature below 0°C) is projected to decrease all over the UK, with the greatest reduction of about 7 days (±1 day) in Scotland.
- Hot spells (defined as periods with daily maximum temperature higher than 25°C) are projected to be prolonged on average by up to 10 days (+1 to 2 days) over Central and Southern England, and by up to 5 days over the rest of the UK.
- Changes in average annual total rainfall have too much uncertainty to say more than that Scotland is likely to become about 10% drier by the end of the century and most of the rest of the UK will not change very much. The average annual maximum length of drought is projected to extend by about 4 to 6 days (±1 day) over much of England and Wales.
- Episodes of very high wind speeds are expected to decline over much of the UK under global warming. However, increases are noted over Wales, North-East England, and North-West Scotland. Changes in the average annual highest maximum daily wind speed are trivial and uncertain.
- Heatwaves of the order of the 2003 event for England will be encountered only occasionally until about 2030. After this, however, they can be expected much more frequently, becoming much more severe in intensity and duration after 2060.
- A shutdown of the North Atlantic thermohaline circulation system leading to colder winters is considered highly unlikely on the centennial timescale considered here.

Recommendations

- Construction of refined climate scenarios focused on health impacts. This will require work on the following issues:
    - further downscaling to finer spatial scales
    - improved representation of urban areas and their heat sources in climate models, in order to model changes in the urban heat island effect
    - focus on indices of extremes of greatest concern for health impacts, e.g. threshold temperatures used in the Heatwave Plan for England
    - consistency with the UK Climate Impacts Programme 08 (UKCIP08) scenarios, which will be probabilistic.

1.1 Introduction

Since the first report on the 'health effects of climate change in the UK', the assessment of future climate change has been updated in the revised national scenarios (UKCIP02). The observed warming trends have been confirmed with more recent years. Globally, 2005 was the second hottest year on record, after 1998.

A new generation of high-resolution climate models (Regional Climate Models or RCMs) allows for improved estimates of future changes in the frequency, intensity and duration of extreme events in the UK.

This chapter briefly describes the current scientific consensus on the current and future effects of climate change on the UK climate, as well as introducing the scenarios that are used in the later chapters to estimate future health effects of climate change.

1.2 Observed trends in UK climate

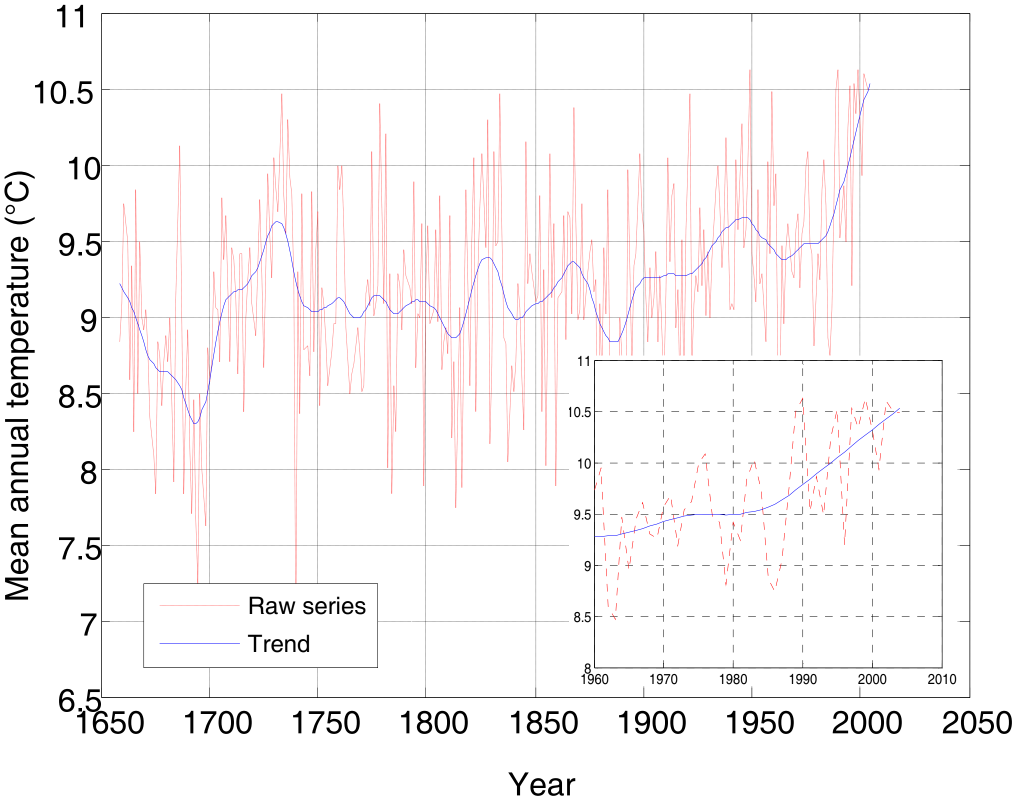
1.2.1 Observed warming in England

The Central England Temperature (CET) series provides time-series of air temperature at the surface for an area covered by the triangle with coordinates Preston, Bristol, and London. The mean monthly series is available from 1659 to present and is the longest instrumental temperature record in the world (Manley, 1953 and 1974). Daily time-series of the CET are available from 1772, and daily maxima and minima from 1878 (Parker *et al.,* 1992).

Figure 1.1 shows the mean annual CET series based on monthly data from 1659 to 2004. The trend is shown using a numerical filter. This decomposes the time-series into its non-stationary time trend and stationary residual components. Here, the term 'stationary' is used in its statistical sense to denote a time-series with a constant mean. Clearly, therefore, a time-series with trend induced by global warming, for example, must be a non-stationary series. The same filter is applied to all time-series in this chapter.

Following the coldest period of the 'Little Ice Age' in about 1690, temperatures in the Midlands climbed until about the year 1730, then fell by 0.5°C until 1750, and remained essentially stable until about 1900. Temperatures then peaked once more around the year 1950, fell slightly until 1960, and then climbed steeply (by about 1°C) to the present day. The detailed inset in Figure 1.1 focuses on the period 1960 to 2004, when temperatures started and continued to rise. Mean annual CET values are now 2°C higher than in the coldest period of the 'Little Ice Age'. Half of this increase occurred in the last 40 years, which is consistent with theories of anthropogenic warming of the atmosphere. In the case of global temperature, the Intergovernmental Panel on Climate Change (IPCC) has stated that 'there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities' (see Houghton *et al.*, 2001).

Figure 1.1 Mean annual Central England Temperature: full record and last 44 years



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1.2.2 Hot days and days below freezing

The number of hot days in the UK has been increasing along with mean temperature. Both increases are consistent with theories of anthropogenic climate change. The number of days per year when mean daily CET values exceeded 20°C (Figure 1.2a) was quite stable until about 1960, after which temperatures began a persistent and rapid climb to present levels.

The behaviour of the number of days per year with temperatures below 0°C is, however, quite different, with a continuous decrease since the 1770s (Figure 1.2b). The onset of anthropogenic warming coincides with the end of the 'Little Ice Age', so the ambient climate was already warming at that point. It is difficult to disentangle the influence of the two causes. However, it is clear that daily variability has reduced considerably since about 1960, although the number of cold days has continued to fall. Given the similar timing of the increase in numbers of warm days (Figure 1.2a), it is reasonable to assume that the decline in numbers of cold days over recent decades has the same causal mechanism.

2003 was the fourth hottest summer in the CET record. It was exceptional in terms of absolute maxima (with new record maxima for both England and Scotland) and for the extent and persistence of very high night-time temperatures (Burt, 2004a and b). On 10 August 2003, maximum temperatures greater than 37°C were recorded from at least 13 locations in South-East England (Burt, 2004a). Analyses of the very hot summer of 2003 from a climatic perspective have, however, tended to focus on France, Germany, Italy and, in particular, Switzerland (Beniston, 2004; Luterbacher *et al.*, 2004; Schar *et al.*, 2004; Stott *et al.,* 2004). These studies indicate that the summer of 2003 was probably the hottest in Europe since the year 1500 and that human influence has at least doubled the risk of a heatwave of this magnitude occurring.

Figure 1.2a Number of days per year with daily mean CET exceeding 20°C

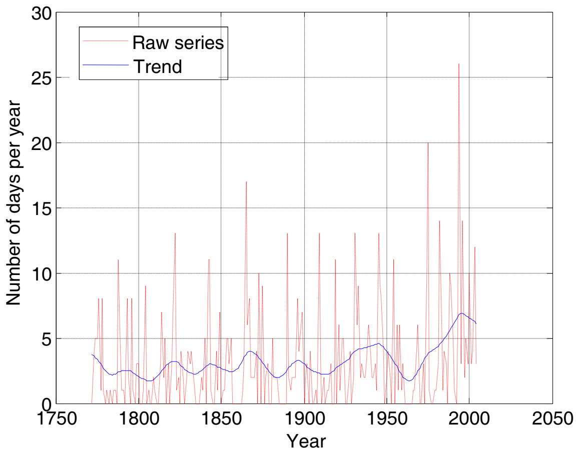

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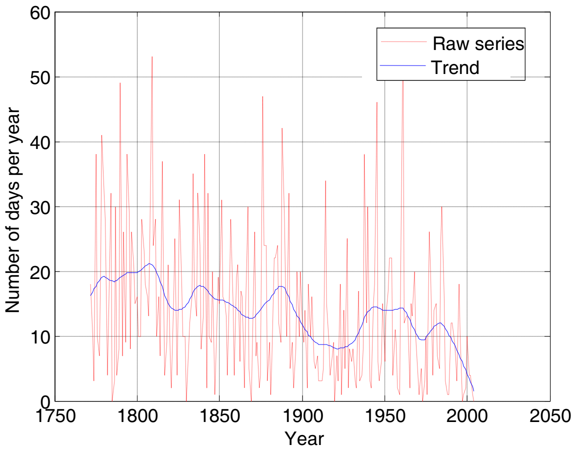
Figure 1.2b Number of days per year with daily mean CET below 0°C



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1.2.3 Rainfall

There has been a rising trend in annual total rainfall in England and Wales since about 1970, but this is well within the natural variability found over the series as a whole (Wigley *et al.*, 1984; Jones and Conway, 1997).

When rainfall is broken down into its seasonal components, however, pronounced linear trends are identified in all seasons apart from spring. Summer rainfall has fallen by about 50mm over the last 250 years, whereas winter and autumn rainfall have each increased by about the same amount over this period. As with cold temperatures (section 1.2.2), these trends are consistent over much too long a period to be associated fully with global warming. It is possible that for the first part of the record the trend is due to recovery from the 'Little Ice Age'. Given the absence of abrupt changes in rainfall regime over the last few decades, such as those described for temperature, it is not possible to attribute any of the recent England and Wales precipitation trend to anthropogenic warming.

The England and Wales rainfall series discussed above allows examination of long-term rainfall variability, but does not tell us anything about spatial variability in rainfall trends. Analysis of 146 UK weather station records for the period 1961–2000 indicates increased rainfall totals and increased frequency and contribution of heavy rainfall events during winter, and decreases during summer (Osborn and Hulme, 2002). These changes tend to be spatially coherent, i.e. broadly similar across the UK, although the largest winter changes tend to occur in the Western UK (especially North-West England and Western Scotland) and summer rainfall decreases are less evident in Western Scotland, South Wales and parts of Northern Ireland. Changes in rainfall due to climate change are discussed in relation to flood risk in Chapter 3.

1.3 Future climate change in the UK: the UKCIP02 scenarios

The world's changing climate is a result of both natural and anthropogenic factors. A stable climate requires a balance between incoming solar radiation and outgoing radiation. Fundamental to this stable state is the natural greenhouse effect, the process whereby greenhouse gases such as carbon dioxide, methane and nitrous oxide absorb and emit infrared radiation, trapping heat within the atmosphere and maintaining a suitable temperature for human habitation.

Anthropogenic climate change is caused by the rising concentration of greenhouse gases and aerosols in the atmosphere. These arise from various human activities performed with increasing intensity since the beginning of the Industrial Revolution in the late 18th century. Natural variations in climate have historically been associated with a number of factors, including variations in solar output, changes in the orbital characteristics of the Earth, and volcanic eruptions – ash and sulphur dioxide emissions alter the reception and reflection patterns of solar radiation. However, the balance of evidence indicates that that warming experienced in the last 50 years is 'very likely' to be due to human activities (Houghton *et al.*, 2001).

The UK is fortunate in having national climate scenarios (Hulme and Jenkins, 1998; Hulme *et al.,* 2002). The current set of scenarios – called UKCIP02 – is based upon the latest socio-economic scenarios (the special report on emissions scenarios (SRES), see Nakicenovic *et al.*, 2000) and was constructed from a high-resolution RCM HadRM3h, developed by the Hadley Centre.[1] For these and other reasons, the UKCIP02 scenarios represent a significant improvement in scenario construction. Box 1.1 summarises the main differences between the UKCIP02 and the UIKCIP98 scenarios which were used in the first climate change and health report (Department of Health, 2001/2002).

It is important to be aware that climate models such as those used in the construction of the UKCIP scenarios do not provide a definitive prediction of what climate will be like at a particular time in the future. The models simulate climate change according to a particular set of assumptions about the world, including a particular regimen of greenhouse gas emissions.

There are two main categories of uncertainties in all climate scenarios: future emissions of greenhouse gases, which depend on future human activities; and scientific uncertainties. The latter are, in theory, reducible. Climate model uncertainties, for example, can, in part, be addressed by considering output from a number of different models rather than from a single model. The UKCIP02 scenarios are based on output from a single suite of models, although some intercomparisons with other models are presented in the Scientific Report (Hulme *et al.*, 2002) and the Hadley Centre has subsequently undertaken some more detailed intercomparisons with output from other RCMs (Jenkins and Lowe, 2003; Rowell, 2004). The most recent Hadley Centre commentary on the UKCIP02 scenarios considers the effect of global dimming[2] (a reduction in global radiation at the surface due to changes in atmospheric aerosols and clouds). While the underlying HadCM3 simulations do show global dimming over the past few decades, this is only a small fraction of that observed.

The UKCIP02 scenarios are described in a Scientific Report (Hulme *et al.*, 2002) and summarised in a briefing report (both available from the UKCIP website). These reports contain many maps showing the scenario changes. Most of these show a North-West to South-East gradient, with the largest changes occurring in the South-East. Table 1.1 summarises the changes in mean winter and summer temperatures and rainfall for this region of largest change.

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[1] The Hadley Centre for Climate Prediction and Research, the Met Office, UK.

[2] www.ukcip.org.uk/news_releases/28.pdf

Table 1.1 UKCIP02 scenario changes in mean seasonal temperature and rainfall for South-East England (taken from Figures 31–38 in Hulme et al., 2002)[3]

	2020s Winter	**2020s Summer**	**2050s Winter**	**2050s Summer**	**2080s Winter**	**2080s Summer**
Temperature (°C)						
Low	0.5 to 1	1 to 1.5	1 to 1.5	2 to 2.5	1.5 to 2	2.5 to 3
Medium-low	0.5 to 1	1 to 1.5	1 to 1.5	2 to 2.5	1.5 to 2	3 to 3.5
Medium-high	0.5 to 1	1 to 1.5	1.5 to 2	2.5 to 3	2.5 to 3	>4.5
High	0.5 to 1	1 to 1.5	1.5 to 2	3 to 3.5	3 to 3.5	>4.5
Rainfall (%)						
Low	0 to +10	-10 to -20	+10 to +15	-10 to -30	+15 to +20	-20 to -30
Medium-low	0 to +10	-10 to -20	+10 to +15	-20 to -30	+15 to +20	-30 to -40
Medium-high	0 to +10	-10 to -20	+10 to +15	-20 to -30	+20 to +30	-40 to -50
High	0 to +10	-10 to -20	+15 to +20	-30 to -40	+25 to >+30	>-50

Box 1.1. UKCIP02 versus UKCIP98

The differences in the climate predictions produced by UKCIP98 and UKCIP02 are due to the use of different climate models and different assumptions about future greenhouse gas emissions, particularly the upper estimate of 'high' greenhouse gas emissions.

UKCIP02 scenarios are slightly warmer than UKCIP98 scenarios because they are based on generally higher carbon dioxide emissions and lower sulphur dioxide emissions (the latter cause cooling rather than warming), and the HadCM3 model tends to be more sensitive to the greenhouse gas forcing (see Table 3 in Hulme *et al.*, 2002).

However, changes in the representation of thermal expansion of sea water and the dynamics of glacier melting mean that the UKCIP02 scenarios show slightly less sea level rise than UKCIP98.

The UKCIP02 scenarios suggest that summers may become drier across the whole of the UK, not just in England and Wales, and by a larger amount than UKCIP98 suggests. UKCIP02 also indicates slightly drier conditions in spring and autumn, rather than wetter as UKCIP98. For Scotland, the UKCIP02 scenarios show significantly different patterns in rainfall change, with a much smaller increase in autumn rainfall than shown by UKCIP98.

There are also some differences in the pattern of changes in wind between the UKCIP98 and UKCIP02 scenarios, but despite the model improvements, the UKCIP02 changes in wind are considered so uncertain that no level of confidence can be assigned to them (whereas changes in other variables are ranked in terms of their relative confidence – high, medium and low).

The use of a suite of models providing a range of integrations allows a more rigorous analysis of uncertainties and extreme events.

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[3] See Table 5 in Hulme *et al.*, 2002 for uncertainty margins at the 50km grid-box scale.

1.4 Future climate change in the UK: extreme events

The UK is projected to experience substantial changes in extreme climate events due to anthropogenic climate change by the end of this century:

- warmer winters and hotter summers
- widespread increases in the duration of hot spells in parts of England
- extended summer drought periods over much of England and Wales
- lower extreme wind speeds.

The recent availability of output from a number of European RCMs has allowed new analyses focusing on climate extremes which are important to human health (heavy rainfall, hot and cold spells). Results are discussed for the UK using the available RCM data[4] for two time periods: 1961–90 (current climate) and 2070–99. All results presented here are for one emissions scenario – the A2 scenario (Nakicenovic *et al.*, 2000) which is comparable to the UKCIP02 medium-high scenario.

The analyses of future UK climate use data from three RCMs:

- HadRM3P – Hadley Centre, UK Met Office (Hadley Centre, 2002 and Hudson and Jones, 2002)
- HIRHAM4 – Danish Meteorological Institute (Christensen *et al.*, 1996)
- RCAO – Rossby Centre, Swedish Meteorological and Hydrological Institute (Döscher *et al.*, 2002).

Validation of the RCMs is described elsewhere (e.g. Holt *et al.*, 2005 for HadRM3P). In general, annual indices of extremes compare reasonably well between National Centres for Environmental Prediction (NCEP) reanalysis data and HadRM3P, although the model extremes of temperature and wind speed generally compare better than rainfall. Duration extremes, such as longest spell of drought, compare better than indices based on absolute values.

All three RCMs were forced with output from the HadAM3P high-resolution General Circulation Models (GCM) (a slightly updated version of the GCM used to construct the UKCIP02 scenarios). At the start of the modelling chain, HadAM3P was driven by output from the HadCM3 coupled atmosphere-ocean GCM. For the A2 emissions scenario, HadCM3 gives a global temperature change of 3.3°C by 2100. This is in the middle of the 1.4–5.8°C range quoted in the last IPCC assessment report (Houghton *et al.*, 2001) based on the full range of 35 SRES scenarios and a number of climate models.

We consider temperature, rainfall, and wind speed extremes represented by a single maximum value per year. The change in climate is assessed by comparing the change in mean value of the climate extreme between the periods 1961–90 and 2070–99, averaged over the ensemble of three models. The cross-model average is known as the ensemble mean. Uncertainty in the ensemble mean is assessed using a bootstrap method in which the data from all models are re-sampled with replacement 1,000 times and the difference between means calculated on each iteration. The confidence limits at the 5% significance level are then defined by the 25th and 975th values of the sorted 1,000 differences (Davison and Hinkley, 1997).

The indices fit the Generalised Extreme Value (GEV) distribution (Coles, 2001) which enables the calculation of robust estimates of return levels for different return periods. We compare the difference in return levels between the present and the 2080s. For example, return levels of annual maximum length of dry spell for a 100-year return period,

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[4] This problem was overcome in the UKCIP02 scenarios by using a technique called pattern-scaling. However, this approach is not appropriate for application to the climate extremes considered here.

calculated from a GEV distribution using 1961–90 data, have a 1% chance of occurring in a given year. Given the probability that warming will lead to extended dry periods in 2070–99, the 100-year event calculated using data from the end of the century will be considerably longer than at present. Similarly, the current 100-year event will have a much higher chance of occurring at the end of the century than 1% in a given year.

Projected changes in temperature, rainfall and wind extremes are presented in sections 1.4.1 to 1.4.4. It is stressed that these are based on a single emissions scenario (A2/medium-high). They are also based on RCM simulations forced by one underlying set of GCM simulations. It has been demonstrated that inter-model variability associated with the choice of driving models is a major source of the scientific uncertainty (Christensen *et al.*, 2007). In section 1.5, we consider how the probability of experiencing heatwaves of the order of the 2003 event might evolve over the coming century.

A standard format is used to illustrate changes in climate. A map of the projected climate change (e.g. Figure 1.3a) is accompanied by a map of the uncertainty in the change (e.g. Figure 1.3b). The uncertainty is determined at the 5% significance level.

1.4.1 Temperature extremes

Change in mean annual mean temperature

The projected change in mean annual temperature over most of the UK (Figure 1.3a) is generally less than 3°C, with the greatest increases being found in the South. The uncertainty in these estimates (Figure 1.3b) is quite low, being typically ± 5% of the projected change in temperature for a particular area. Looking at South-East England in Figure 1.3a, we can see that an area roughly covering Kent, Surrey, and Hampshire could expect mean annual temperatures to rise by between 3 and 4.5°C under the A2 scenario by the 2080s. Looking at the uncertainty in Figure 1.3b, we find this region to have uncertainty of ±0.1–0.15°C. Therefore, concentrating for the sake of simplicity on the upper end of the range, we can say that mean annual temperature in this area is projected to increase by 3.5°C ±0.15°C, or that 95% of the time mean annual temperatures at the end of the century would be between 3.35 and 3.65°C warmer than present, under the A2 scenario.

The changes in mean summer temperatures are considerably larger than those for winter. The biggest summer increases of between 3.5 and 4°C (±0.3°C) are projected for virtually the whole of Southern England, while winter changes are generally less than 2.2°C.

Figure 1.3a Change in mean annual temperature (°C) between 1961–90 and 2070–99, under the A2 scenario (darker red is warmer in future)

Figs 1.3a–1.14b © CRU, UEA, Norwich

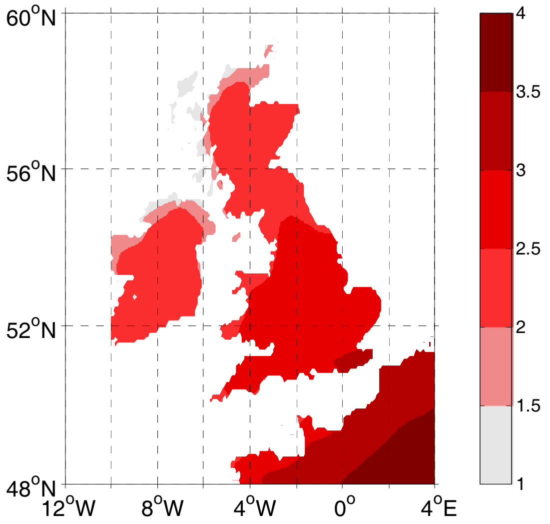
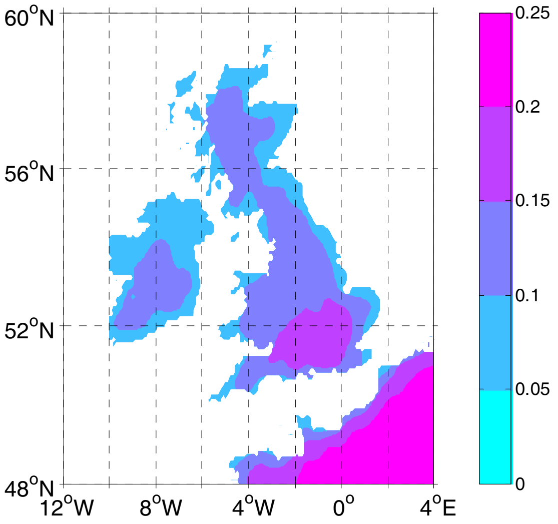


Figure 1.3b Uncertainty (± the amount shown in °C) in the change in mean annual temperature shown in Figure 1.3a (pink is greater uncertainty)



Change in duration of hot and cold spells

Cold spells. Figure 1.4a shows the projected change in the longest spell in a year with daily minimum temperature below freezing. This longest cold spell is expected to become shorter over the whole of the UK. The biggest change is to be found in Scotland where the main freezing period is projected to shorten by about a week. The small changes in Ireland and around the coast of the UK are due to these maritime areas generally not having freezing episodes over long periods. The uncertainty in the projected change in the length of cold spell is quite high (Figure 1.4b) at about ±16%.

Figure 1.4a Change in longest spell (days) with daily minimum temperature below 0°C between 1961–90 and 2070–99, under the A2 scenario (darker blue is least shortening of cold spells in the future)

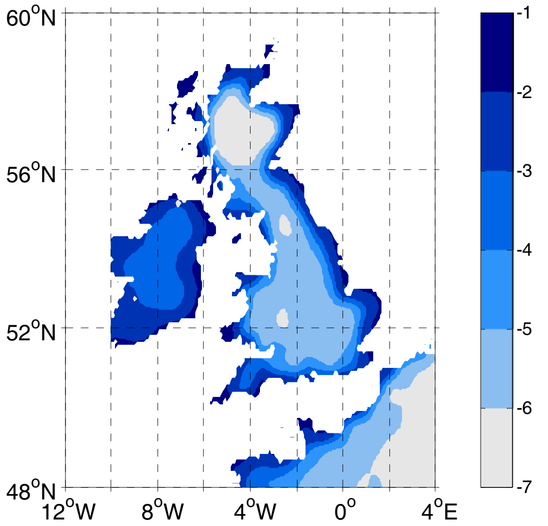
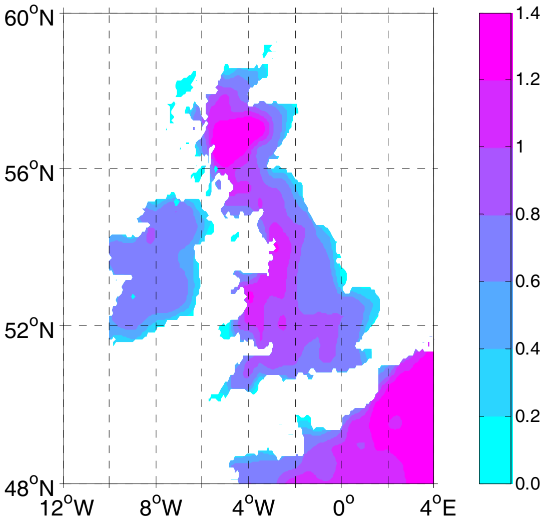


Figure 1.4b Uncertainty (± the amount shown in days) in the change in the longest cold spell shown in Figure 1.4a (pink is greater uncertainty)



Hot spells. Projected changes in the length of hot spells, defined as the longest spell with daily maximum temperature above 25°C, are shown in Figure 1.5a. Note that this climatic definition of a hot spell does not correspond to a heatwave as might be defined in health impact terms, which would be a more extreme event of shorter duration. Generally, only Central and Southern England experience periods with grid-box temperatures as high as this, but these hot spells are projected to increase by between 5 to 10 days in places. The uncertainty in these estimates is about ±10–14% (Figure 1.5b).

Note in Figure 1.5a that large changes in the duration of high-temperature episodes are indicated for Northern France. Studies over the whole of France indicate that extreme heatwaves similar to the 2003 episode are likely to become common over Central and Southern France.

Figure 1.5a Change in longest spell (days) with daily maximum temperature above 25°C between 1961–90 and 2070–99, under the A2 scenario (darker red is longer warm spells in the future)

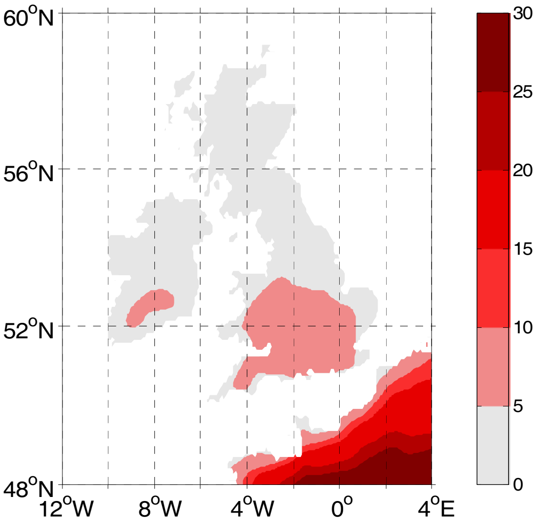
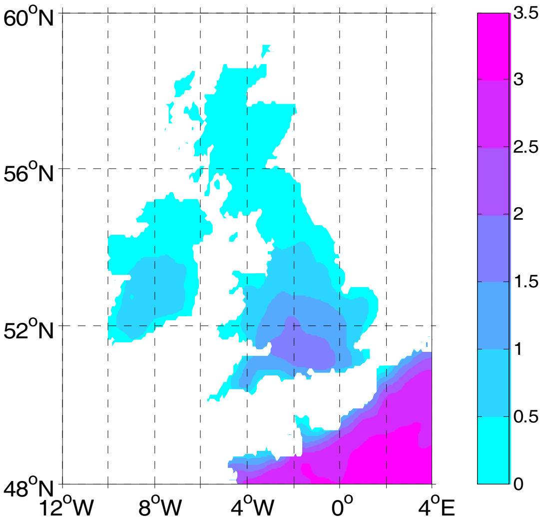


Figure 1.5b Uncertainty (± the amount shown in days) in the change in the longest hot spell shown in Figure 1.5a (pink is greater uncertainty)



1.4.2 Rainfall extremes

Rainfall is one of the most difficult physical parameters to model. This is reflected in the relatively large uncertainty in the analyses below.

The projected changes in annual total rainfall shown in Figure 1.6a give a mixed picture for the UK. Generally, the wetter North and Ireland are projected to become drier and the southern coast is likely to become wetter. However, even the biggest of these changes is quite small, being typically less than 7% of the rainfall total in a particular region. Given the very high uncertainty in these projections (Figure 1.6b), often ±60% of the projected change, it is difficult to assess their severity. For example, applying the upper bound uncertainty assessment, Scotland and Ireland can expect to lose about 12% of their annual total rainfall by the end of the century.

Figure 1.6a Change in total annual rainfall (mm) between 1961–90 and 2070–99, under the A2 scenario (dark green is wetter in future)

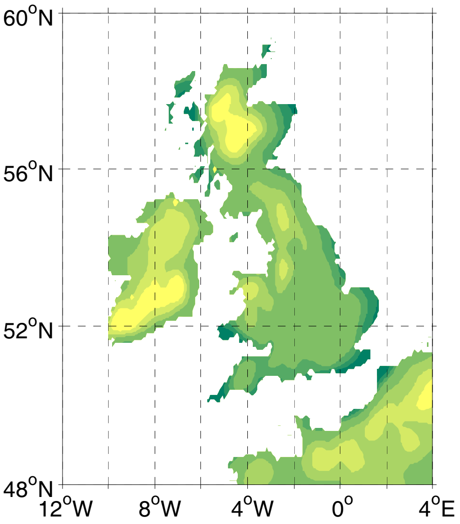
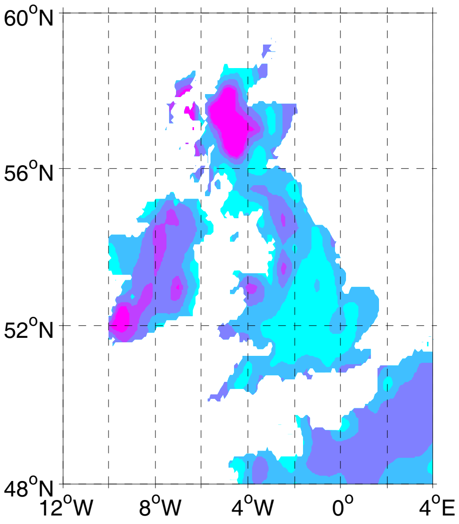


Figure 1.6b Uncertainty (± the amount shown in mm) in the change in total annual rainfall shown in Figure 1.6a (pink is greater uncertainty)



Change in length of longest wet and dry spells

The projected changes in the maximum length of dry spell are shown in Figure 1.7a. The worst-affected areas are Southern and Western England with an extension of the longest period of drought by between 4 and 6 days. The large uncertainty (Figure 1.7b) could however extend this by 2 days. In itself, such an increase is unlikely to stress water supplies unduly. However, since this is an average, it indicates that the most extreme droughts could be considerably longer than at present. This is considered further in the examination of changes in return levels in section 1.4.4.

Figure 1.7a Change in maximum length of dry spell (days) between 1961–90 and 2070–99, under the A2 scenario (red is longer dry spells in the future)

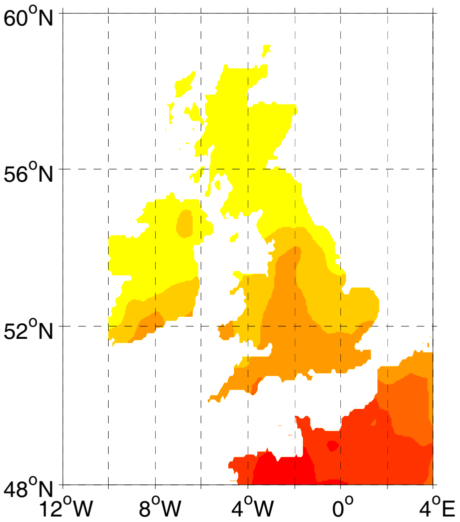


Figure 1.7b Uncertainty (± the amount shown in days) in the change in maximum length of dry spell shown in Figure 1.7a (pink is greater uncertainty)

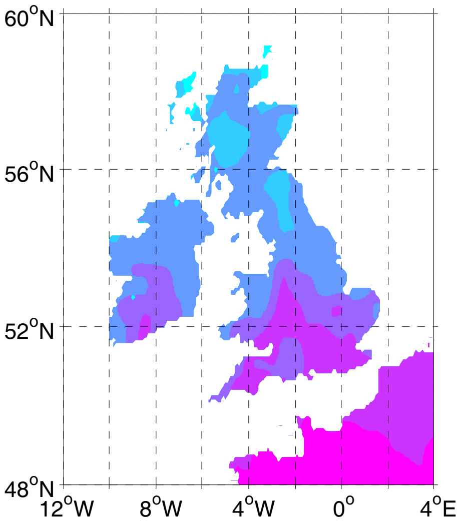


Figure 1.8a shows projected changes in the longest period of rainfall in a year. Apart from a few coastal areas, this is shown to shorten by a couple of days over most of the country. The uncertainty in this estimate is very high, reaching ± 70% in places (Figure 1.8b).

Figure 1.8a Change in maximum length of wet spell (days) between 1961–90 and 2070–99, under the A2 scenario (blue is longer wet spells in the future)

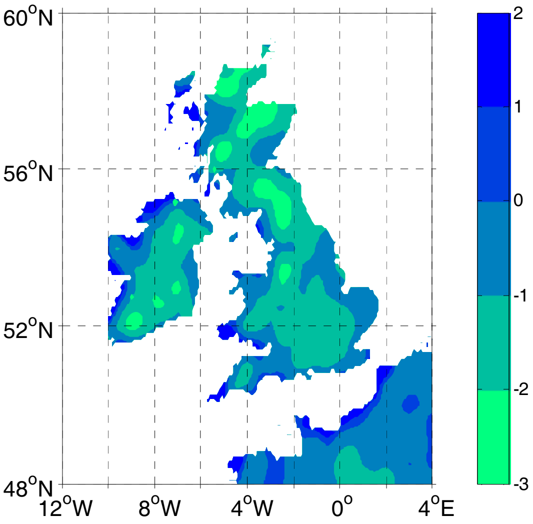
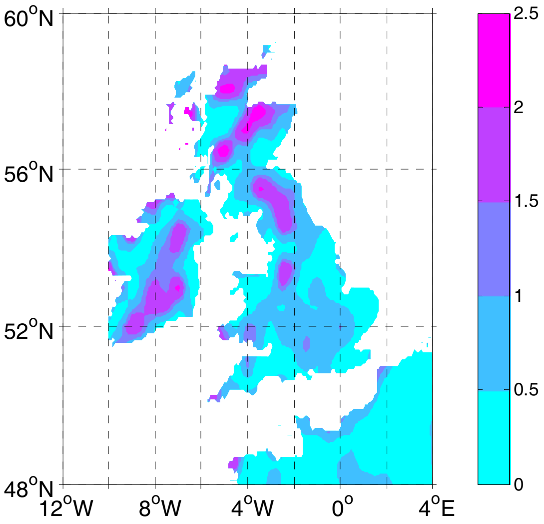


Figure 1.8b Uncertainty (± the amount shown in days) in the change in the maximum length of wet spell shown in Figure 1.8a (pink is greater uncertainty)



1.4.3 Maximum daily wind speed

The direct impact of wind on human health is caused by high wind speeds (see Chapter 2). Maximum daily wind speed is the highest wind speed in a day occurring instantaneously on a model timestep, and has no equivalent in observed meteorological data. For this reason, a number of RCMs, although none of those considered here, are starting to include an estimate of maximum gust, intended to simulate the 10-minute gust speed recorded by anemometers.

The projected change in the annual highest maximum daily wind speed (Figure 1.9a) is relatively trivial over most of the UK, particularly considering the relatively large uncertainty (Figure 1.9b). Most of the country is projected to experience slightly higher wind speeds in the most severe storms. The greatest increases in wind speeds are indicated over South-East England, Central Ireland, and Northern Scotland.

Figure 1.9a Change in annual highest maximum daily wind speed (m/s) between 1961–90 and 2070–99, under the A2 scenario (darker brown is higher future wind speeds)

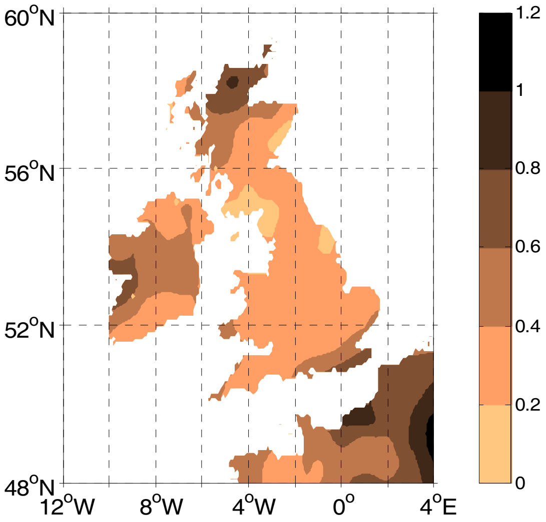
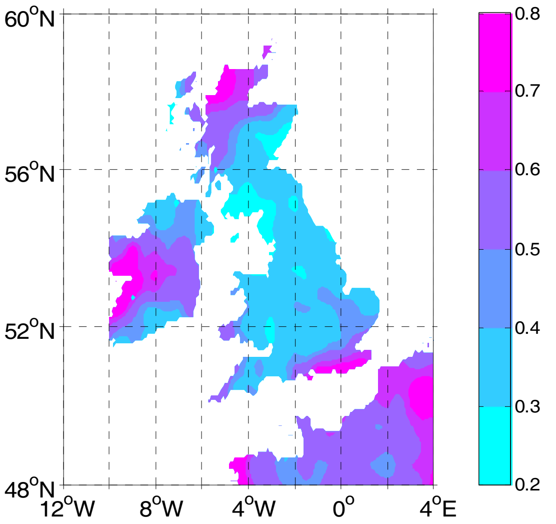


Figure 1.9b Uncertainty (± the amount shown in m/s) in the change in annual highest maximum daily wind speed shown in Figure 1.9a (pink is greater uncertainty)



1.4.4 Projected changes in return levels

Calculation of return levels for periods longer than the length of record necessarily involves extrapolation. This is supported by extensive theory, based on the fit of the data to the GEV distribution, and the validity of certain underlying assumptions about the statistical properties of the data (Coles, 2001). Beyond certain somewhat arbitrary "rules of thumb", there appears to be no robust definition of what is the maximum reliable return period for a given length of record. Here we use 100 years because it is convenient, commonly used, and only slightly over three times the length of the record.

The calculation of return levels is successful only if the data on each RCM grid square fit the GEV distribution, defined by mean, variance, and shape parameters (Coles, 2001). The three models used here do not always yield valid GEV parameters at the same grid points for each extreme index. Generally, the HadRM3P model provides more consistent GEV parameters than the HIRHAM4 model which, in turn, is better in this regard than the RCAO model. The discrepancies between the models make it impossible to examine a valid ensemble mean return level. Therefore, we present return levels for the HadRM3P model only, bearing in mind that the results have none of the safeguards of an intermodel comparison and that it is not possible to provide a meaningful estimate of uncertainty.

Cold spells

Figure 1.10a shows the 100-year return level for cold spells over the UK using 1961–90 data. A one-in-a-100-year cold spell is approximately 20–30 days with temperatures less than 0°C in Southern England for the baseline climate. Cold spells lasting between 60 and 70 days can be expected, on average, once every 100 years over Central and Western Scotland. Under the A2 scenario of climate change, the length of 100-year return period cold spell in Scotland is projected to be reduced by up to 40 days (Figure 1.10b).

Just as a return level can be calculated from the parameters of the GEV distribution and a specified return period, so can a return period be calculated from the GEV and a specified return level. This gives us a slightly different way of looking at Figures 1.10a and 1.10b which may be considered more informative.

Using the midpoint of each data 'bin', according to the 1961–90 data (Figure 1.10a) there is a 1% chance of having a cold spell of at least 65 days in Scotland in a given year. With predicted climate change, however, the 2070–99 data (Figure 1.10b) show a 1% probability of a cold spell lasting at least 35 days in Scotland in a given year. This dramatic reduction in the risk associated with a low-probability event by the end of the century can also be considered in terms of today's climate. A 35-day cold spell in Scotland would currently be quite common and expected about once every five years, or have a 20% chance of occurring in a given year (compared with 1% by the end of the century).

Figure 1.10a 100-year return level (days) for the annual longest period with daily minimum temperatures less than 0°C, based on 1961–90 extremes using HadRM3P data only (bright blue is the longest cold period)

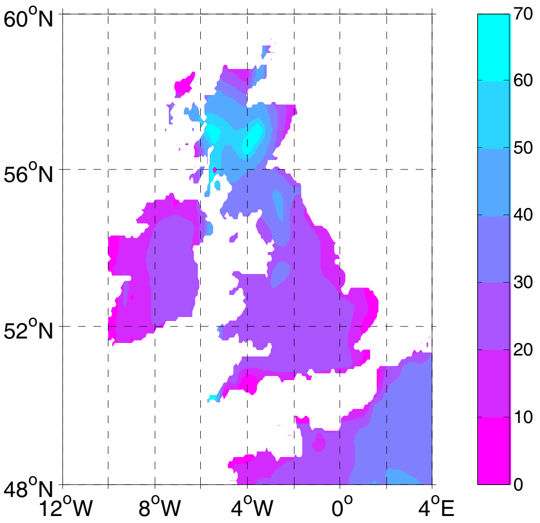
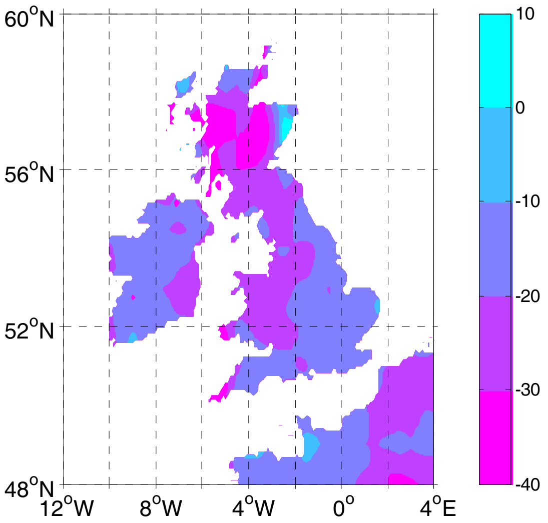


Figure 1.10b Projected change, under the A2 scenario, in the 100-year return level (days) for the annual longest period with daily minimum temperatures less than 0°C (pink shows the greatest reduction)



Prolonged hot spells

Figures 1.11a and 1.11b present changes in return levels of the longest annual hot spell (defined as a period with daily maximum temperatures above 25°C for each 90km grid square), according to 1961–90 and 2070–99 data respectively.

There is a 1% chance of a hot spell longer than 35 days in a given year over Central Southern England, according to 1961–90 data (Figure 1.11a). By the 2080s, this area is projected to have a 1% chance of hot spells longer than 60 days in a given year (Figure 1.11b). Currently, there is only a 0.01% chance of hot spells exceeding 60 days in Southern England in a given year.

Figure 1.11a 100-year return level (days) for the annual longest period with daily maximum temperatures above 25°C based on 1961–90 extremes, using HadRM3P data only (pink is the longest warm period)

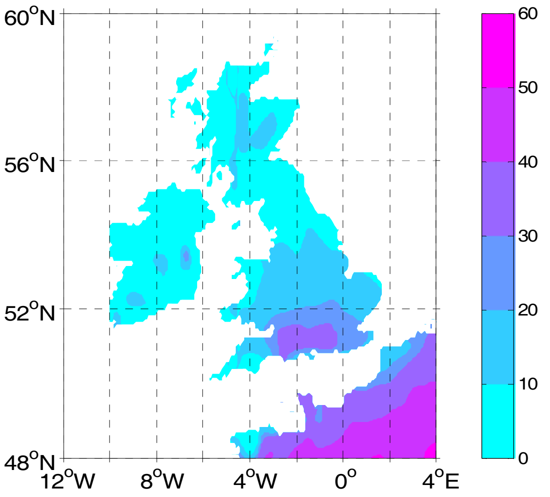
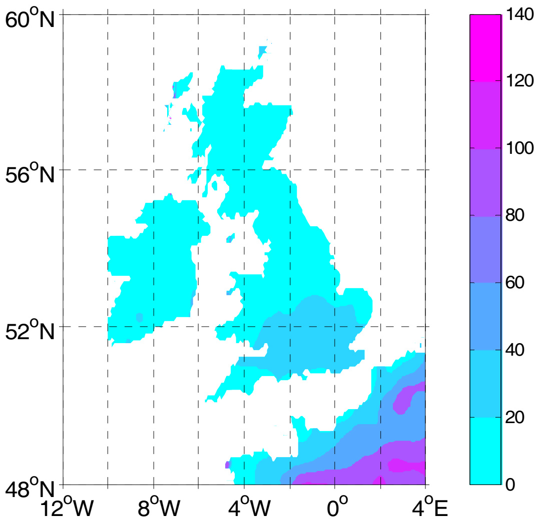


Figure 1.11b Projected change, under the A2 scenario, in the 100-year return level (days) for the annual longest period with daily maximum temperatures above 25°C (pink shows the greatest warming)



Wet and dry spells

The return levels for prolonged wet spells, based on 1961–90 data (Figure 1.12a), show that apart from a few western extremities with a 1% chance of wet spells in excess of 85 days, most of the country has a 1% chance of spells of around 25 days. The effect of climate change on the duration of severe wet spells is complex. Using data from the 2070–99 period (Figure 1.12b), most of the country is predicted to see a decline of about 30% in the length of 1% wet spells. The Western Isles of Scotland, however, see 1% wet spells increase in length to about 100 days by the end of the century. This is equivalent to a 1-in-400-year event now, or a chance of about 0.025% of wet spells occurring in a given year.

Figure 1.12a 100-year return level (days) for the annual longest wet spell based on 1961–90 extremes, using HadRM3P data only (blue is the longest wet period)

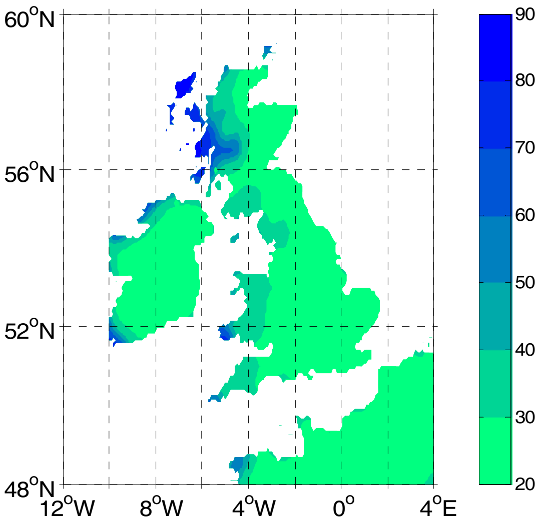
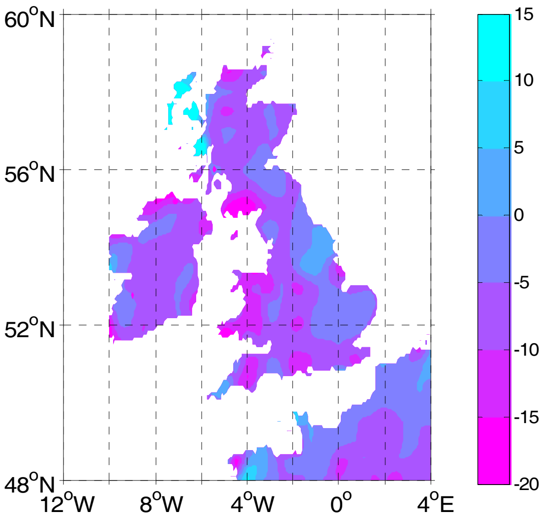


Figure 1.12b Projected change, under the A2 scenario, in the 100-year return level (days) for the annual longest wet spell (bright blue shows longer wet period)



The 100-year drought (defined as the maximum number of consecutive days without rain) is about 45 days for the UK (Figure 1.13a). The average increase in length of drought predicted for 2070–99 is about 10 days under global warming (Figure 1.13b), apart from in Central Southern England; this is consistent with expectations of longer hot spells. Here, there is a 1% chance of drought exceeding 75 days in a given year by the end of the century. This is equivalent to a 0.013% chance of drought occurring under current climate conditions. Given these projections, water shortages are likely to become a regular feature of UK summers unless infrastructure changes are planned now.

Figure 1.13a 100-year return level (days) for the annual longest dry spell based on 1961–90 extremes, using HadRM3P data only (yellow is the longest dry period)

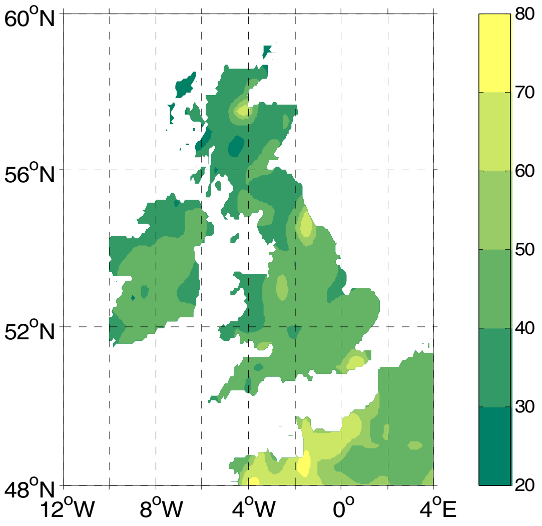
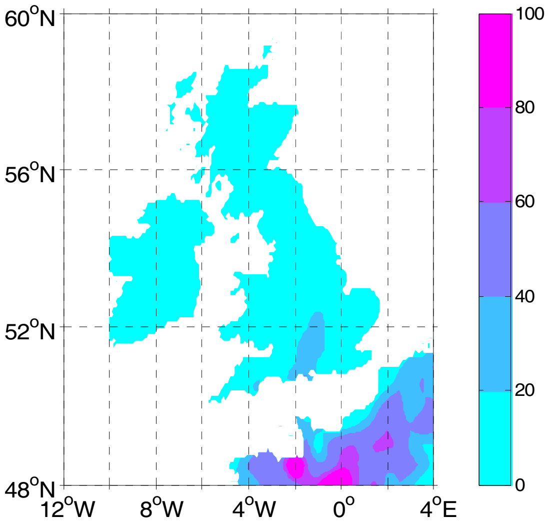


Figure 1.13b Projected change, under the A2 scenario, in the 100-year return level (days) for the annual longest dry spell (pink shows biggest extension of dry period)



Highest daily maximum wind speed

The highest 100-year return levels for annual highest daily maximum wind speed based on 1961–90 data are around the coast of the UK (Figure 1.14a), with isolated locations exceeding 40m/s. The effects of climate change (Figure 1.14b) are quite complex, with most parts of the UK experiencing lower extreme wind speeds by the end of the century, apart from increases over much of Wales, North-East England and North-West Scotland. Over much of Northern Ireland, for example, current 1% daily maximum wind speeds of 25m/s are predicted to decline to 15m/s by the end of the century. This is equivalent to a 10% chance of occurrence in a given year under the climate of today, a much less hazardous event. Over Wales, future 1% daily maximum winds are predicted to be about 5m/s stronger than at present, equivalent to 0.025% winds under current climate.

Figure 1.14a 100-year return level (m/s) for the annual highest daily maximum wind speed based on 1961–90 extremes, using HadRM3P data only (darker brown is the highest wind speed)

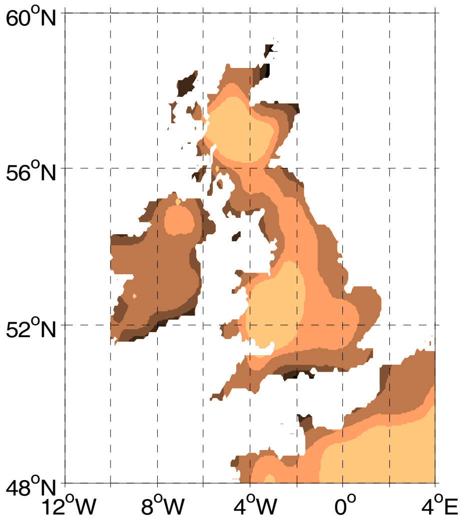
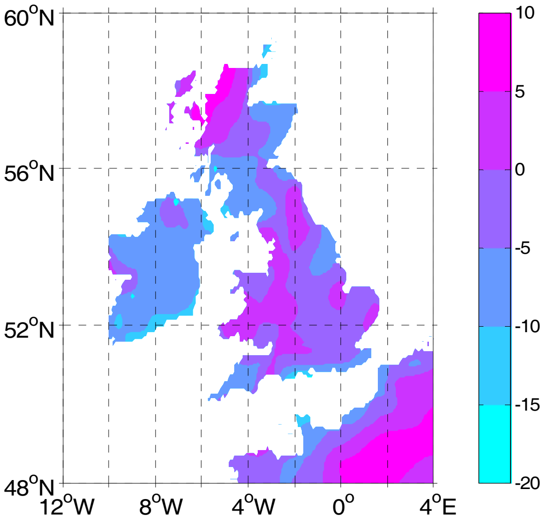


Figure 1.14b Projected change, under the A2 scenario, in the 100-year return level (m/s) for the annual highest daily maximum wind speed (pink shows higher future wind speeds)



1.5 Changes in the frequency of heatwaves of the order of the 2003 event

Following the heatwave event of 2003, the UK has introduced a heatwave plan which includes a system for triggering alerts as soon as the Met Office forecasts ‘threshold temperatures’ for at least 3 days ahead in one region, or an 80% chance of temperatures being high enough on at least 2 consecutive days to have significant effects on health. For the London region, the operational daytime threshold temperature is 32°C. It would clearly be desirable to have projections of how the frequency of occurrence of threshold temperatures will change for each region. The grid-box nature of climate model output means, however, that thresholds defined from point locations are not directly comparable to the model grid boxes. Further downscaling would thus be required in order to construct such scenarios. Here, however, we explore future changes in the frequencies of heatwaves of the order of the 2003 episode using a simple yardstick applied to output from a GCM simulation for the period 1990–2100.

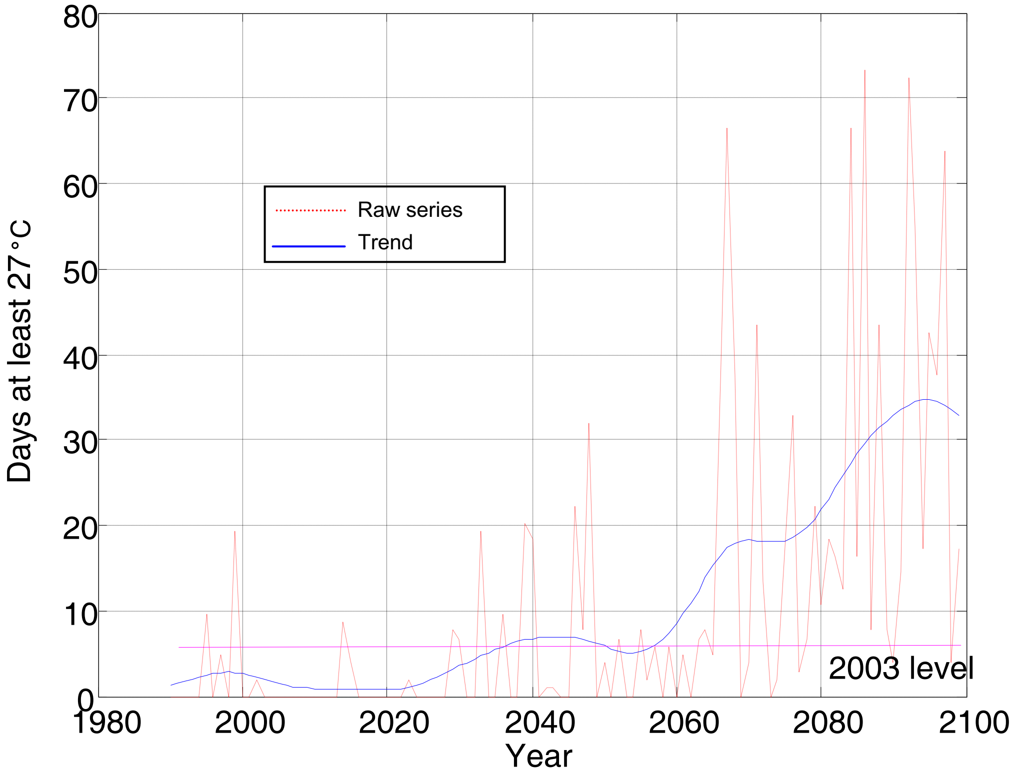
GCM output is used for this analysis because it allows us to examine the evolution over time of the impacts of climate change. RCMs offer undeniable improvements in physics and reliability over the coarser-resolution GCMs. They have a much higher grid resolution – typically 50km, rather than the 300km typical of GCMs. However, currently output is only available for ‘snapshot’ periods, i.e. 1961–90 and 2070–99 (see Section 1.4).

We use data from the UK Met Office HadCM3 global model from 1990 to 2100 to provide estimates of changes in the frequency of heatwaves of the order of the 2003 event under the A2 emissions scenario. The model data are interpolated onto a 2 x 2 degree latitude/longitude grid to give improved coverage over the UK. A point located roughly at Cambridge is selected for the analysis. It is not possible to select a point further south because of the coarseness of the grid. However, the climate of Cambridge is broadly representative of South-East England. To give a yardstick against which to compare the model estimates, we select data for the Cambridge location from the NCEP reanalysis for 2003. The reanalysis is based on observational data from a variety of sources and is placed on a grid of roughly 2.2 degrees latitude/longitude. The gridding process smooths the data, making them more suitable for comparison with the gridded model data than point observations from stations.

The variable we chose to analyse is a 7-day running mean daily maximum temperature at the surface. This is a sufficiently long averaging period to indicate a persistent hot spell. The NCEP reanalysis yielded 6 days when temperatures averaged over 7 days were 25°C in 2003, the hottest running mean in the year for Cambridge. Comparison of NCEP maximum temperature percentiles over Cambridge with HadCM3 percentiles suggests that the model data are about 2°C warmer than NCEP. Thus, to compare HadCM3 with NCEP, we impose a penalty of 2°C and search for days when the 7-day running mean from HadCM3 was 27°C or higher.

The results of the analysis are shown in Figure 1.15. The 6 days with a 7-day running mean of at least 25°C from the NCEP data are shown by the pink continuous line at the bottom of the plot. This is the yardstick against which the severity of future warming can be assessed. Bearing in mind that 27°C from the model running mean is equivalent to the NCEP 25°C, it is clear that the equivalent of the 2003 event for the South of England will be encountered occasionally until about 2030 (approximately 4 times in the 40-year period). The first 3 decades of the century are shown to be no different from the present in terms of variability. After this, however, heatwaves such as that of 2003 can be expected much more frequently, becoming increasingly more severe in intensity and duration after 2060.

Figure 1.15 Number of days per year when the 7-day running mean daily maximum temperature from HadCM3 is at least 27°C. The pink line shows the comparable 6 days above 25°C experienced in the 2003 heatwave, according to the NCEP data



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1.6 Low probability, high impact events

Low probability, high impact events are, by definition, rare. Such events can have a number of different climatic causes and impacts. Certain geophysical events are also of concern as these may impact indirectly on the climate of the British Isles. The major geophysical events of concern are large volcanic eruptions, sometimes referred to as super-volcanoes. Such eruptions, especially those that occur in the tropics, can have a cooling impact upon the global climate. Ash and debris emitted into the atmosphere can cause a veil of reflective particles that reduces the amount of incoming short-wave radiation from the sun, thus causing cooling. It is not, however, possible to predict whether such a volcanic event will occur in the coming century.

The major climate events that we are most concerned with in terms of impacts on the British Isles are: a shutting down of the North Atlantic thermohaline circulation (THC); a collapse of the West Antarctic Ice Sheet (WAIS); and accelerated climate change as a result of the release of naturally stored greenhouse gases.

The first of these, THC collapse, has been very much discussed and the idea was popularised in the Hollywood film *The Day after Tomorrow*. Palaeoenvironmental data suggests that there have been a number of abrupt changes in the climate of the Northern Hemisphere during the last 250,000 years. These changes are believed to have occurred as a result of the input of a large amount of fresh water into the North Atlantic, caused by rapid melting of a large ice sheet or series of ice sheets. The input of fresh water breaks down the THC, thus deflecting (or stopping) the North Atlantic Drift (Gulf Stream). The Gulf Stream acts to warm North-West Europe, providing it with a mild maritime climate which is some 9°C warmer than the average for this latitude. Thus, during periods of THC shutdown, the absence of the Gulf Stream results in a colder continental-type climate for North-West Europe, including the British Isles.

It has been hypothesised that during a period of warming (such as that which we are experiencing now and is projected for the future) there may be a reoccurrence of the shutdown of the THC as a result of increased freshwater inputs due to the melting (or partial melting) of the Greenland Ice Sheet and an enhanced hydrological cycle. Observations are showing a slight weakening in the strength of the THC, while experiments using coupled ocean-atmosphere GCMs have shown that current-generation climate models are able to induce a shutdown of the THC and associated cooling if large amounts of fresh water are artificially added to the North Atlantic. To date, however, no GCM experiment has produced a shutdown of the THC when forced with realistic scenarios of greenhouse-gas-induced climate change, although most GCMs, including the Hadley Centre simulations used in sections 1.3 and 1.4, project a general weakening of the THC. It must also be taken into account that if the THC were to shut down, it would be against the backdrop of very much higher greenhouse-gas-induced climate change. The scientific consensus is that a shutdown of the THC is unlikely without the rapid collapse of the Greenland Ice Sheet and that this is highly unlikely to occur before 2100 within the range of temperatures projected by the current generation of SRES-forced GCM experiments.

Through the thermal expansion of sea water and the melting of small (alpine-type) glaciers, global sea level rise has been occurring in line with human-induced warming. Future rates of change under the SRES scenarios suggest that during the 21st century sea level rise will be in the order of 20–80 cm (Houghton *et al.,* 2001). There is concern, however, that more rapid rates of sea level rise are likely as a result of the collapse of the WAIS. Evidence from satellite sensor data has shown areas of weakness in the WAIS which some scientists have suggested could indicate that it is relatively unstable and prone to collapse. If such a collapse occurred, then global sea level would rise by some eight metres over the course of a number of centuries. At present, there is no consensus on the timing or possibility of such rapid sea level rise, though it is generally considered highly unlikely to occur in the present century.

Climate change as a result of human activities is causing rapid rates of temperature rise and there is some concern that this may trigger positive non-linear feedbacks in the climate system. Such feedbacks could affect both the biogeochemical and physical systems. The natural environment stores large amounts of greenhouse gases in reservoirs, primarily in the form of methane and carbon dioxide. It is a concern, therefore, that climate change may cause the release of these gases and thus enhance their concentrations in the atmosphere. The major reservoirs can be found locked in organic matter in the permafrost of the Northern Hemisphere; in the terrestrial carbon sink, e.g. the Amazonian rain forest; and locked in particulate matter on the ocean floor. Recent monitoring has shown that the permafrost regions are starting to melt and are releasing carbon dioxide and methane. Modelling work undertaken by the Hadley Centre has shown that, as a result of increased temperatures, the Amazon is likely to become a source of carbon dioxide by the end of the century due to forest die-back. Rapid release of methane from deep ocean deposits is also a feasible scenario. However, as yet, there is little evidence to suggest whether, and if so when, this is likely to happen.

The major physical feedback that is likely to accelerate climate change, and which is factored into climate models, is reduction in snow and ice cover in the high latitudes. Snow and ice have a high albedo and thus reflect much of the incoming solar radiation. As a result of warming, sea ice extent (especially in the Arctic) is reducing, thus lowering the albedo and causing more of the incoming solar energy to be absorbed at the surface. This in turn leads to higher temperatures, increased reduction of sea ice and more warming – i.e. a positive feedback effect. The Arctic sea ice extent during the summer of 2005 was at its minimum level yet recorded.

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- UKCIP02 scenario data are available from the UKCIP02 Scenario Gateway at www.ukcip.org.uk/resources/tools/scenarios.asp

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2 Flooding, windstorms and climate change

(See also section 4.5 (windstorms) and section 4.6 (flooding) of 2001/2002 report)

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Summary

- Currently, floods are an important problem in the UK. Floods are associated with few direct deaths, but the full effect on health, in terms of indirect mortality and morbidity due to infectious disease, mental health, and injuries, is not known.
- Current evidence indicates that certain types of floods, such as spring floods due to snow melt, are likely to become less frequent under climate change, while others, such as those directly linked to sustained autumn and winter precipitation, are likely to become more frequent. Risks will evolve differently in different regions and river catchments.
- There is good evidence to expect an increase in the frequency of heavy precipitation, with the greatest increases in frequency occurring for short-duration, high-intensity events. Hence an increased risk of flooding may accompany no change, or even a decrease in mean rainfall or in the duration of wet spells.
- Along the North Sea coast there is a low risk of a very severe flood event (as in 1953), but this risk will increase due to rising sea levels unless coastal defences are upgraded appropriately.
- The direct health effects due to changes in windstorm intensity or frequency are likely to be small relative to other health effects of climate change in the UK.

Recommendations

- Implementation of flood health risk assessments.
- Improved implementation of interventions to reduce health impacts associated with flood events, including the better use of current measures, such a guidelines for dealing with chemical contamination of flood waters, and post-flood support and counselling.
- Strengthening emergency planning and preparedness.

2.1 Introduction

Flooding and windstorms are a regular occurrence in the UK. Flash floods in Boscastle, Cornwall destroyed homes and businesses and swept away cars in August 2004. Heavy rainfall in early January 2005 also caused extensive, and in places repeated flooding across the North of England and Wales. In January 2005, a severe gale across Northern Ireland and North-West Scotland, with wind speeds in excess of 120mph, resulted in seven fatalities and loss of power to 85,000 households. The contribution of climate change to our current flood and windstorm risk has yet to be definitively quantified. Evidence has been strengthened, however, of the threat that climate change presents in terms of future flood risk in the UK, and the consequent implications for human health.

The first part of this chapter (section 2.2) reviews advances in understanding the health impacts of flooding and windstorm events, while the second part (sections 2.3 to 2.6) discusses the physical and model-based reasons why we may expect the risk of such events to change.

2.2 The health effects of flooding and windstorms

Since the last report for the Department of Health (2001/2002), little new research on the health effects of flooding has been completed in the UK. Two reviews of the epidemiological literature have described the range of health effects: drownings, injuries, mental illness and infectious diseases (Hajat *et al.,* 2003; Ahern *et al.,* 2005). A study following the flooding in Lewes in 2002 found that people who were flooded experienced a range of illnesses (Reacher *et al.,* 2004). However, important knowledge gaps remain regarding the impact of flood events on long-term anxiety and depression, and indirect effects on mortality and use of health services in the months following a flood event. Qualitative studies following flood events in Oxfordshire have shown that impacts on quality of life can be severe and long-lasting (Ohl and Tapsell, 2000; Tapsell *et al.,* 2002).

2.2.1 Flooding

Deaths

The Department of Health 2001/2002 report reviewed coastal and riverine flood risks separately. However, the health implications of these two types of event are essentially the same. One of the most important factors for the risk of drowning is the speed of onset of the flooding, and the presence or not of some kind of warning.

Deaths associated with flooding in the UK are relatively few compared with other European countries. Only eight deaths have been reported since 2001 (Table 2.1). The Environment Agency and Defra have no formal criteria for a flood death, but collate the information from situation reports that are completed for each flood. It is likely that official flood deaths are limited to persons who are swept away or drown in or near their own homes.

Recent reviews have confirmed that in industrialised countries such as the UK, flood deaths are primarily associated with flash floods (Jonkman and Kelman, 2005), and are often vehicle-related (French *et al.,* 1983). A review by Kelman (2007) also identified several other types of drownings associated with floods, e.g. people drowning after entering swollen rivers. Risk of death is also apparent from electrocution and carbon monoxide poisoning in the clean-up stages after the flood. More than 20 episodes of electrocution and 5 deaths from carbon monoxide poisoning were reported after Hurricane Katrina in the USA in 2005 (CDC, 2005).

Table 2.1. Major floods in the UK since January 2000 and associated deaths

Area	***When***	***No of households flooded***	***Reported deaths***
Central and Southern England	New Year floods, 2002/03	1,029	1
Wales	February 2004	150	None
Boscastle, Cornwall	August 2004	60	None
Carlisle	January 2005	3,000	3
River Tyne	January/February 2005	100	None
Central and Southern England	June/July 2007	49,000*	4**

Source: Flood Risk Management, Environment Agency
* Number of residential properties where habitable accommodation was affected.
Source: Cabinet Office
** Number of deaths reported as a direct result of the floods. Source: Cabinet Office

The Royal Society for the Prevention of Accidents (RoSPA) reports drownings per year associated with rivers or streams, and some drowning deaths attributed to flooding and high tides (RoSPA, 2005). Such numbers of drownings are likely to be incomplete as the 'cause' will not be systematically reported. Defra and the Environment Agency do not collate national statistics on flood deaths or injuries, and, as discussed above, the definition of what constitutes a flood death is unclear and narrowly interpreted.

Age- and gender-related information on flood deaths is also incomplete. Published reviews have shown that men are much more at risk of drowning than women, probably due to more risky or heroic behaviour. Elderly people are particularly at risk of drowning in their own homes. For example, in the Carlisle floods two of the three deaths were of elderly women in the same street. In the 1953 'Big Flood' in East Anglia, the majority of the deaths were of elderly people (Baxter, 2005). Small-scale flooding can also claim lives: an elderly person drowned in a basement flat in North London during an episode of very heavy rainfall in 2002.

Chemical hazards

The Health Protection Agency (HPA) Chemical Hazards and Poisons London Regional Unit has reviewed the implications of flooding for chemical hazards (Euripidou and Murray, 2004). There are risks to health from the contamination of flood waters with chemical waste, oil, diesel, pesticides, fertilisers, etc. Flooding may lead to mobilisation of dangerous chemicals from storage or remobilisation of chemicals already in the environment, e.g. pesticides. A case study of heavy metal soil contamination after the flooding of the river Meuse during the winter of 1993/94 concluded there was a potential health risk for river-bank inhabitants as a consequence of lead and cadmium contamination of the soil (Albering *et al.,* 1999). Hazards may be greater when industrial or agricultural land adjoining residential land is affected. The UK has a high population density, with people living close to industrial installations.

Mental health

Effects on mental health are now recognised as an important health consequence of flooding (Ohl and Tapsell, 2000). A systematic review of the epidemiological literature found that studies, mostly from the USA, did provide good evidence of long-term (>6 months post-flood) mental health complications (Ahern *et al.,* 2005). A study in an elderly population affected by the 1993 US Midwest floods found that flooding increased the incidence of common mental disorders, even after adjusting for pre-flood morbidity (Ginexi *et al.,* 2000). A case-control study from the UK found a fourfold increase in psychological distress among adults whose homes were flooded compared with those whose homes were not flooded (Reacher *et al.,* 2004).

Infectious disease

Infectious disease risk concerns relate to contact with raw human or animal sewage/effluent. The HPA provides guidance advising against the consumption of food that has been exposed to flood water. Flood water itself is unfit for drinking and notices advising that tap water should be boiled are issued as necessary. Enhanced surveillance during floods for gastro-intestinal illness has revealed no apparent increases that can be attributed to recent flood events. However, an increase in self-reported illnesses, including skin diseases, respiratory diseases and stomach upsets, was apparent following the floods in Lewes (Reacher *et al.,* 2004). The role of heavy rainfall in outbreaks of waterborne disease is discussed in more detail in Chapter 5.

Effect of flooding on health service delivery

Flood events may also indirectly affect health by causing damage to hospitals, clinics and general practices. The siting of hospitals, care homes, schools, nurseries and clinics in flood risk areas should be assessed. In Lewes, one general practitioner's office was flooded and most of the patients' notes were destroyed.

Floods in Dresden, Germany, in 2002 left large parts of the city without power and fresh water for several days (Meusel and Kirch, 2005). Four of the six main hospitals in Dresden were sited near the River Elbe and affected by the flooding. Two of the hospitals were evacuated.

2.2.2 Deaths and injuries from windstorms

Deaths from windstorms are not collated by the Environment Agency. Information is available from a range of press reports. Many deaths are vehicle-related, and a small but significant number are in outdoor workers.

Some recent deaths attributable to high winds:

- Four men died in 1999 when they fell off a gantry while working on the Avonmouth Bridge in high winds.
- In January 2005, a severe gale across Northern Ireland and North-West Scotland, with wind speeds in excess of 120mph, resulted in seven fatalities and the loss of power to 85,000 households.

A retrospective study of the injuries caused by high wind speeds during the storms of early 1990 found that that high wind speeds were associated with an increased risk of injury, especially when wind gusts exceeded 60 knots (Cugnoni and Whitworth, 2002). The apparent wind speed threshold above which injury is more likely corresponds to the curve used by the Met Office to predict wind-related structural damage.

2.3 Climate change, riverine flooding and extreme precipitation

The relationship between precipitation and flood risk depends critically on regional hydrology. There is no single type of extreme precipitation event that is relevant to flood risk. The floods of autumn 2000 and January 2003 were associated with sustained (of the order of 30 days or longer) catchment-scale rainfall anomalies that resulted in a gradual increase in water table levels as precipitation exceeded run-off capacity. In contrast, the Boscastle flood in August 2004 was associated with a localised, slow-moving thunderstorm that resulted in over 180mm of rainfall in under 5 hours over a single, relatively small river catchment area. Summer floods tend to be associated with short-duration extreme precipitation (for example, the Carlisle floods in 2005 were associated with a specific storm system), but in other seasons all timescales are relevant.

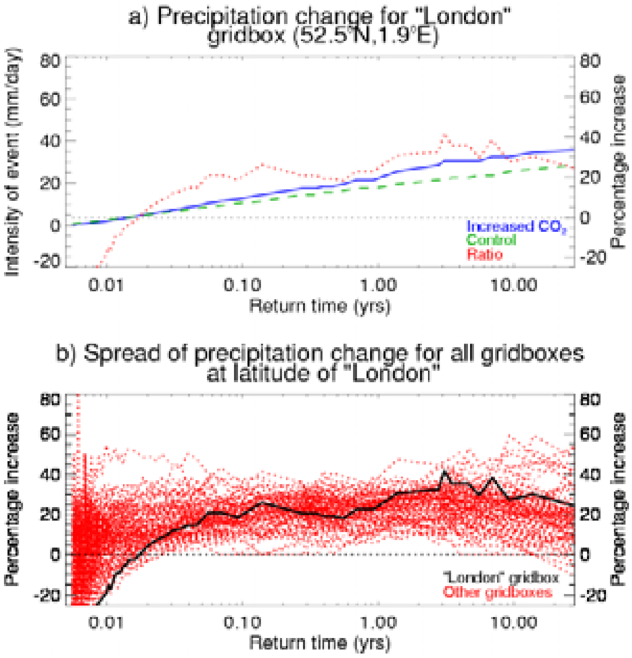
Our understanding of the influence of climate change on large-scale, sustained precipitation anomalies is further advanced than our understanding of short-term, localised anomalies. On physical grounds, it could be argued that we should expect more severe thunderstorms in a warmer, moister atmosphere, but since many factors affect the intensity and distribution of thunderstorms, a simple link between temperatures and thunderstorm-related flood risk cannot be expected.

Modelling studies of short-term extreme precipitation show a tendency for greater fractional increases in intensity at higher return times: that is, the percentage increase in precipitation events that are expected to occur once every 30 years is greater than the percentage increase in events that are expected to occur once per year (see Chapter 1). This is illustrated in Figure 2.1 (adapted from Allen and Ingram, 2002), using data from the HadCM3 climate model. The green dashed line in the upper panel shows the intensity, in millimetres per day, of rainfall events as a function of their return time (the reciprocal of the number expected in a given year) in the model control climate, while the blue solid line shows how these intensities change by years 2070–2100 in a simulation of the response to the A2 emissions scenario (the medium-high scenario). The red dotted line shows the percentage increase (how much the blue curve is higher than the green one): for this particular model, scenario and grid-box, there is a tendency for the percentage increase in the intensity of frequent events (e.g. 0.1-year return time, or 10 events per year) to be less than the fractional increase in rarer events (e.g. 3-year return time).

If we examine all grid-boxes at the same latitude (lower panel), a noisier picture emerges. Nevertheless, there is still a significant shift upwards in the distribution of increases as we move from frequent (10 per year) to infrequent (one-in-10-year) events. The apparent downturn towards the most infrequent events is almost certainly a sampling artefact, since the simulations in question will have contained very few events of these magnitudes.

This overall result is confirmed by assessments using higher-resolution regional climate models, as described in Chapter 1. Changes in precipitation tend to be concentrated in high-intensity, short-duration events, so no change or even a decrease in seasonal mean rainfall may be accompanied by an increase in flash flood risk. Hence the **decline** in the length of extreme wet spells reported in Chapter 1 is, somewhat counter-intuitively, consistent with an **increase** in the risk of floods associated with short-duration precipitation events.

Figure 2.1 Intensity of daily precipitation events as a function of return time for the HadCM3 climate model, comparing control climate (top panel, green dashed line) with years 2070–2100 of a run driven with the SRES A2 forcing scenario (top panel, blue solid line). Red dotted lines and right-hand axes show percentage increase in intensity as a function of return time



(Figure courtesy of Pardeep Pall, University of Oxford, based on data provided by Jonathan Gregory, Met Office)

When we consider longer duration precipitation events, such as those responsible for the autumn 2000 and winter 2002/03 floods, the picture becomes more complicated and results more model-dependent. Figure 2.2 (left panel) shows, purely as an illustration, how the intensity of 30-day extreme precipitation events varies in the grid-boxes corresponding to the Lewes catchment area (which suffered severe flooding in autumn 2000) as greenhouse gases are increased from 1860 conditions (solid line), through 2000 (heavy dotted line) to 2090 (dashed line), following a simple 1% per year increase from 1990.[5] In this particular model (HadRM2 nested into the HadCM2 global climate model: see Huntingford *et al.,* 2003, for further details) we see that a monthly average rainfall of 6.7 mm/day would occur on average once in 10 years in 1860, while in 2090 a monthly average of 8.3 mm/day would occur with this same frequency. Similarly, a 30-year event in 1860 becomes a 12-year event in 2000, and a 4-year event in 2090. As in Figure 2.1, the fractional increase in intensity is greater for rarer events, with a 13% increase between 1860 and 2090 for 1-year events, rising to a 23% increase for 10-year events.

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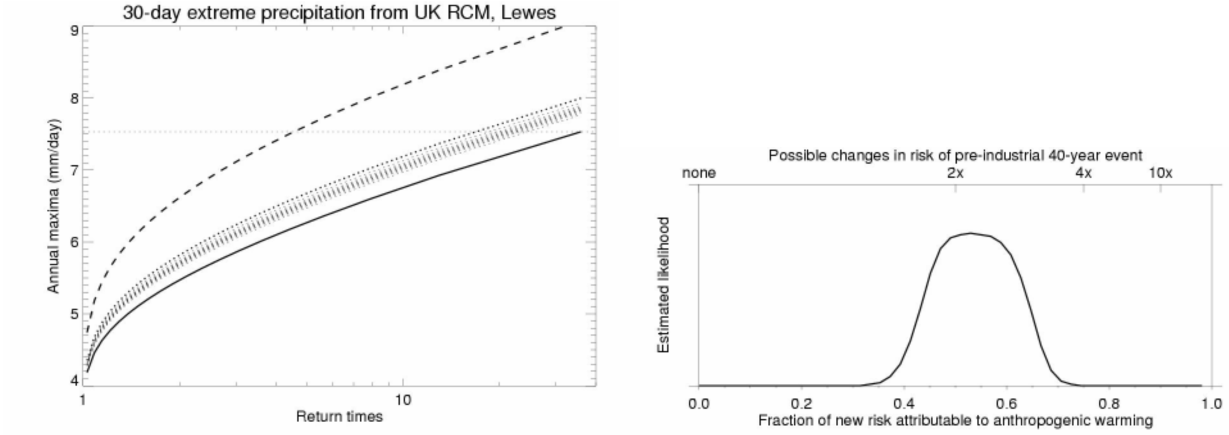
[5] Note that this represents a stronger forcing than that used in Figure 2.1

Figure 2.2. Left panel: magnitude (mm/day for 30-day average rainfall) of precipitation events as a function of return time in 1860 (solid line), 2000 (dotted lines) and 2090 (dashed line) in the HadRM2 regional climate model, averaging over points corresponding to the Lewes river catchment, forced with observed greenhouse gas increase to 1990 followed by 1% per year to 2100. Right panel: illustration of the implications of these figures for the risk of 30-day average precipitation exceeding 7.5mm/day due to past human influence on climate, in this particular regional climate model. Data from Huntingford et al., 2003



Source: Allen *et al.*, 2000 Source: Allen *et al.*, 2000

The light dotted lines in the left panel of Figure 2.2 show how a simple representation of uncertainty in the global mean response, following Allen *et al.* (2000), can provide a range of possible changes in the distribution of extreme precipitation that are attributable to past human influence on climate. The light dotted lines are all lower than the heavy dotted line because all estimates of the net anthropogenic climate change to date are lower than the estimated greenhouse-only warming simulated by the HadCM2 climate model, primarily because the net effect of non-greenhouse anthropogenic drivers of climate change almost certainly leads to a reduction in ambient temperatures.

Allowing for uncertainty in the response provides a distribution of possible changes in risk that are consistent with data available to date: this is shown in the right panel of Figure 2.2. The top axis shows the factor by which an occurrence of monthly mean precipitation exceeding 7.5mm/day (a 40-year event in the 1860 climate of this model, light horizontal line in the left hand panel) is estimated to have increased due to past human influence on climate. The best estimate (peak of the distribution) corresponds to a doubling of risk, with some uncertainty on either side. Should such an event occur, the bottom axis shows what fraction of the risk is attributable to, or to what extent it can be 'blamed on', the influence of previous human activities on climate. (See Stott *et al.,* 2004 for a description of the application of the epidemiological concept of attributable risk to weather events and an application to the 2003 European summer heatwave.)

We emphasise that these results are presented simply to illustrate the methodological progress that has been made since the previous report. Results remain too model-dependent for quantitative conclusions to be drawn regarding risks in the real world: a follow-up study using the HadRM3H regional climate model found results consistent with no increase or even a reduction in the risk of extreme 30-day precipitation events. Hence, uncertainty exists in modelling at both global and regional scales, and both should be taken into account.

2.4 Climate change and windstorms

Evolving windstorm risk in the UK has been comprehensively assessed using data from the UKCIP02 scenarios (Hansen *et al.,* 2004). This study focused on windstorm risk due to deep cyclonic depressions[6] that are responsible for the bulk of windstorm damage in the UK, primarily occurring in autumn, winter and spring. High winds associated with thunderstorms, squall lines or tornados would not be resolved by current models.

Reflecting the modest changes in cyclone activity in the regional climate model, changes in maximum daily wind speed and numbers of days with gales are also small and spatially variable, with small reductions projected in some regions and small increases in others. Any projected change in large-scale (cyclonic) windstorm activity is much smaller than the minimum estimated uncertainty in the projections, leading us to conclude, on the basis of evidence available to date, that climate change will not significantly effect health via changes in windstorms.

An important caveat to this conclusion is that windstorm risk is known to be closely associated with the value of the North Atlantic Oscillation (NAO), and while the evidence is ambiguous, there are some indications that current climate models are underestimating the response of the NAO to anthropogenic climate change (Gillett *et al.,* 2003). If the next generation of models projects larger changes in the NAO, we can expect correspondingly larger changes in windstorm risk.

2.5 Sea level rise, coastal flooding and storm surges

Coastal flooding and storm surge risks respond both to changes in windstorm activity and to the background sea level. The 1953 Big Flood, which killed 307 people, was caused by a windstorm in the Atlantic that caused a major storm surge at the same time as a very high tide.

In a study using the HadRM2 regional climate model, which generally simulated much larger changes in cyclonic activity than HadRM3, similar contributions from both factors were found to increase storm surge risks around the British Isles (Flather and Smith, 1998). With the smaller changes in windstorm activity predicted by HadRM3, the relative contribution of background sea level rise is higher. While the considerable uncertainties in windstorm activity were noted in the previous section, sea level rise (particularly that due to thermal expansion of the oceans) is much more predictable. Hence we can predict with some confidence that the risk of coastal flooding will increase due to anthropogenic climate change over the 21st century.

Projected changes in storm surge risk are highly variable between locations, but can be substantial. The frequency of a 1-in-500-year extreme water level at Immingham on the North-East coast was projected to increase to once every 15 years. The relative contributions of windstorm versus background sea level rise also vary between regions. Windstorm activity may dominate storm surge risk in Scotland, while both windstorm and background sea level rise contribute to the flood risk in East Anglia (Tsimplis *et al.,* 2005).

The distinction between changes in storm surge risk due to windstorms and those due to background sea level is important because of their different relative predictability. The actual flood risk of an increase in background sea level is likely to be small provided this (highly predictable) factor is taken into account in the design of coastal defences, sewage systems and other susceptible infrastructure.

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[6] A depression was defined as a coherent synoptic system with a minimum central pressure ≤1,000HPa, while a deep depression was defined as having a minimum central pressure ≤970HPa and/or a deepening rate ≥9.5HPa in 12 hours.

2.6 Populations at risk of flooding

Many factors affect the flood risk for a given catchment, and climate changes represent only one part of this risk. The Environment Agency estimates that currently around 5 million people in 2 million properties live in flood risk areas in England and Wales. Defra estimates that 80,000 properties in towns and cities are at risk from flooding caused by heavy downpours that overwhelm urban drains – so-called 'intra-urban' flooding.

Sea level rise and tidal surge flooding are already threatening coastal lowlands, for example around the Wash, Norfolk, Suffolk and the Humber. The Thames Barrier protects the 150km^2 of London that lies below the high tide level. It was closed 55 times between 1983 and 2004 to protect London from tidal surges, and more than 50% of these closures have occurred during the last five years. Of floodplains in the UK, that of the Humber river has the greatest concentration of people apart from that of the Thames. The tidal barrier in Hull and other flood defences in the area protect over 300,000 people.

Flood risk is not distributed equally among the population in terms of socio-economic status. In England, the people at greatest risk of coastal flooding are those on lower incomes, particularly in the East of England, Yorkshire, the Humber and London regions (Environment Agency, 2006). For river flooding, the risk is more evenly distributed across income groups, although there is some regional variation.

An important consideration is **residual flood risk**. Where there is a high standard of defence, the probability of flooding is low, but the consequences in terms of damage and threats to life, should flooding occur, are enormous. An estimated 1.25 million people live and work in the defended Thames tidal floodplain.

Box 2.1 Foresight Flood Project – main findings (Foresight Report, Department of Trade and Industry, 2004)

- Climate change is an important factor in increasing flood risk, particularly through the impacts of rising sea levels and more stormy weather.
- Other important factors include the way we use land, increased urban development and the effects of increased wealth and higher standards of living.
- The number of people at a high risk from flooding could rise from 1.5 million to 3.5 million by 2100.
- More effective land management will help reduce the risks in most scenarios. However, in the worst case scenario these will be of little benefit and greater use of flood defences and coastal realignment will be required.

The Foresight Flood Project did not estimate future flood deaths or costs attributable to the health effects of flooding.

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3 Vector-borne diseases and climate change

(See also section 4.3 of 2001/2002 report)

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Summary

- Health authorities need to remain alert to the possibility of future European malaria outbreaks or to the arrival in the UK of better European vectors of malaria.
- Any malaria outbreaks in the UK, however, are likely to be rare and on a small scale, involving a small number of people. Prompt reaction to any outbreaks will reduce the chances of endemic malaria transmission in the UK.
- Any increase in tick-infested areas is more likely to be the effect of changing agricultural and wildlife management practices than of changes in climate alone.
- People engaging in leisure activities are most likely to come into contact with 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.
- None of the predicted climatic changes suggest that the UK will be threatened by tick-borne encephalitis (TBE). Overall there may be a marked decrease in the extent of this pathogen, although some areas of continental Europe free at present may be invaded.
- A range of other insect-related health problems may change with the predicted climate changes in the UK.

Recommendations

- Monitor changing risks as they are happening, both within the UK and to holidaymakers.
- 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.
- Establish a surveillance system for monitoring the distribution and abundance of arthropod vectors in the UK.

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
- 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 involved (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. This causes vectors to bite more frequently (increasing transmission rates), but may also cause higher vector mortality rates (decreasing transmission rates). Increased dryness may exacerbate vector mortality, and additionally decrease 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 UK for subtropical vectors, either a hot dry summer or a cold winter may act as a bottleneck, 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.

3.2 Methodology

3.2.1 Baseline and modelled climatologies

The Climatic Research Unit (CRU) Norwich 50km British Isles climatology and 0.5° Global climatology (UKCIP02 scenarios based on the HadRM3H regional model – see Chapter 1) were used to interpret and model present-day distributions of vector-borne diseases. To these surfaces were added the HadRM3H 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 (UKCIP98 section, ΔT columns) 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 (Mike Hulme, CRU, University of East Anglia, Norwich *pers. comm.*). Thus the future scenarios are a combination of the observed 1961–90 climatology and the predicted GCM differences under the variety of scenarios considered; this, rather than using both modelled 1961–90 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).

3.2.2 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 some of the alternatives.

a) The biological approach

All biological processes are temperature-sensitive, but the impact of this sensitivity on disease transmission is often difficult to predict (see section 3.1). 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 disease 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.

While biological modelling of this sort is the ideal solution to the problem of predicting the impact of future climates on disease transmission, at present there are insufficient data to use such models to predict how mosquito abundance (an important component of these 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 the results of model predictions of future risks relative to those of the present assume constant vector populations. A further limitation is that 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, but is again difficult to assess.

Methods such as this, and the ones described below, 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 result of climate change might be that tropical vectors and the diseases they transmit may arrive in Northern Europe, and the statistical approach gives some indication of the probability of this occurring. 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 stepwise inclusion of temperature, vapour pressure and precipitation variables. Before analysis, all climate surfaces were temporally Fourier-smoothed (Rogers *et al.,* 1996) and the means, maxima and minima of the smoothed variables were used in the analysis. The stepwise 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 **malaria globally** and **TBE in Europe**. The changing distributions of both diseases are modelled for a variety of future scenarios. Changing risks, both to the UK population directly 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 prevalent in such areas may be those we will 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 (O'Connell *et al.,* 1998) reflects either biological reality or inadequate diagnosis; increasing recognition in the UK has resulted in increased numbers of reported cases here (Cannell *et al.,* 1999), which probably has nothing to do with climate change. When 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 UK leisure activities in the future warmer world will affect human interactions with these 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 UK, 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 of these 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 and large parts of Europe.

- **Expert opinion** is also used in this 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 blackflies** (*Simulium* spp.).

3.3 Malaria

Malaria is one of the world's most important infectious diseases, killing 742,000 children under 5 years old every year (Snow *et al.,* 2003). 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 and 660 million clinical cases each year and this number may be rising (Snow *et al.,* 2005). 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 malaria.

3.3.1 Domestic malaria (predicted using the biological approach)

Malaria was once common in many marsh communities in Southern England between the 16th and 19th centuries (Dobson, 1997) and some indigenous malaria still occurred at the beginning of the 20th century. Those areas most badly affected included the Fens, the Thames estuary, South-East Kent, the Somerset Levels, the Severn estuary and the Holderness area of Yorkshire (Shute and Maryon, 1974). 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 they 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 (Newman, 1919).

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 (James, 1920). 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

There are six species of anophelines in the UK capable of transmitting both temperate and tropical strains of *vivax* malaria: *Anopheles algeriensis*, *An. atroparvus*, *An. claviger*, *An. daciae*, *An. messeae* and *An. plumbeus* (Linton *et al.,* 2005). In the past, UK malaria was associated with salt marshes where *An. atroparvus* was common. The aquatic stages of this mosquito are found in fresh or brackish water and the adults occupy houses and feed readily on people. *An. atroparvus* can also transmit European strains of *P. falciparum*, but is completely refractory to strains of the same parasite from the tropics (Ramsdale and Coluzzi, 1975). This mosquito is therefore considered the most important potential vector of malaria in the UK. However, field studies on the Isle of Sheppey, the last place in England to experience a malaria epidemic, show that this mosquito is now relatively rare and is unlikely to bite large numbers of people. Another possible vector is *An. Plumbeus,* which has a widespread distribution that includes London and its suburbs. It typically breeds in tree holes, although larvae have also been found in water held in old tyres (Karch, 1996). Recently it has been shown that *An. plumbeus* is capable of transmitting *P. falciparum* (Curtis, 2003).

How likely is it that *vivax* or *falciparum* malaria could be transmitted in the UK? Malaria transmission requires a potential vector to feed on someone carrying gametocytes, the stage of the parasite that is capable of maturing and becoming infective within a mosquito. Between 9 and 24 days after taking an infectious blood meal of gametocytes (depending on the temperature (Boyd, 1949)), a vector mosquito will be able to transmit the infection to anyone that it bites.

In 2003 there were 206 cases of imported *vivax* malaria and approximately 66% of these were contracted by visitors to the Indian subcontinent (HPA, 2004). Since there are relatively few *vivax* cases in the UK, and most of these are among people of Asian descent, who tend to live in major urban areas, the possibility of *An. atroparvus*, a coastal mosquito, biting an infectious patient are remote. It is therefore extremely unlikely that *vivax* malaria will be locally transmitted within the UK.

With *falciparum* malaria, the risk assessment is not so straightforward. In 2003 there were 1,339 imported cases of *falciparum* malaria, of which 71% were from West Africa, mainly involving Nigerians and Ghanaians. Many of these people live in London (Williams *et al.* 2002) and other urban areas in Southern England, areas where *An. plumbeus* occurs. An important question is, are these mosquitoes likely to feed on patients carrying gametocytes? A person bitten by an infective mosquito will become ill after about 14 days (Gillies and Warrell, 1993) and then go on to produce gametocytes about 10 days later (Boyd, 1949). Since nearly 90% of *falciparum* cases are not detected until 1–5 months after arrival in the UK (HPA, 2004) it suggests that many sufferers will be carrying gametocytes in their bloodstream for several weeks. It is also the case that gametocytes may not be completely eliminated by chemotherapy (Targett *et al.,* 2001). A further consideration is that the peak in imported malaria cases coincides with the period when *An. plumbeus* is most abundant (Williams *et al.* 2002). We are not suggesting that *An. plumbeus* is responsible for local transmission, since it is a relatively rare mosquito and will bite few people. We would therefore not expect more than a very few cases of autochthonous malaria in the UK over the next 50 years. Indeed one is more likely to be struck by lightning than to get malaria from an English mosquito.

Malaria and climate

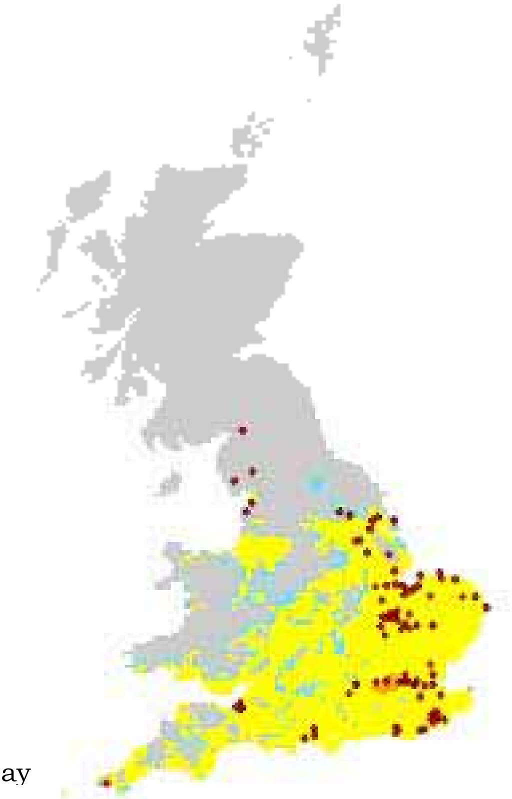
P. vivax is better suited to the British climate than is *P. falciparum*. It requires lower temperatures (by 1–2°C) than *falciparum* to develop equally rapidly in mosquitoes, and thus does better at cooler temperatures. *Vivax* parasites, unlike *falciparum* parasites, also sequester in the liver of 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 in the UK is between June and September.

Temperature and rainfall both influence the level of malaria transmission (Lindsay and Birley, 1966). 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 to vector survival.

Impact of temperature changes

Here the risk of *vivax* malaria in the UK is modelled for *An. atroparvus*. Maps of malaria suitability under recent climate (average 1961–90) and a range of future climate scenarios (Figures 3.1 and 3.2) show the number of months for which *vivax* malaria, if it were introduced, could persist each year in different parts of the country. These maps are a rough guide to 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 mosquito breeding sites. These latter factors may not be so critical for the UK, because the risk of malaria transmission is likely to be highest near extensive areas of wetland, which provide numerous breeding sites and are less affected by small changes in rainfall.

Figure 3.1 Present areas where the climate could support* vivax *malaria. Shading represents the number of months during which* vivax *malaria could be transmitted (grey=0, blue=1, yellow=2, orange=3). Red circles show malaria cases in the 19th century. Based on the UKCIP for 1961–90



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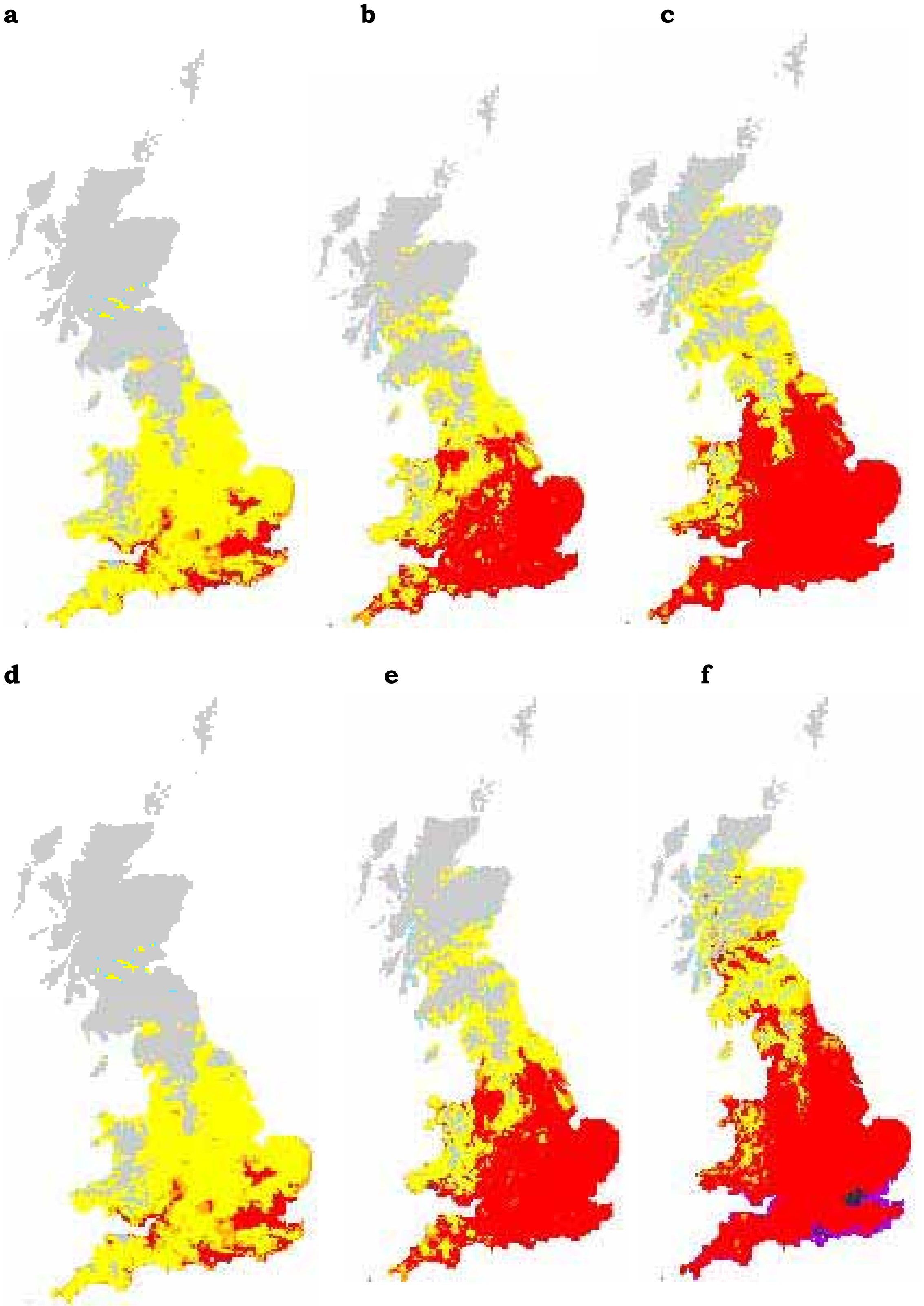
The present-day distribution of malaria risk corresponds extremely well to past records of the distribution of malaria in England (Figure 3.1) (Nuttall *et al.,* 1901). Thus, we are confident that our temperature/malaria model is relatively robust. Under all climate change scenarios, the risk of transmission is predicted to increase in Southern England, spreading northwards to the Scottish Borders.

At present, in only a few months in the south of the UK are temperature conditions permissive of 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’ (malarial fever). If the climate becomes warmer, conditions for transmission will 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.

Figure 3.2 Projected future risk maps for malaria transmission under a medium-low (a, b and c) and a medium-high (d, e and f) climate change scenario. Maps show risk for the period 2020s (a and d), 2050s (b and e) and 2080s (c and f). Based on UKCIP02



The different colours represent the number of months each year that *vivax* malaria could be transmitted. Grey=0, pale blue=1, yellow=2, orange=3, red=4, dark purple=5, black=6.

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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 42,251ha of salt marsh in Britain, with the largest areas, totalling 8,525ha, along the greater Thames estuary in Essex and Kent (Davidson *et al.,* 1991). Coastal wetlands are being reduced by drainage and other land 'improvements'. Rises in sea level that breach sea defences and inundate lowlands that are at present prevented from adapting naturally to salt water may result in less salt marsh. Elsewhere, gradual salt water intrusion into coastal lowlands may increase breeding sites for *An. atroparvus*. With summer droughts, there is likely to be a decline in the numbers of *An. plumbeus* as tree holes dry out. In contrast, 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.

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.*

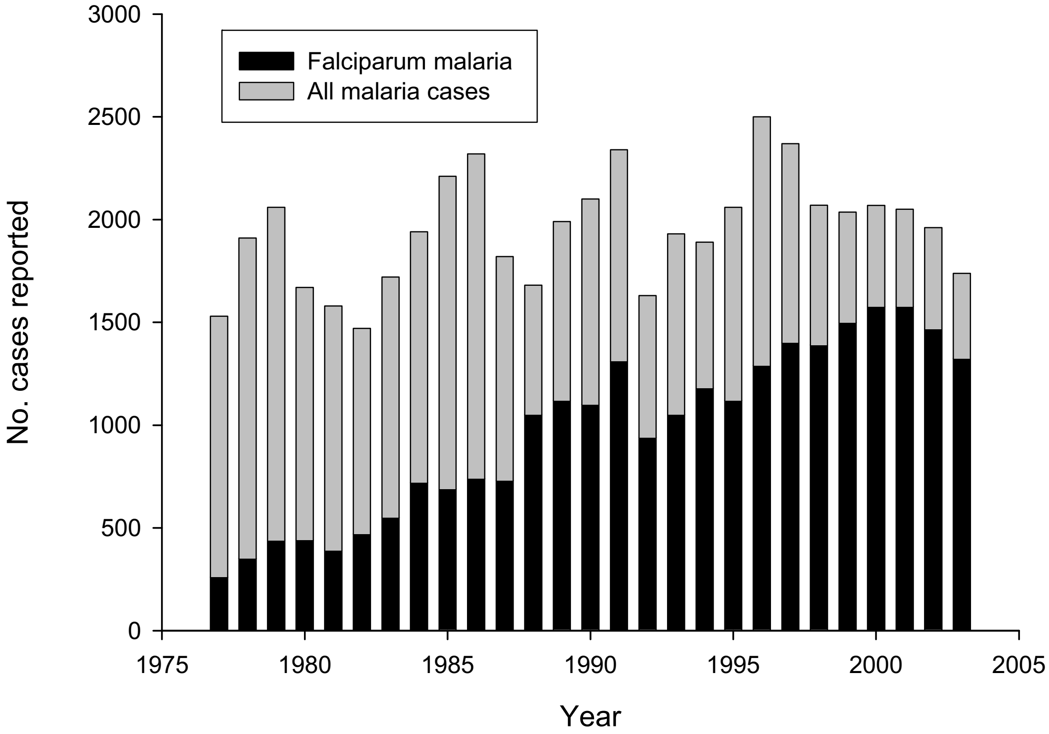
Health authorities need to remain alert to the possibility of future European malaria outbreaks, as occurred in Italy after 40 years of being free of malaria (Simini, 1997), and to the arrival in the UK of better European vectors of malaria. Any malaria outbreaks in the UK, however, are likely to be rare and on a small scale, involving a small number of people. Prompt reaction to any outbreaks will reduce the chances of endemic malaria transmission in the UK.

3.3.2 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. First, aircraft travelling from malaria-endemic countries may bring infected mosquitoes into non-endemic countries. Such outbreaks occur occasionally around international airports. Between 1969 and 1996 there have been 60 such cases reported in Belgium, France, Germany, Italy, the Netherlands, Spain, Switzerland and the UK (Danis *et al.,* 1999). Between 1969 and 1999 there have been 14 cases of airport malaria in the UK (Gratz *et al.,* 2000). In the summer of 2001, 52 aircraft arriving at Gatwick airport from Africa were searched by experts for a total time of 43 hours (Hutchinson *et al.,* 2005). This represented a search of about 25% of all flights that left Africa at night, when one would expect the greatest number of mosquitoes to enter the aircraft. No malaria mosquitoes were found, demonstrating that the current practice of disinfection of aircraft travelling from the tropics to the UK is effective.

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 multi-drug resistant parasites, which are a growing problem. Any increase in malaria-endemic areas, alongside expanding air 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 about 2,000 cases of travellers' malaria are reported each year to the HPA Malaria Reference Laboratory (Figure 3.3). The recent fall in malaria cases probably reflects the reduction in travel that has occurred since 9/11. Of the cases reported in 2003, the most recent year for which figures are given, around 78% are infections with life-threatening *P. falciparum* (HPA, 2004). The numbers of *falciparum* cases have continued to rise over the last decade, with 71 deaths from *falciparum* malaria occurring between 1998 and 2003.

Figure 3.3 Annual cases of malaria reported to the HPA Malaria Reference Laboratory, UK



Source: adapted from *CDR Weekly* (2004)

Global changes in falciparum *malaria endemicity*

The present distribution of *falciparum* malaria is captured well (78% accuracy) by four climate variables, minimum and maximum temperature conditions, precipitation and vapour pressure (Figure 3.4a). Only in Iran and South-East Brazil are there significant areas of false positive predictions (South-East Brazil is in fact shown as a low-risk area on some malaria maps). Under the medium-high climate change scenario (Figures 3.4b–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 the USA. The potential spread 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.

Figures 3.4a–d Global* falciparum *malaria

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The present-day distribution of* falciparum *malaria is adequately described by temperature, precipitation and vapour pressure data (Figure 3.4a, 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 scenarios of 2020, 2050 and 2080 are shown in Figures 3.4 b, c and d.

Figure 3.4a Global malaria: predicted areas of suitability, 1961–90 climate

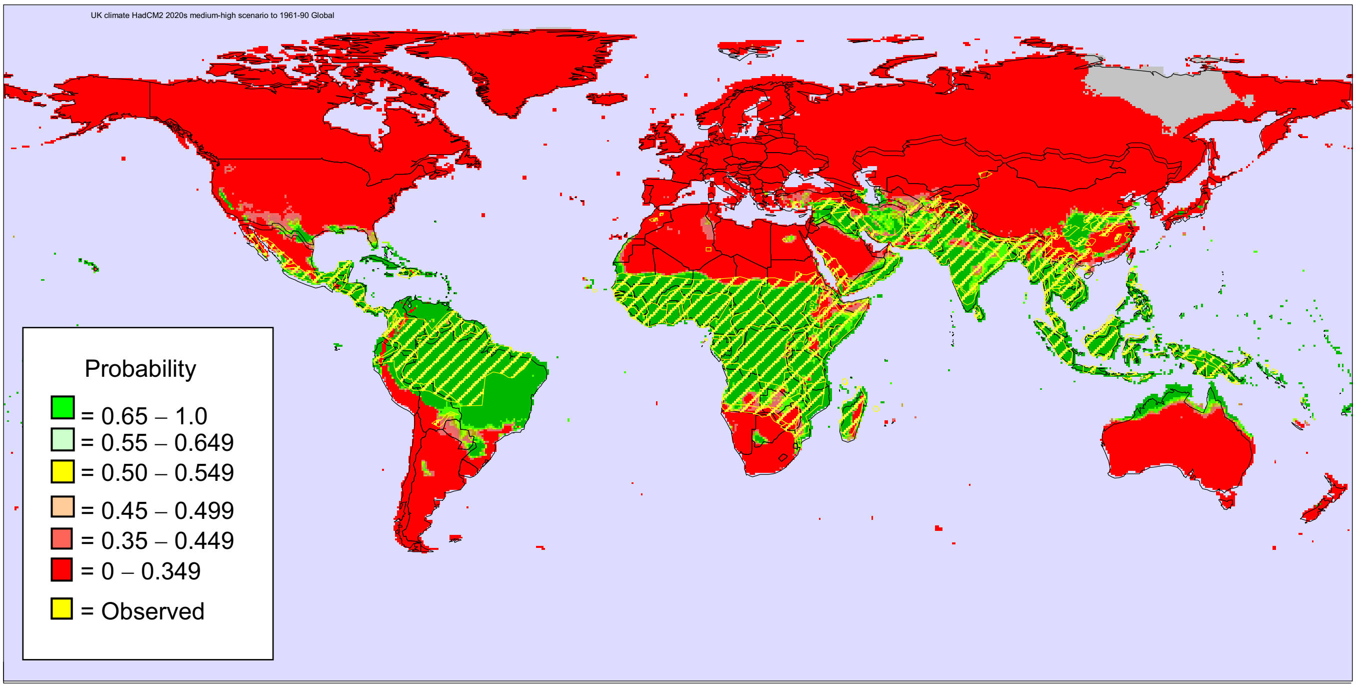


Figure 3.4b Global malaria: predicted areas of suitability, HadCM2 2020s medium-high scenario

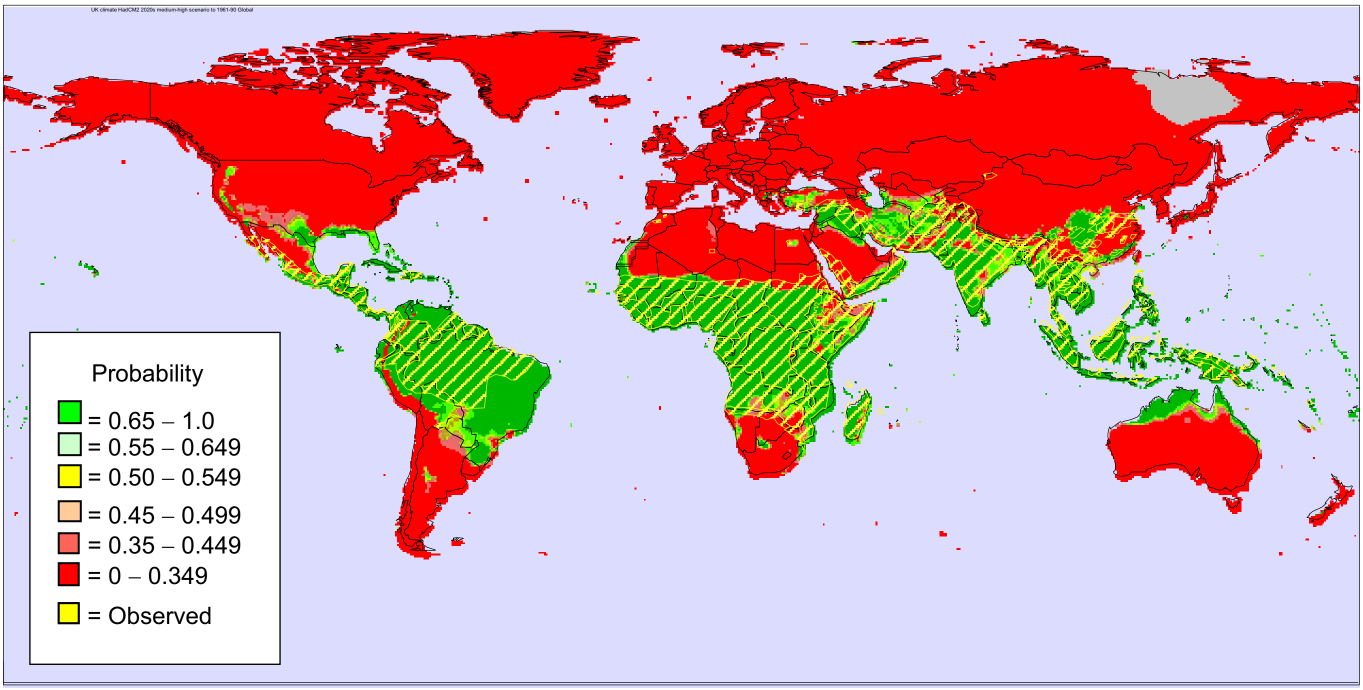


Figure 3.4c Global malaria: predicted areas of suitability, HadCM2 2050s medium-high scenario

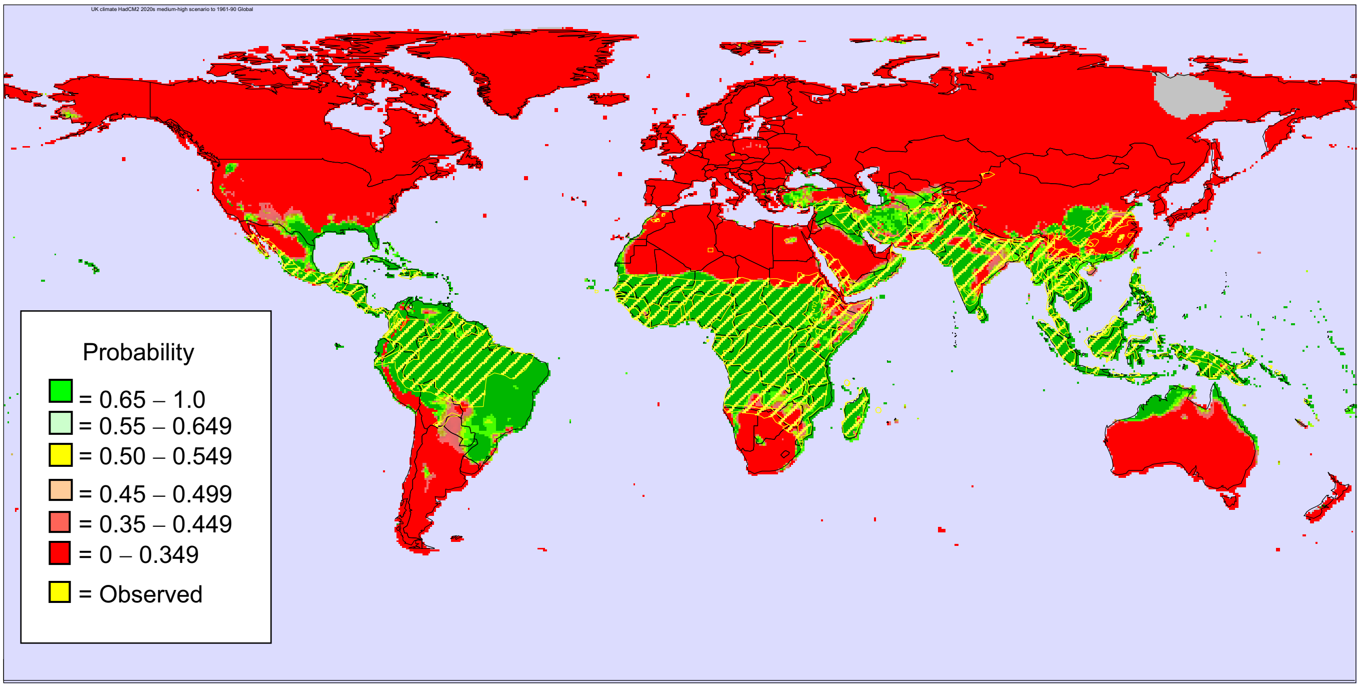
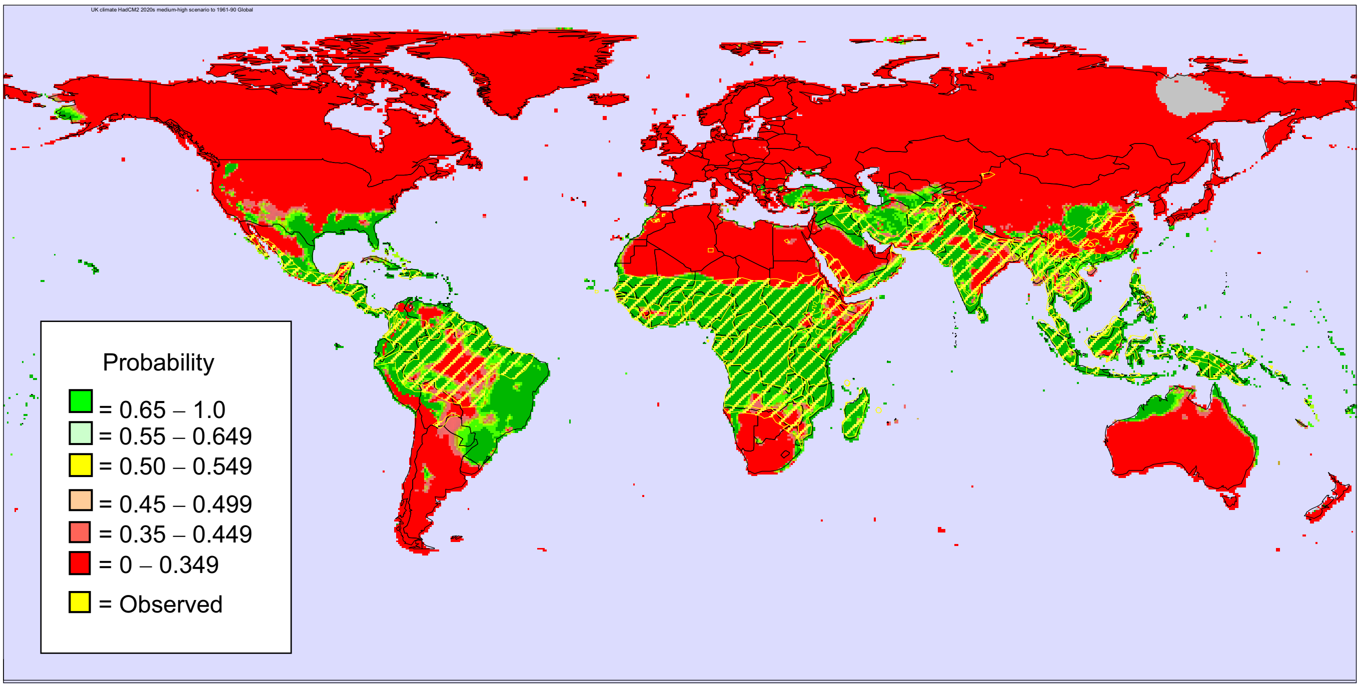


Figure 3.4d Global malaria: predicted areas of suitability, HadCM2 2080s medium-high scenario



These same changes, apart from those in South America, are predicted by the 2050s under all except the lowest scenarios of climate change (Figure 3.5).

Figures 3.5a–d Global* falciparum *malaria

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As for Figures 3.4a–d for the low, medium-low, medium-high and high HadCM2 2050s scenarios

Figure 3.5a Global malaria: predicted areas of suitability, HadCM2 2050s low scenario

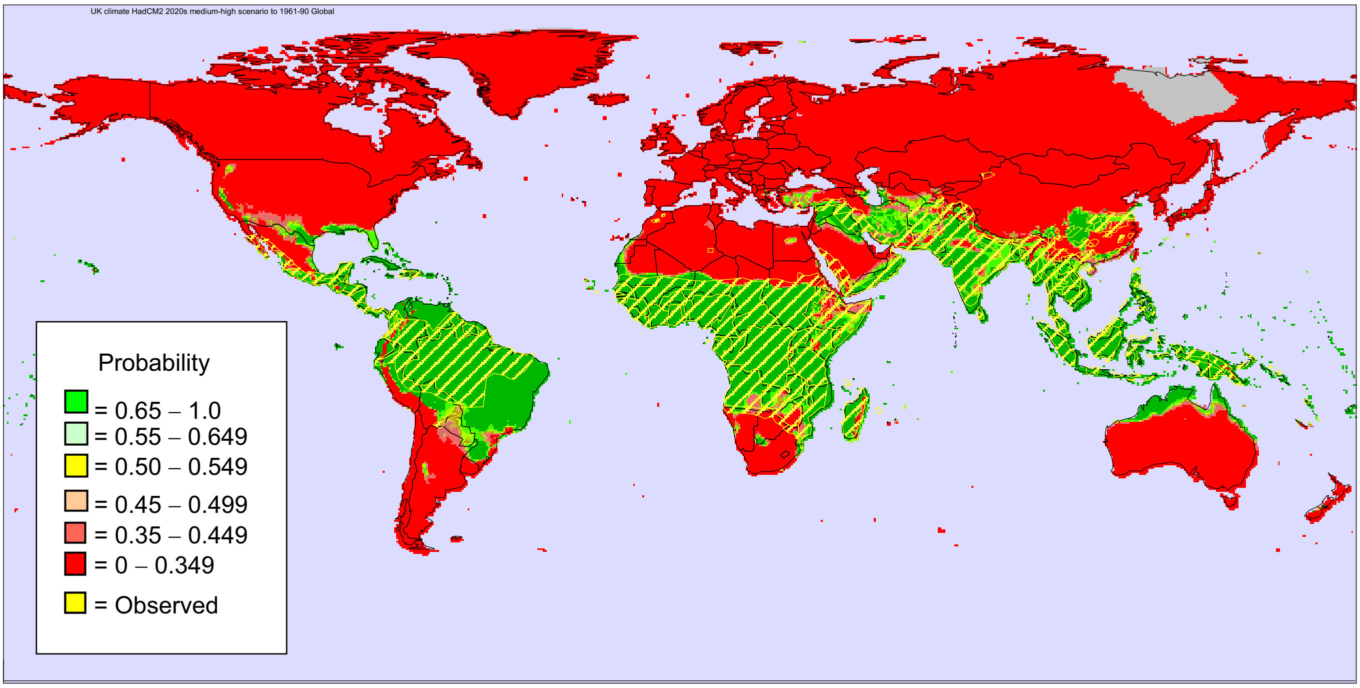


Figure 3.5b Global malaria: predicted areas of suitability, HadCM2 2050s medium-low scenario

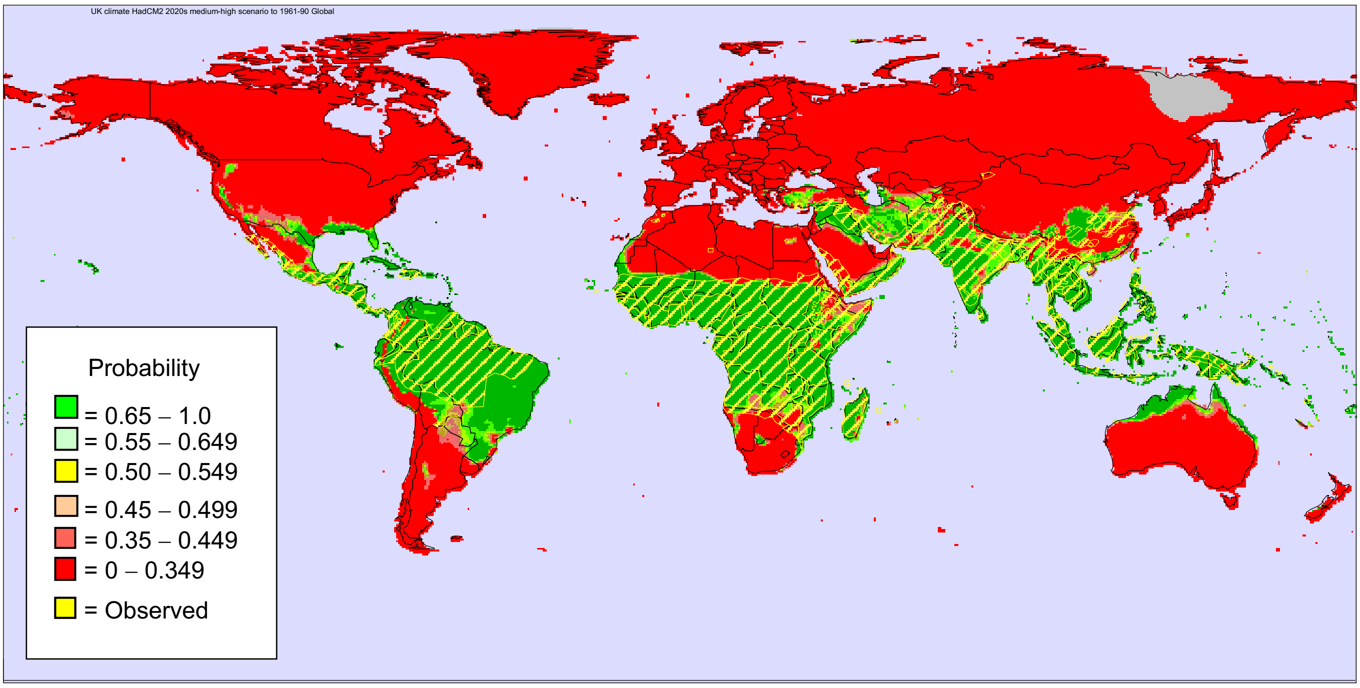


Figure 3.5c Global malaria: predicted areas of suitability, HadCM2 2050s medium-high scenario

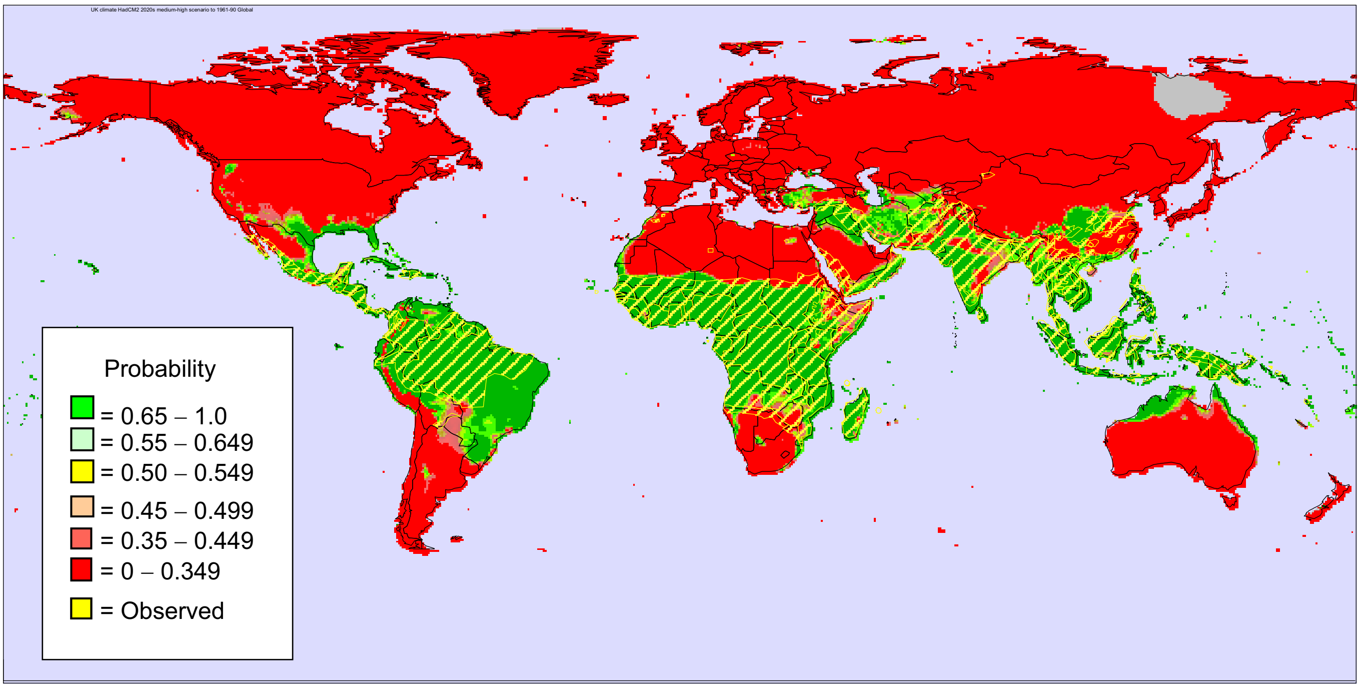
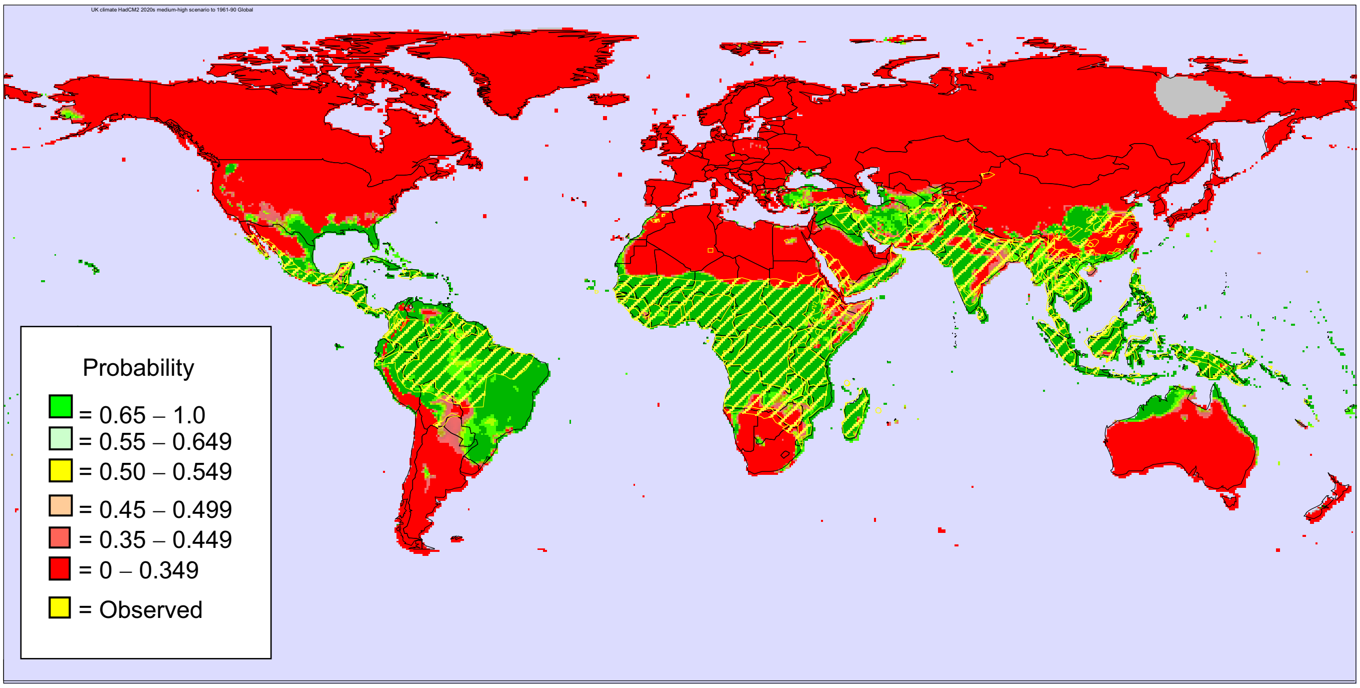


Figure 3.5d Global malaria: predicted areas of suitability, HadCM2 2050s high scenario



Certain parts of the world frequently visited by tourists from the 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 health authorities at these holiday destinations, to combat any increasing malaria risk to UK travellers abroad.

3.4 Tick-borne infections

Tick-borne pathogens are almost all zoonoses, circulating naturally among 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, such as 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 (Randolph, 1998). 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.

3.4.1 **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 UK, <200, (O'Connell *et al.,* 1998) 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 (Livesley *et al.,* 1994). 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.* (1999) show that the annual number of cases reported in the UK from 1986 to 1997 has 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 vegetation cover above a substantial litter or mat layer that retains moisture. This usually coincides with deer habitats (deciduous woodlands) (Daniel *et al.,* 1998) and rough grazing. Pastures improved 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 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:

a) hosts, particularly for the adult stage, are abundant

b) the overall climate is warm enough to allow rapid development between tick stages and sufficiently wet to allow good survival between feeds

c) the vegetation creates a favourable microclimate.

- 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 the UK have distinct transmission cycles via different vertebrate hosts (Kurtenbach *et al.,* 1998). Pheasants, for example, are only competent to transmit two genotypes, *B. garinii* associated with neurological disorders (e.g. Bell's palsy) and *B. valaisiana* which has no associated pathology. In woodlands with large populations of pheasants, circulation of the other genotypes via 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) (Craine *et al.,* 1997; Humair and Gern, 1998). On moorlands dominated by sheep, the specific transmission cycle again results in high infection prevalence only in adult ticks (Ogden *et al.,* 1997).

- 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.

3.4.2 Tick-borne encephalitis (TBE) (predicted by the statistical approach)

At present, TBE is confined to recognisable foci within Central Europe, the Baltic region and extensively throughout the Russian Federation (ImmunoAG, 1997; Korenburg, 1994). 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 (Randolph *et al.,* 1999) 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 (Randolph *et al.,* 2000). 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 3.6a).

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 the TBE virus into higher latitude and higher altitude regions progressively through the 2020s, 2050s and 2080s (Figures 3.6b–d). However, the altitude of the alpine region is too great to allow the TBE virus to become established there. In the 2020s, France, Switzerland, Slovenia, Hungary and much of Austria are cleared of the 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. 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 (Lindgren *et al.,* 2000). The final toe-hold in the 2080s is confined to a small part of Scandinavia, including new foci in Southern Finland.

Figures 3.6a–d TBE in Europe

Source: Randolph S.E. and Rogers D.J. (2000) *Proc.Roy.Soc., Lond B* 267, 1741–44

The present-day distribution of TBE in Europe is adequately described by temperature and vapour pressure data (Figure 3.6a, 86% correct predictions, 12% false positives and 2% false negatives). Predictions for the HadCM2 medium-high scenarios of the 2020s, 2050s and 2080s are shown in Figures 3.6b, 3.6c and 3.6d.

Figure 3.6a TBE in Europe: predicted areas of suitability, 1961–90 climate

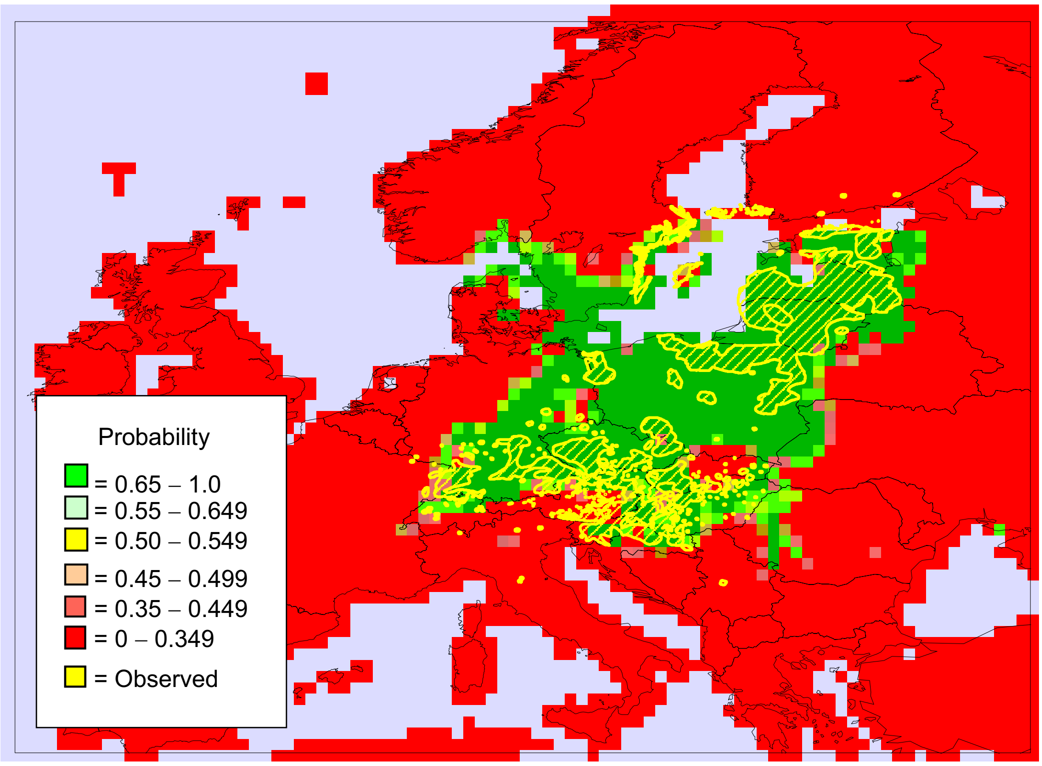


Figure 3.6b TBE in Europe: predicted areas of suitability, HADCM2 2020s medium-high scenario

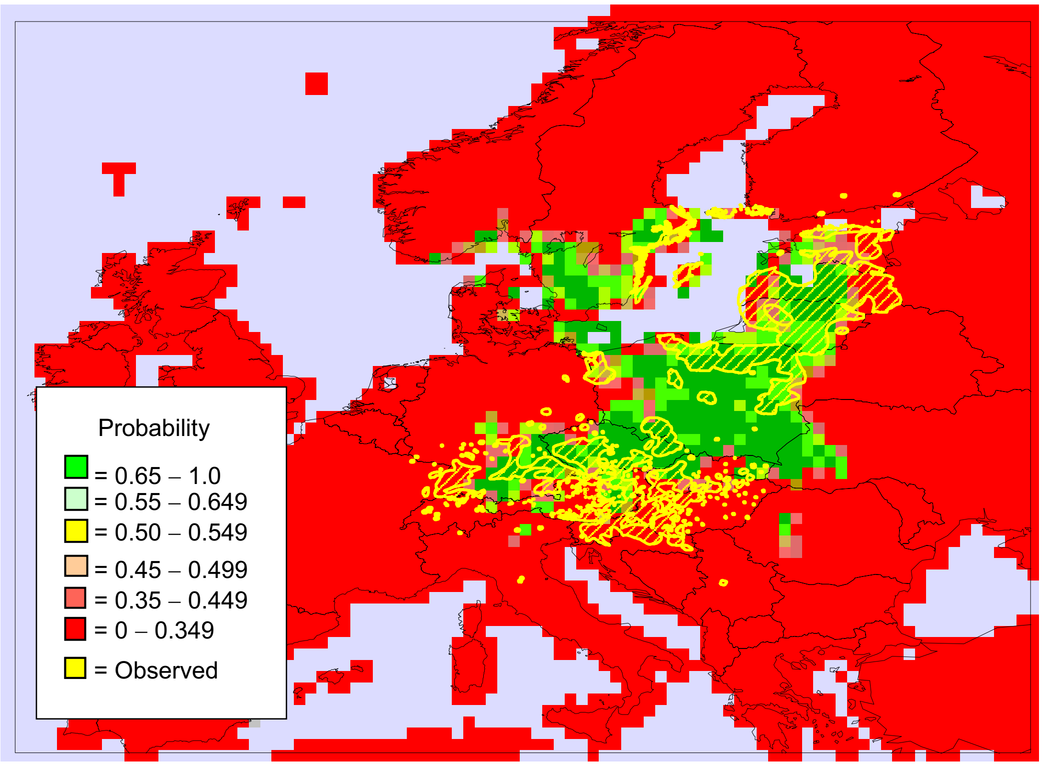


Figure 3.6c TBE in Europe: predicted areas of suitability, HADCM2 2050s medium-high scenario

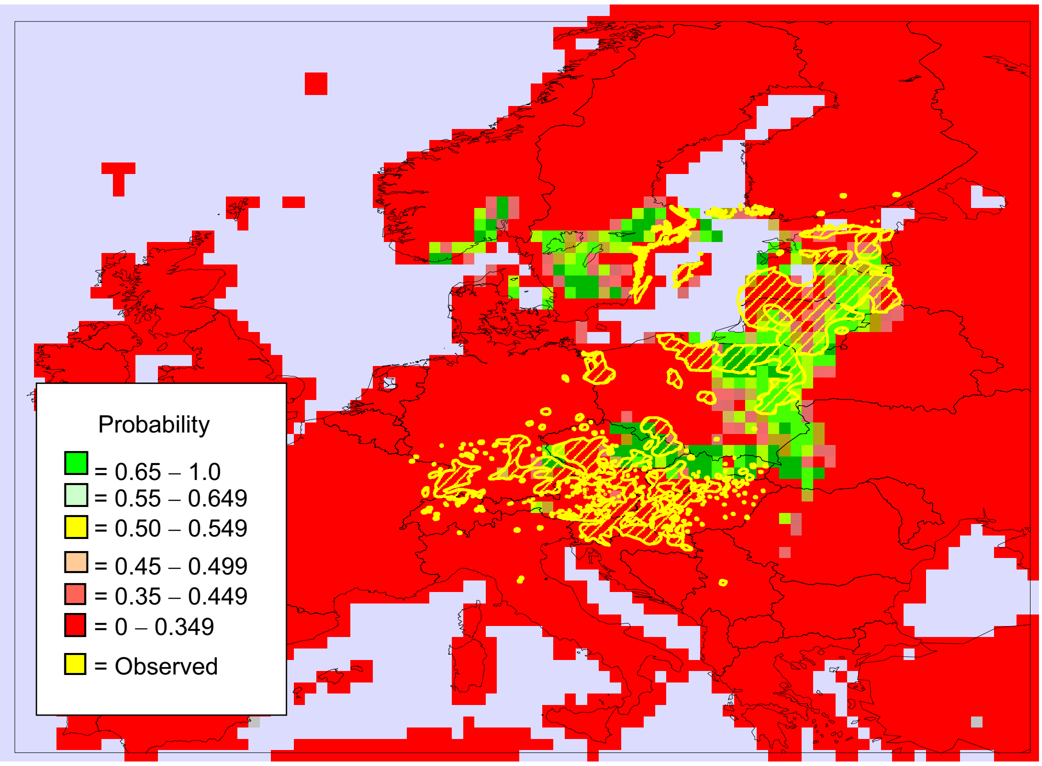
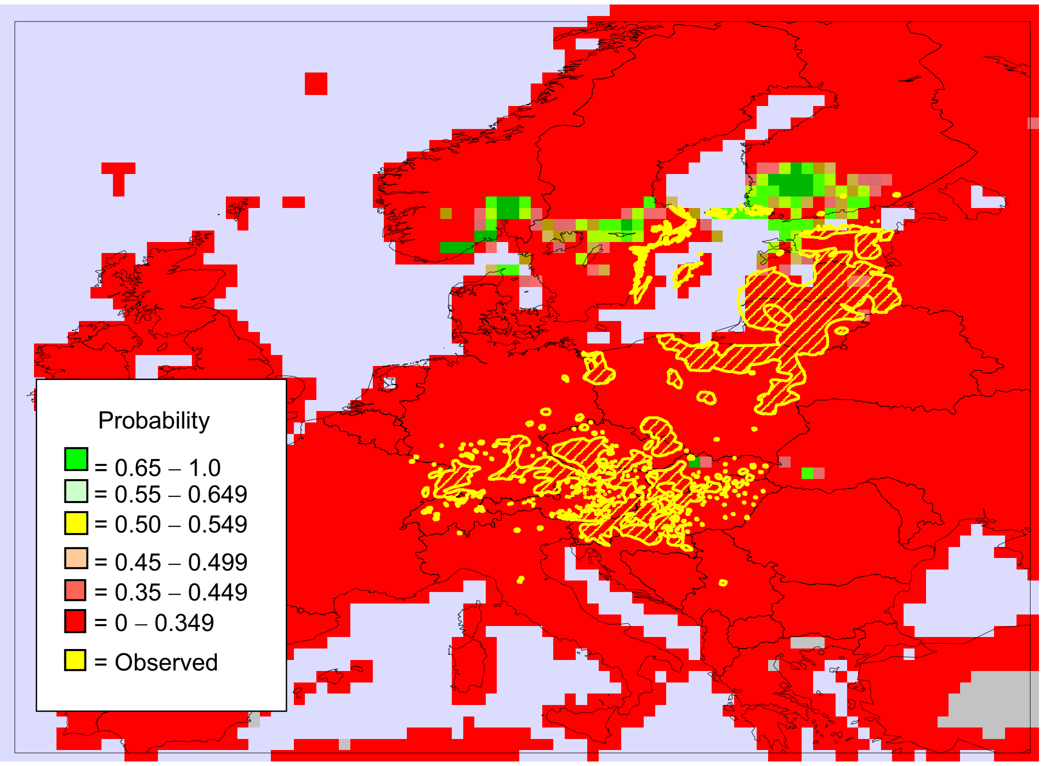


Figure 3.6d TBE in Europe: predicted areas of suitability, HADCM2 2080s medium-high scenario



For a given date, e.g. 2050, a similar pattern of TBE distribution emerges as different scenarios are considered (Figures 3.7a–d): 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.

Figures 3.7a–d TBE in Europe

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As for Figures 3.6a–d, for the low, medium-low, medium-high and high HadCM2 2050s scenarios.

Figure 3.7a TBE in Europe: predicted areas of suitability, HADCM2 2050s low scenario

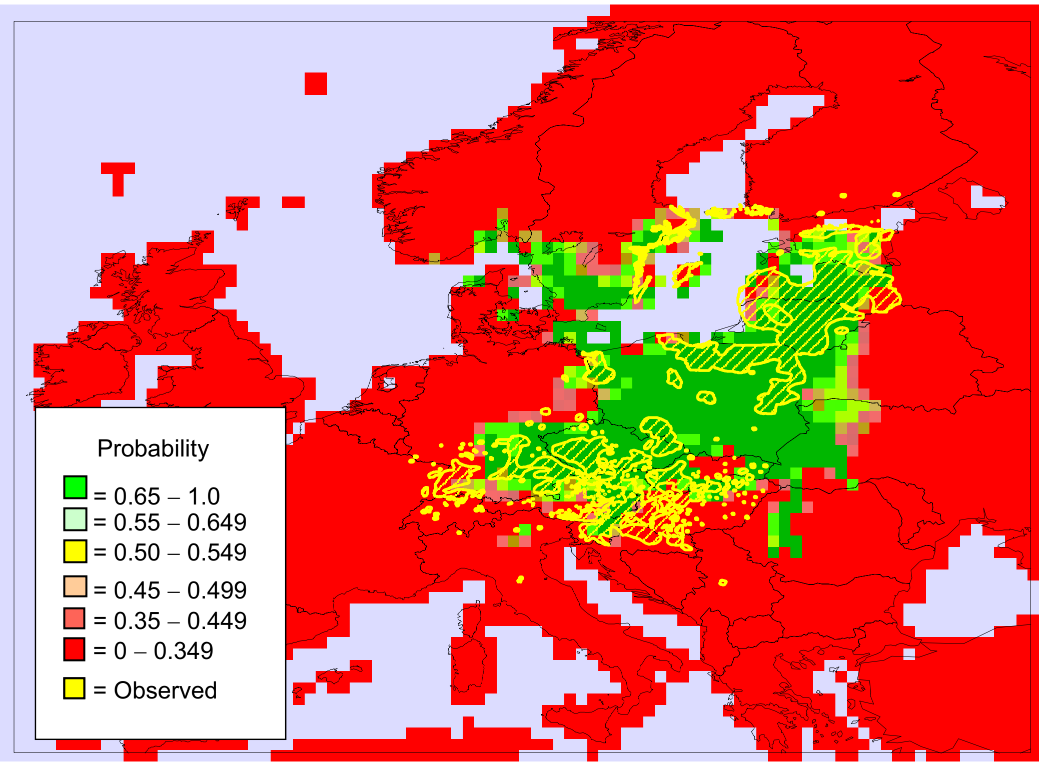


Figure 3.7b TBE in Europe: predicted areas of suitability, HADCM2 2050s medium-low scenario

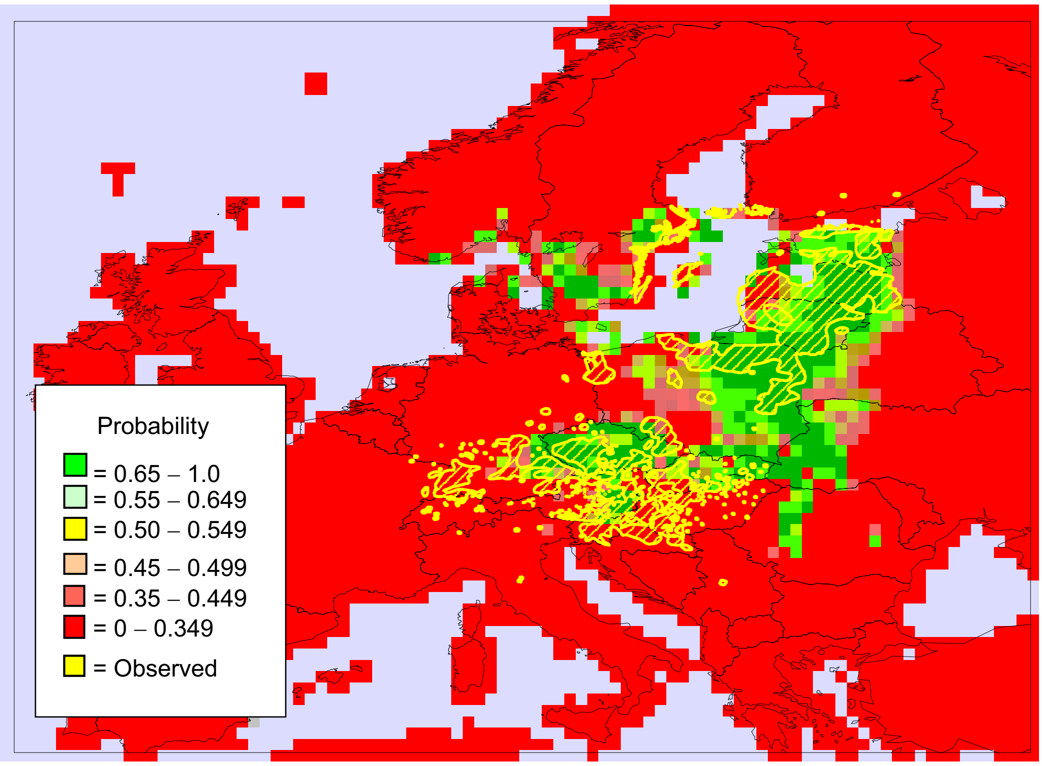


Figure 3.7c TBE in Europe: predicted areas of suitability, HADCM2 2050s medium-high scenario

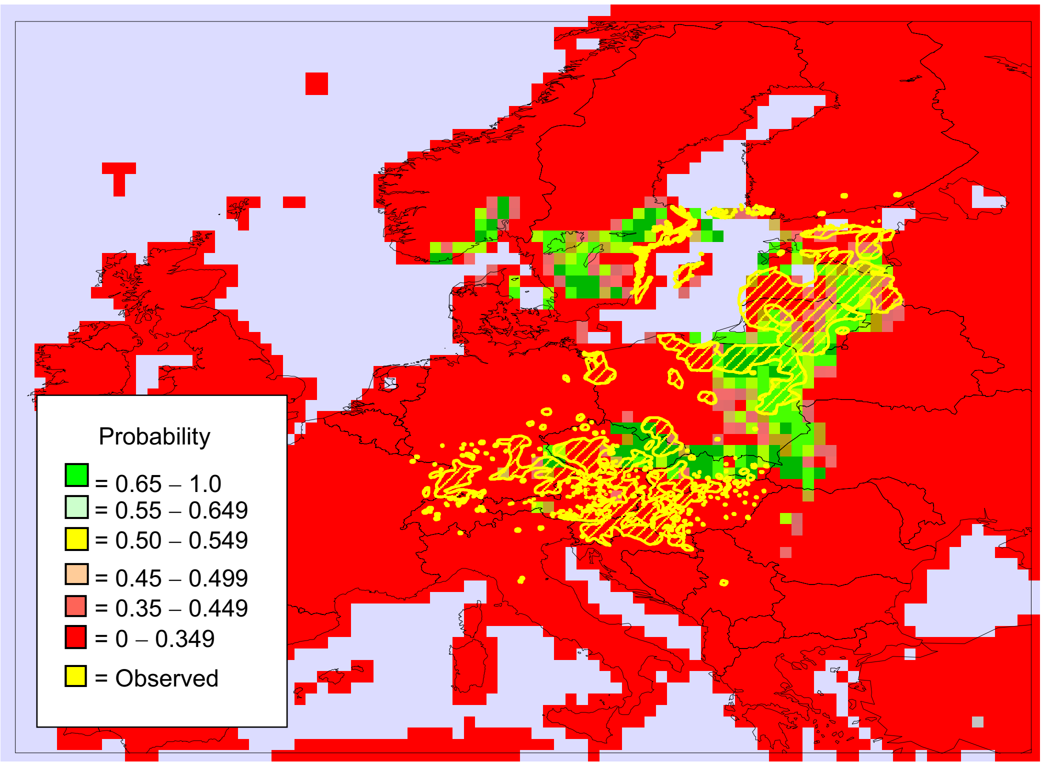
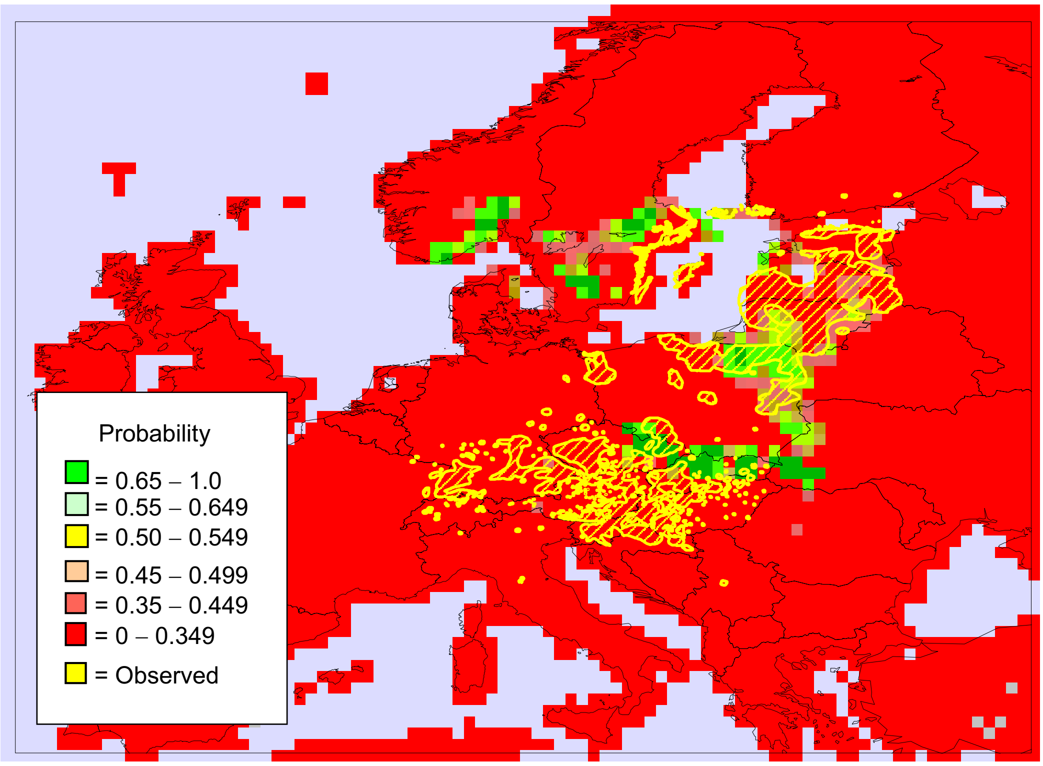


Figure 3.7d TBE in Europe: predicted areas of suitability, HADCM2 2050s high scenario



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.

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 3.8a).

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 3.8b–d). For example, by the 2020s parts of the UK match more of the Mediterranean rim: does this pose a threat of leishmaniasis? Farther 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 the 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 as to the future risks of exotic diseases to inhabitants of the UK.

Figures 3.8a–d Matching the UK to global climates

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Figure 3.8a UK climate 1961–90 matched to 1961–90 global

The UK inset shows the distribution of 10 climatic zones defined in terms of temperature, rainfall and vapour pressure (the mean, maxima and minima) for the period 1961–90. The world map shows the global distribution of these same zones in the same period, with the detail for Europe.

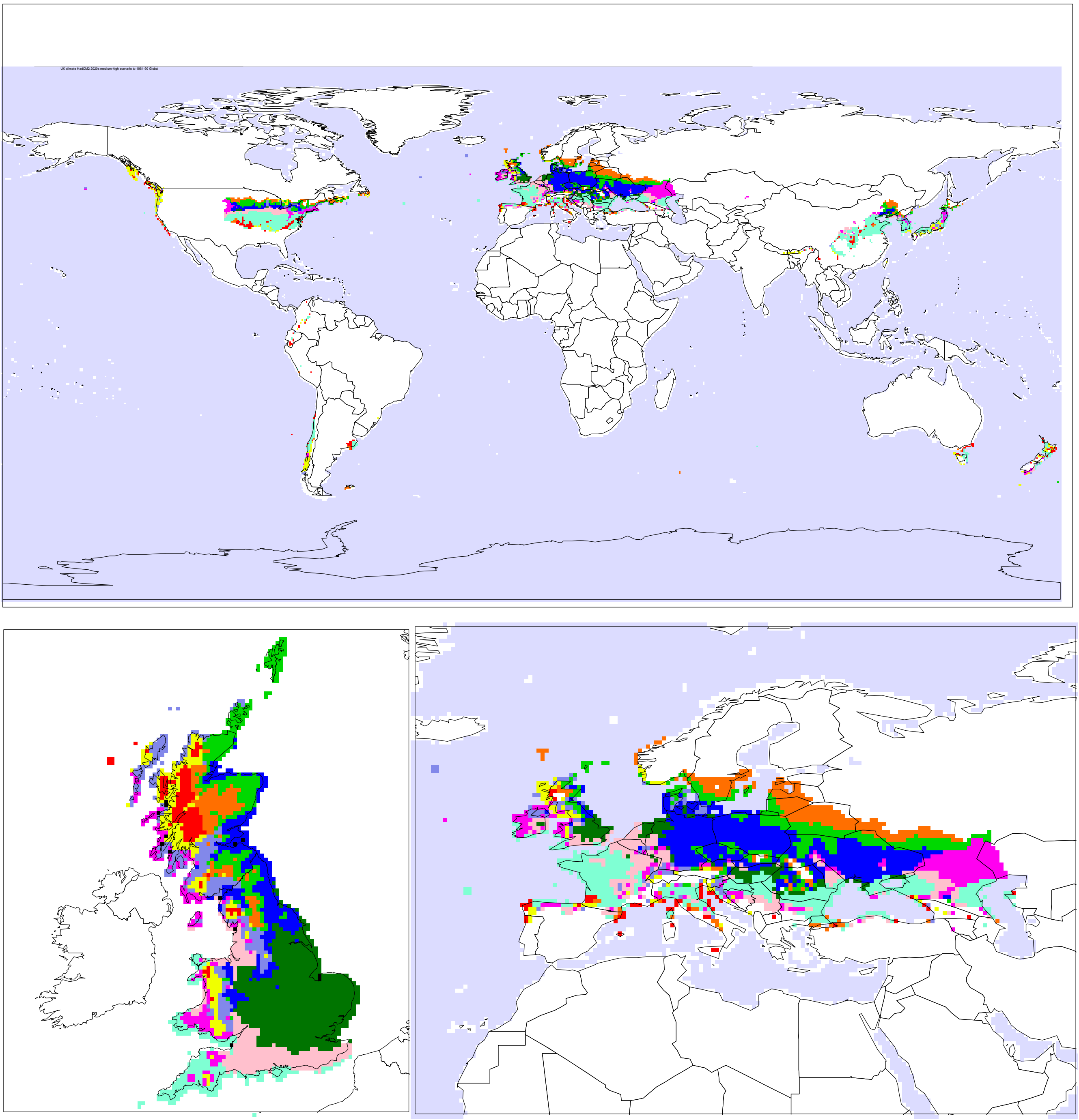


Figure 3.8b UK climate HADCM2 2020s medium-high scenario matched to 1961–90 global

The UK inset shows the distribution of 10 climatic zones defined in terms of temperature, rainfall and vapour pressure (the mean, maxima and minima) for the HadCM2 2020 medium-high scenario. The world map shows the global distribution of these same zones <u>at the present time</u> (1961–90), with the detail for Europe.

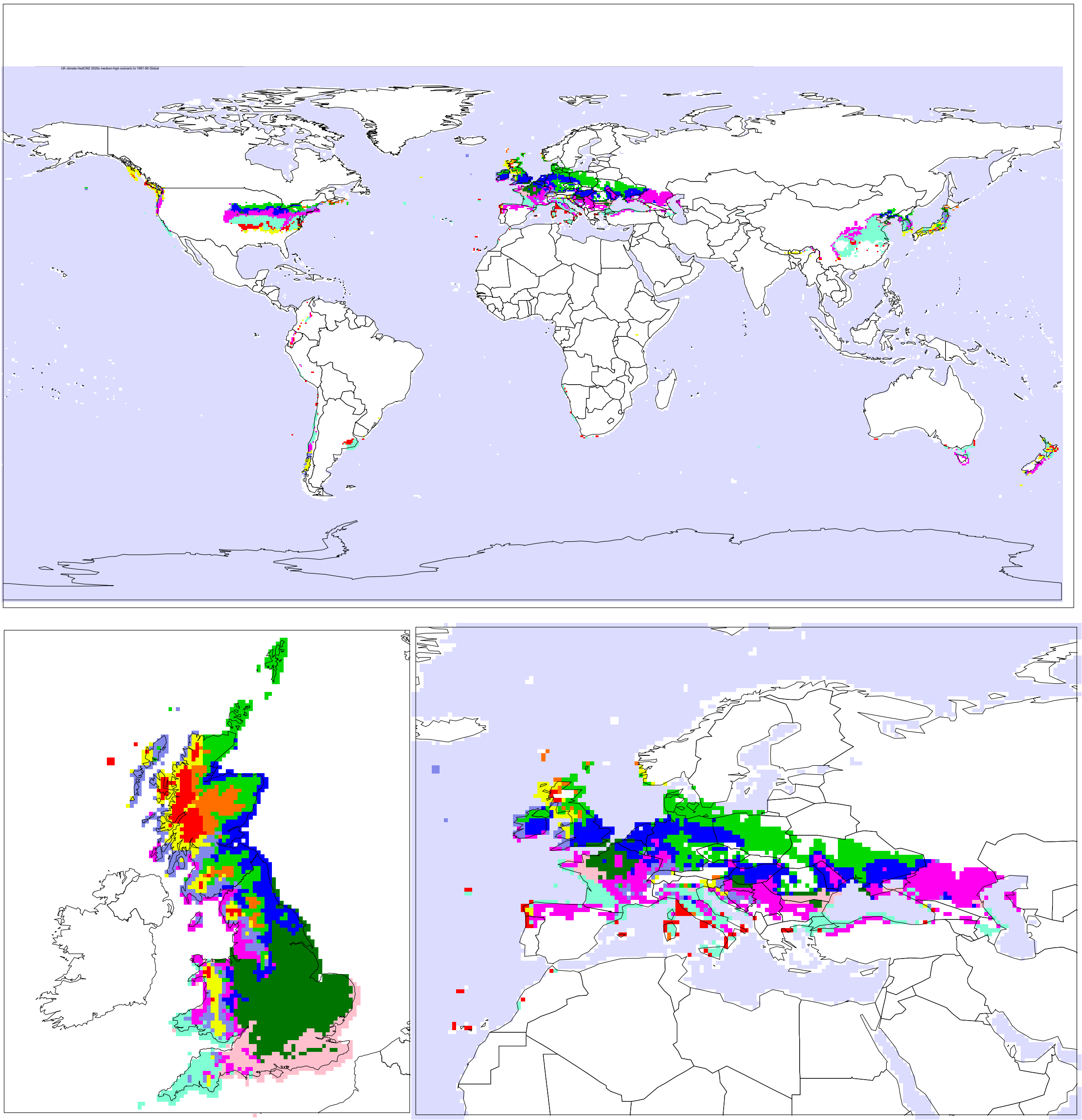


Figure 3.8c UK climate HadCM2 2050s medium-high scenario matched to 1961–90 global

As for Figure 3.8b but using the HadCM2 2050 medium-high scenario.

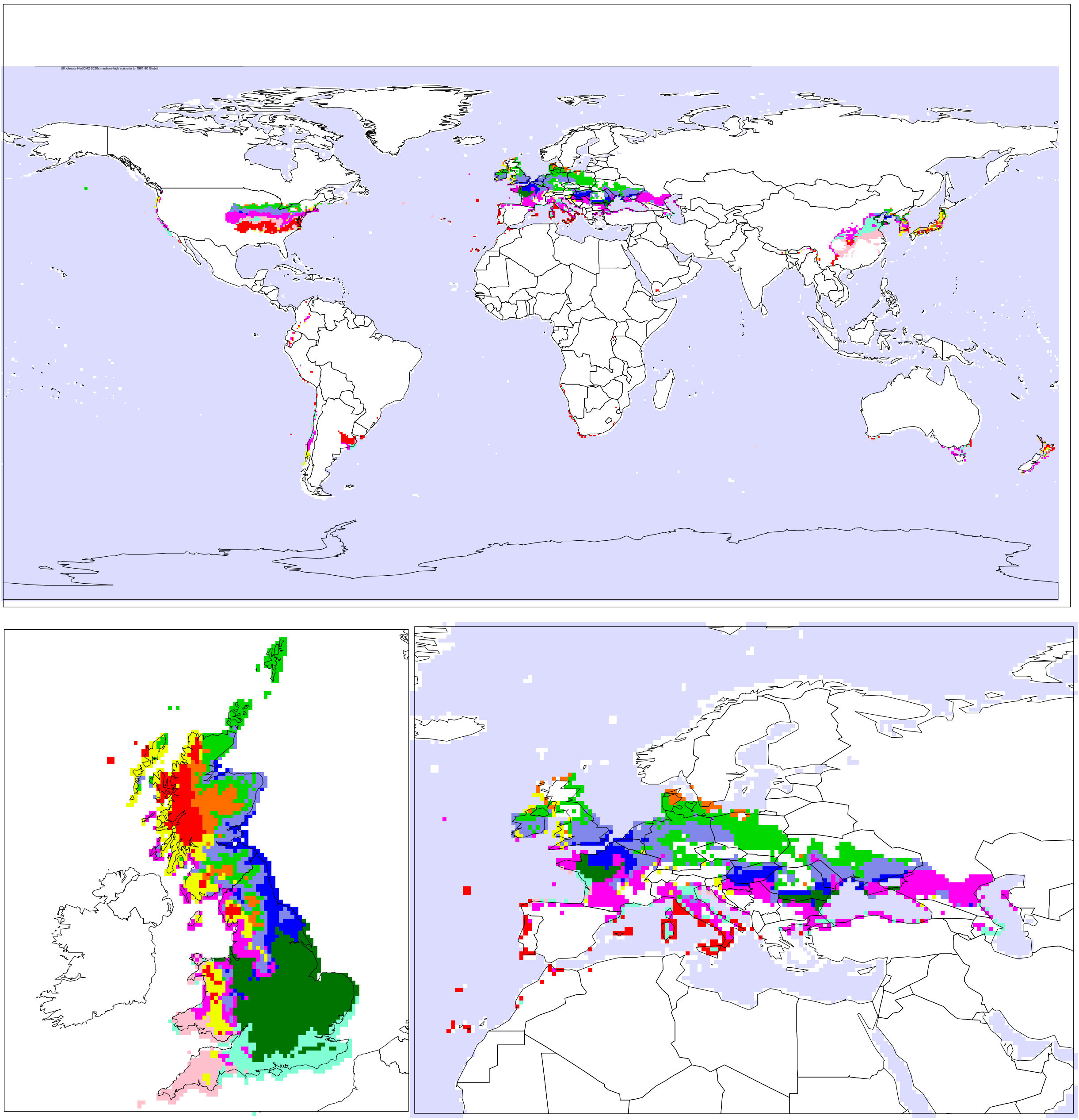
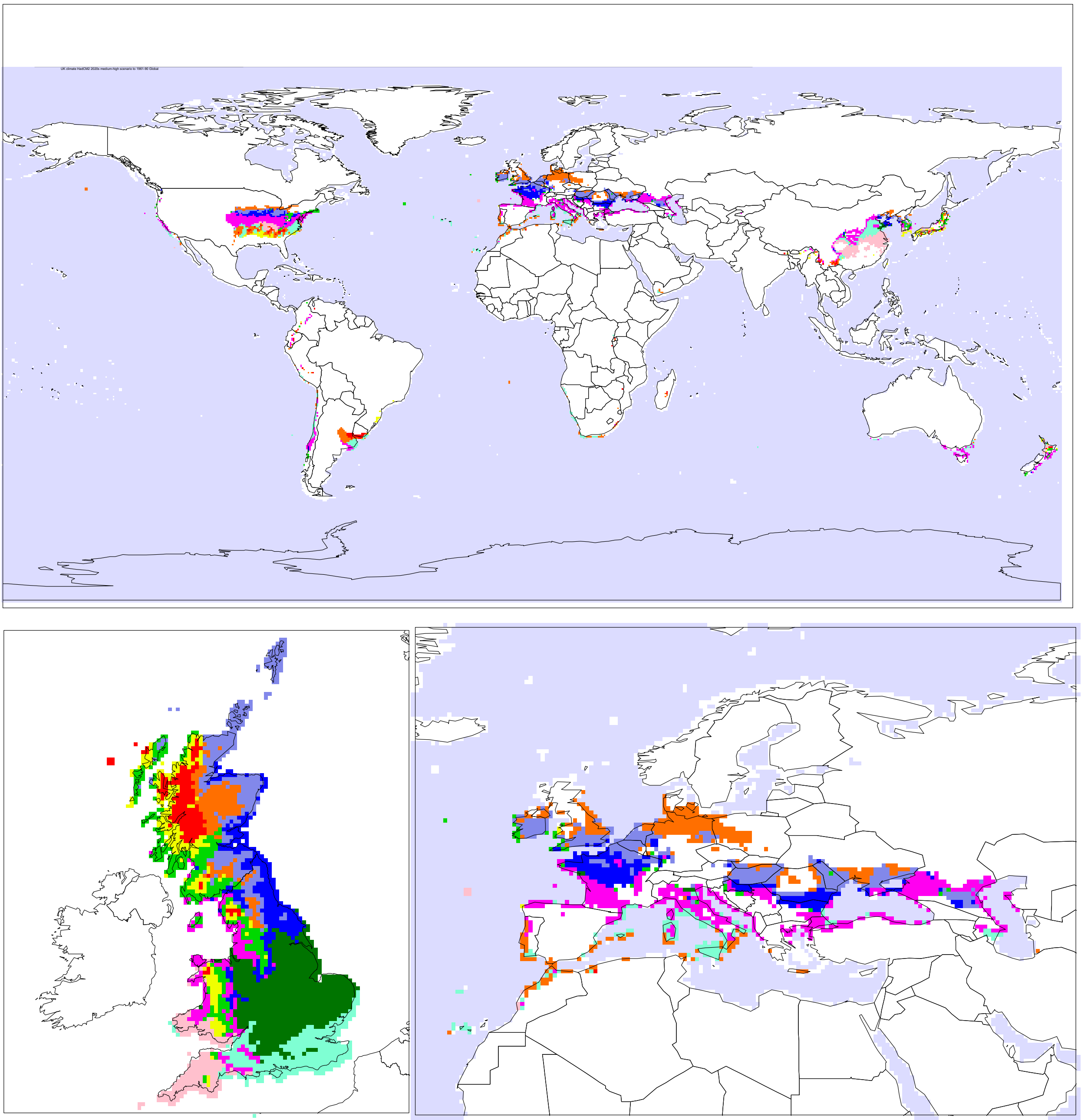


Figure 3.8d UK climate HadCM2 2080s medium-high scenario matched to 1961–90 global

As for Figure 3.8b but using the HadCM2 2080 medium-high scenario.



The same exercise has been done for the various scenarios in the 2050s (Figures 3.9a–d).

Figures 3.9a–d Matching the UK to global climates

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Figure 3.9a UK climate HadCM2 2050s low scenario matched to 1961–90 global

As for Figure 3.8b but using the HadCM2 2050 low scenario.

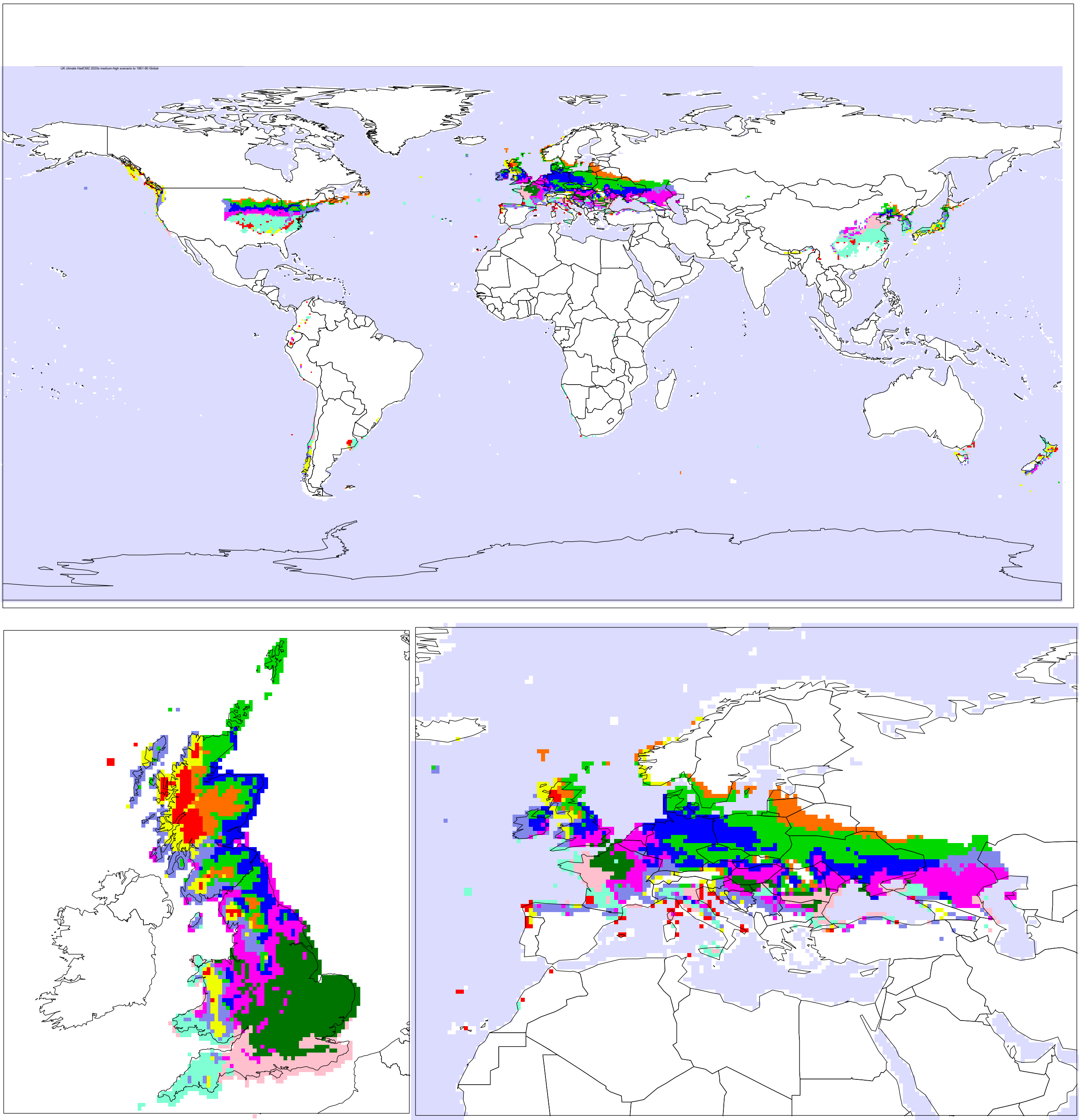


Figure 3.9b UK climate HadCM2 2050s medium-low scenario matched to 1961–90 global

As for Figure 3.8b but using the HadCM2 2050 medium-low scenario.

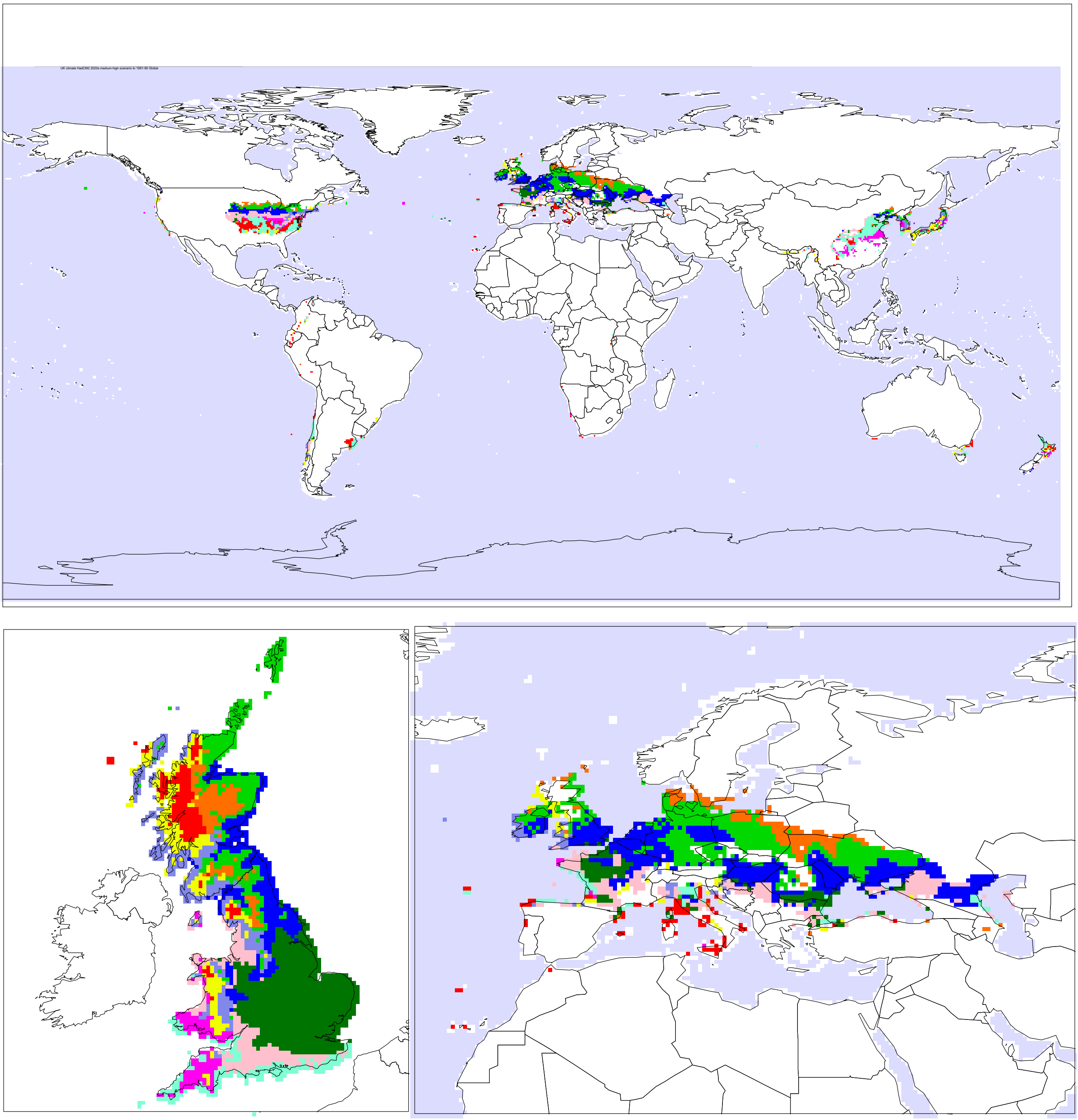


Figure 3.9c UK climate HadCM2 2050s medium-high scenario matched to 1961–90 global

As for Figure 3.8b but using the HadCM2 2050 medium-high scenario.

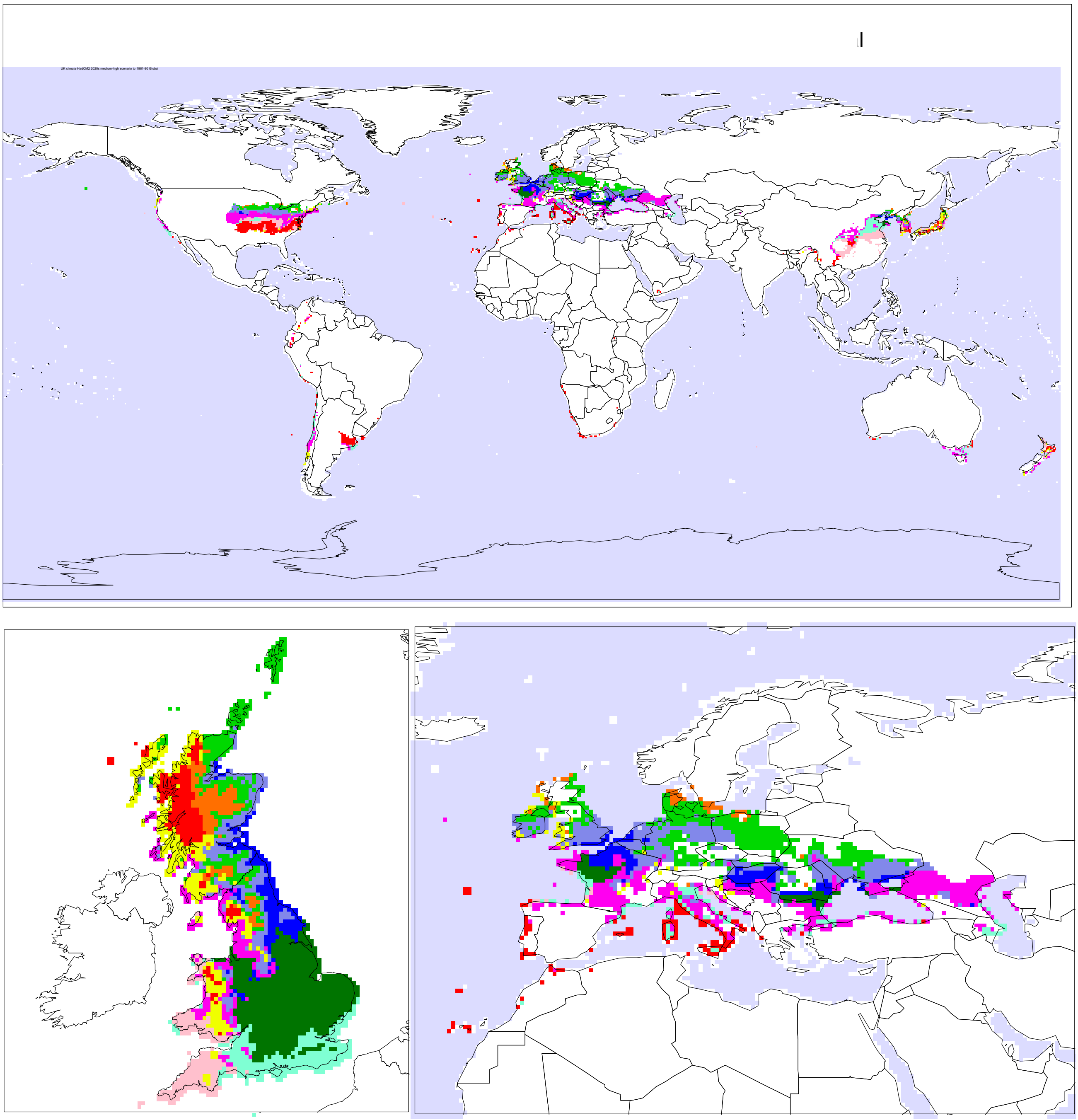
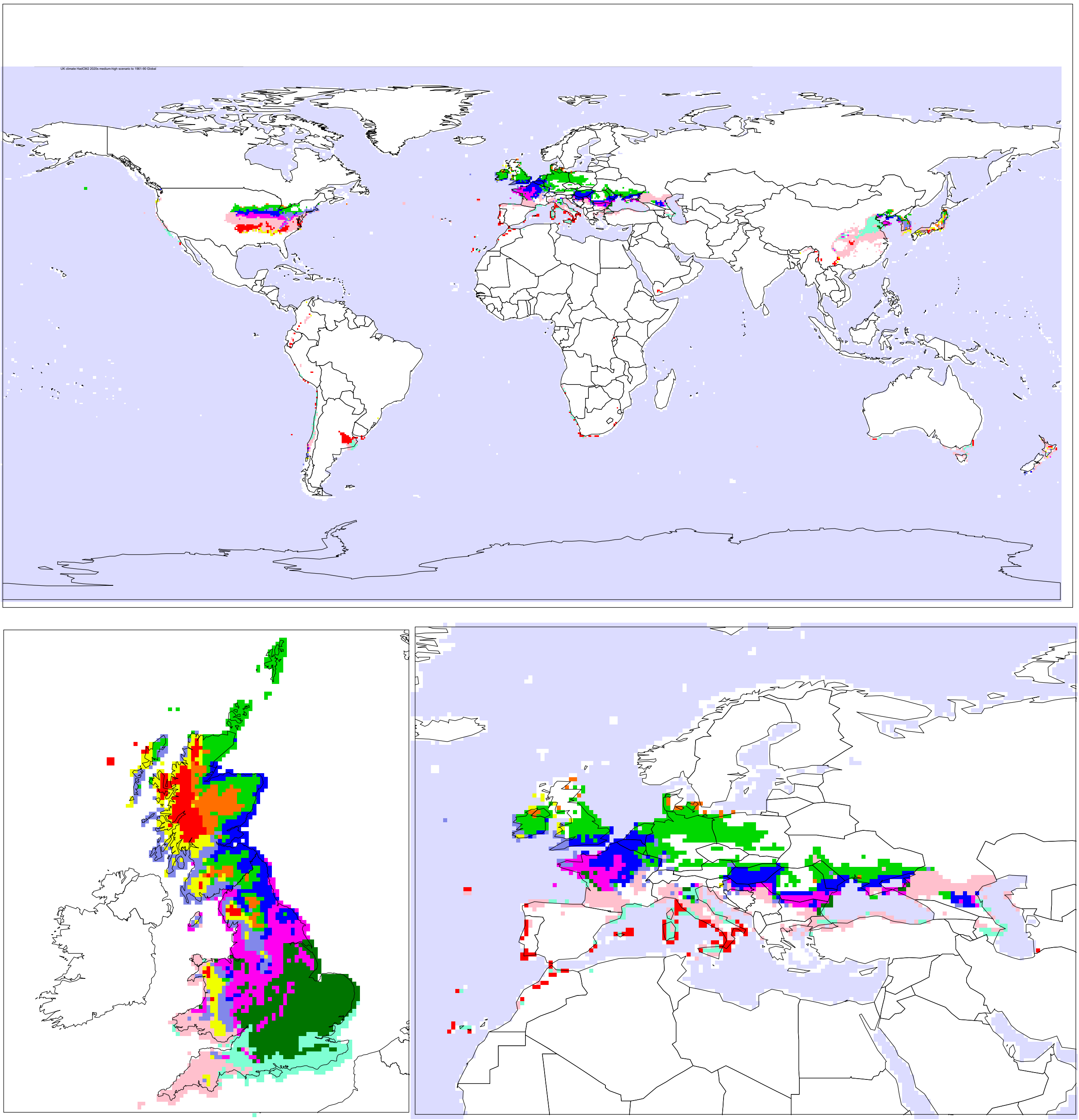


Figure 3.9d UK climate HadCM2 2050s high scenario matched to 1961–90 global

As for Figure 3.8b but using the HadCM2 2050 high scenario.



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 (see also Chapter 4 on foodborne disease).
- *Midges – relevant to tourism.* The midge menace is already well known to local people and holidaymakers 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 human attention. On contact with human skin, the hairs of such insects can cause painful swellings and rashes that persist for many days. We are uncertain of the causes of outbreaks of such caterpillars, 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. *Stegomyia albopicta* (*Aedes albopictus*) – potential vector of both dengue fever and malaria, accidentally introduced to 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 England.
- *House dust mites* – associated with allergies and possibly with asthma.
- *Plague* – endemic in the USA, transmitted by fleas between rats and also 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.

3.7 Priorities for future action

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 holidaymakers. 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.
- Map the distribution and abundance of key vector species in the UK.

Identify the threat to travellers/holidaymakers visiting 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 fever, leishmaniasis, trypanosomiasis and TBE).

- 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.

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Annex

The following text explains the derivation of the maps in Figures 3.1 and 3.2 using a biological approach.

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

The analyses to produce the maps of European *vivax* malaria in Figures 3.1 and 3.2 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, because it was assumed that the maximum biting rate tolerated by people living near these areas would be one bite each night, since we reasoned that most people would avoid being bitten more than 30 times in a month.

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

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

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*, in Jetten and Takken, 1994). ***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 (Detinova, 1962).

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) (Jetten and Takken, 1994).

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

$$n = \frac{f_2}{T-g_2} \text{ days}$$

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 (Jetten and Takken, 1994).

b = the proportion of vector females developing parasites after taking an infective blood meal. The model assumed a value of 0.19 (James, 1931).

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 (Boyd, 1949).

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.

4 Foodborne disease and climate change

(See also section 4.2 of 2001/2002 report)

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Summary

- New scientific evidence confirms the effect of temperature on salmonellosis.
- The role of temperature in *Campylobacter* transmission remains uncertain.
- The effect of warmer summers on foodborne disease incidence will depend on future food hygiene behaviour and the relative contribution of different pathogens, as well as changes in temperature.

Recommendations

- Vulnerability to the effects of climate change could be reduced by continuing efforts to improve the microbiological standards of food at all stages in the food chain, including production, distribution, storage and preparation.
- There may be a case for educating and warning food producers and the public about the particular risks associated with hot weather.
- The existence of lags between high temperatures and effects on humans offers the possibility of instituting a warning system.

4.1 Introduction

The previous review noted that food poisoning is an important cause of morbidity in the general population associated with significant costs of treatment and loss of working time. The 1990s had seen a large increase in incidence for reasons that remain controversial, but may include changes in methods of food production such as the shift towards intensive rearing of poultry and other animals, changing patterns of retailing and catering as well as changing behaviour of consumers.

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 had led to the suggestion that climate change could increase food poisoning risk (McMichael *et al.,* 1996). However, at the time of the previous review there was only a very limited body of published evidence on which an assessment of the potential impacts of climate change on food poisoning could be based.

In recent years there have been major changes in the number of cases of food poisoning in England and Wales and in the relative importance of different pathogens. The number of food poisoning notifications increased steadily during most of the 1990s to reach a peak in 1998. Since then there has been a marked decline, with notifications for the most recent year (2004) being about 25% lower than at the peak with especially large reductions being evident for infections from *Salmonella* which decreased by 60% between their peak (in 1997) and 2004.

4.2 Current impacts of climate and weather

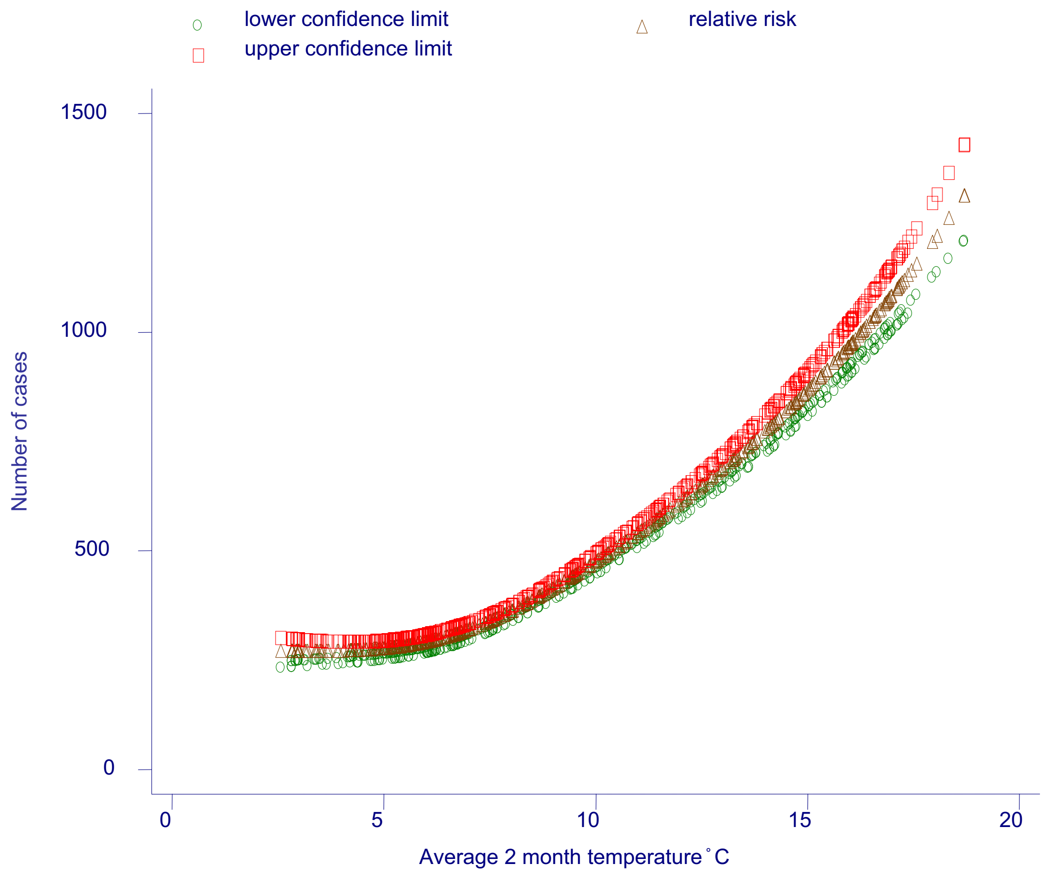
The existence of a pronounced seasonal pattern, with a higher incidence in the summer, points to a role for weather and climate in the aetiology of food poisoning. High temperatures favour the multiplication of some pathogenic micro-organisms in food, including the *Salmonellas* that are an important source of food poisoning in the UK. 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.

Since the previous review, several empirical studies have been published on the relationship between environmental temperatures and the incidence of foodborne illness. Bentham and Langford (2001) analysed the association between weekly notification of food poisoning and temperatures in England and Wales for the period 1974–96. This confirmed the findings of earlier studies (Bentham and Langford, 1995; Bentham, 1997) of a positive association between food poisoning and temperature, with the strongest effects being for conditions 2–5 weeks earlier. A significant limitation of this study is that the data used do not record which pathogens are responsible for the notified cases. This is important because the different common types of food poisoning pathogens are known to respond differently to environmental temperatures. The rate of multiplication of *Salmonella* is strongly related to temperature in the range from approximately 7° to 37°C, providing opportunities for ambient temperatures to affect the numbers of bacteria in food at various stages in the food chain. *Campylobacter*, on the other hand, replicates most readily at temperatures between 37° and 42°C in a low-oxygen environment. This makes it well adapted to the guts of birds and other animals, but multiplication in food at typical ambient temperatures is unlikely. Simple direct relationships with environmental temperatures are therefore less likely than for *Salmonella,* although more complex effects of temperature on the ecology of animal reservoirs or on patterns of human behaviour leading to exposure are possible.

Salmonella

D'Souza *et al.* (2003) investigated the association between monthly salmonellosis notifications and temperature in five Australian cities. They found a significant positive association between mean temperature of the previous month and the number of salmonellosis notifications in the current month, with the estimated increases for a 1°C increase in temperature ranging from 4% to 10% depending on the city. Kovats *et al.* (2004) analysed the association between laboratory-confirmed cases of salmonellosis and monthly temperatures in 10 European countries. The estimated change in incidence above a common 6°C threshold ranged from 0.3% in Denmark to 12.5% in England and Wales. The strongest effects were found for temperatures 1 week before the onset of illness rather than the longer lag of 1 month found in the Australian study.

Figure 4.1 Modelled association between temperature and number of reported cases of salmonellosis in England and Wales (adjusted for outbreaks, seasonal factors and holidays)



© S. Kovats (Data supplied by HPA)

Campylobacter

At the time of the earlier review, information was sparse on the relationship between environmental temperatures and human disease resulting from infection by *Campylobacter,* but since then new evidence has been published. In a study of *Campylobacter* infection in Denmark, Patrick *et al.* (2004) found a significant positive association with temperature, the strongest effects being for lags of 4 weeks. The study also showed that the prevalence of *Campylobacter* infection in broiler flocks at slaughter was positively associated with temperatures 3 weeks earlier. In Denmark consumption of poultry is an important risk factor for campylobacteriosis in humans. Increasing *Campylobacter* carriage rates in chicken meat following warm weather may therefore be one of the factors underlying the association between incidence and temperature in humans. A positive association between rates of campylobacteriosis in humans and temperature (unlagged) has also been reported for England and Wales (Louis *et al.*, 2005). However, a limitation of both these studies is that they did not adjust for seasonal factors that could confound the association between campylobacteriosis and temperature. Influences on the seasonality of campylobacteriosis in 13 countries has been investigated by Kovats *et al.* (2005). Although most of these countries showed seasonal patterns, the study was unable to find a strong effect of temperature variability on *Campylobacter* transmission. Unlike *Salmonella*, a simple direct relationship between temperature and *Campylobacter* infections is therefore not likely. However, what cannot be excluded is the possibility of more complex effects of weather and climate via their influence on factors such as the size of animal reservoirs of infection (Skelly and Weinstein, 2003) or the ease of transmission to humans, for example by vectors such as flies (Nicholls, 2005).

4.3 Future impacts of climate change

One study (Bentham, 1997) had used regression analysis to develop statistical models of the relationship between the monthly incidence of food poisoning and temperatures in England and Wales for the period 1975–95. 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 ~4,000, ~9,000 and ~14,000. It was emphasised that because of the under-recording of food poisoning the real number of additional cases might be considerably higher. It was concluded 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, it was emphasised that the estimated changes were small relative to the large increases that had occurred over the previous 20 years as a result of other factors.

The 2001/2002 report concluded that a 1°C increase in temperature might result (*ceteris paribus*) in about a 4.5% increase in food poisoning. Subsequent published studies have strengthened the evidence that environmental temperatures affect the risk of food poisoning by *Salmonella*, with Kovats *et al.* (2004) yielding an estimated effect of +12.5% per 1°C increase in temperature. This could be taken to indicate that the earlier estimate is too low. However, the impacts on total incidence of food poisoning resulting from all pathogens will clearly depend also on the temperature sensitivity of disease caused by other pathogens, especially *Campylobacter*. Unfortunately, in spite of the new data that have become available, the published evidence remains insufficient to estimate reliably the potential effect of changes in temperature on campylobacteriosis. Another important factor is that in recent years both the absolute and the relative contributions of *Salmonella* infections to the total burden of food poisoning have declined. The fraction of food poisoning cases for which there is clear evidence of a direct relationship with temperature is therefore likely to have fallen. On balance, there appear to be no strong grounds for changing the estimate of the earlier review that a 1°C increase in temperature might result in about a 4.5% increase in food poisoning. The absolute numbers of additional cases will depend on the scenarios for temperature and the baseline number of cases of food poisoning.

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5 Water and disease and climate change

(See also section 4.4 of 2001/2002 report)

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Summary

- Climate change is likely to impact on raw water quality, which in turn could affect treatment efficiency and the stability of drinking water in distribution.
- More frequent extreme rainfall events could lead to increased surface water turbidity and higher numbers of indicator bacteria and pathogens in surface water. This would create a greater challenge for water treatment works, particularly where direct river abstraction is used.
- Changes in the distribution of rainfall may cause local increases in drought. In such areas, there may be an increased likelihood of contaminated surface water reaching groundwater through the opening of short circuits as a result of a lowered water table.
- Increased temperature and nutrient concentrations in surface water could lead to cyanobacterial blooms occurring more often.
- The greatest impact of increased temperature would appear to be on the efficiency of chemical coagulation, which may lead to decreased removal of microbes by subsequent clarification and filtration. The result could be an increased challenge on final disinfection.
- These potential impacts of climate change are unlikely to pose a threat to well-managed water treatment plants, but could cause problems for private water supplies, surface water supplies without filtration and groundwater supplies under the influence of surface water, unless they are adequately filtered.
- Changes in surface water and groundwater availability must be carefully managed to avoid an acute crisis in provision at the household level.

Recommendations

- Improved risk management of water resources in the UK to avoid acute crises in supply.
- Risk assessment by water companies of extreme weather events, particularly intense rainfall.
- Maintenance of monitoring of algal blooms in surface water.
- Improved control of filter operation to minimise breakthrough of filters.
- Increased monitoring of filter performance by means of turbidimeters.

5.1 Introduction

The potential impact of climate change on waterborne infectious diseases has not been particularly well addressed in climate change assessments, in contrast to the treatment of vector-borne diseases. The conclusions of the 2001/2002 report were limited by a lack of research into the effect of weather and climate on waterborne diseases in the UK. Since then, the water industry and the Environment Agency have taken steps to assess potential risks associated with climate change (Nichols *et al.*, 2003; Wilby *et al.*, 2005).

5.2 The effects of heavy rainfall on outbreaks of waterborne diseases

Microbiological contamination of public supplies is an important concern in Europe. However, few studies have investigated an association between rainfall and human disease. Due to the complexity of the causal pathways on the route from surface or groundwater to the household, it is difficult to detect what may be a small contribution to the overall burden of disease.

Several studies have investigated an association between drinking water turbidity and health. Although the methodologies have been criticised, there is some indication that reducing the maximum turbidity of filtered water may reduce the risk of *Cryptosporidium* contamination. Rainfall appears to increase concentrations of *Giardia* and *Cryptosporidium* in surface water through its effect on the amount of solid matter in the water. There may be a link between when *Cryptosporidium* and *Giardia* concentrations peak and when, for instance, turbidity reaches its highest level. Open finished water reservoirs are at risk of post-treatment faecal contamination by animals, including those that shed species of *Giardia* and *Cryptosporidium* that are potentially pathogenic to humans. A study carried out in the US found a statistically significant association between extreme rainfall events and monthly reports of outbreaks (Curriero *et al.*, 2001).

Heavy rainfall can cause abnormal changes in the direction of flow of water through both surface and underground channels. For example, in one outbreak of cryptosporidiosis associated with a borehole extracted groundwater, it was thought that the heavy rainfall led to water running across the surface of a field where cattle were grazing (Bridgman *et al.*, 1995). The water (and cattle faeces) then pooled around the head of the borehole and leaked into the water supply.

In impermeable catchments, microbial contaminants on the land will be carried into rivers more rapidly than those present on permeable catchments, particularly following periods of dry weather during which the surface has become 'baked'. One of the predicted consequences of climate change will be more severe rainfall events. In these situations, microbial contaminants present in biosolids or manures applied to agricultural land may be transferred to surface water sources more rapidly than under conditions of more 'normal' rainfall. The contamination of surface water sources used for drinking water production by storm drain overflow may be brief, with a bolus of infected water being followed by substantial dilution as a result of the excess water flow. Well-run water utilities should be able to plan for these events and have a system that keeps the risks of contamination low, irrespective of the weather.

Cryptosporidiosis is the most significant waterborne disease associated with the public water supply in the UK. The spring peak in cases of cryptosporidiosis is likely to be associated with spring rainfall and high levels of contaminated manure on the land, especially from lambs (Lake *et al.*, 2005). These relationships show that rainfall may have played an important role in sporadic cases of the disease in the springtime. The response by the water industry to the UK Cryptosporidium Regulations has led to a reduction in cryptosporidiosis and to fewer outbreaks of this disease (Sopwith *et al.*, 2005). Although outbreaks of drinking water-related disease do still occur, within the last few years they have nearly all been due to *Cryptosporidium* and are associated with supplies that are inadequately treated. It is likely that the Water Safety Plan approach being sponsored by the World Health Organization will lead to further improvements to water quality. There are still many private supplies in use in the UK and these are frequently poorly treated. The microbiological quality of such supplies is generally very poor and can deteriorate markedly after heavy rainfall (Rutter *et al.*, 2000). A greater number of extreme weather events could worsen this situation although probably not substantially.

5.3 The effects of drought on water quality and water availability

A real concern is the effect of decreases in water availability. Changes in surface water and groundwater availability, particularly in the South of England, will need to be carefully managed to avoid any threats to domestic water supplies. Water shortages can, if they are severe, have dramatic effects on populations. The shortages in the supply of drinking water through Yorkshire Water in 1995 highlighted the limitations of planning using historical records in an era of changing climate.

Warmer, wetter winters and drier summers will influence river flows. These are one of the main indicators used to monitor the impacts and progress of climate change. Variable river flows are obviously important since over 60% of the UK's water supplies are abstracted from rivers. A recent project funded by the Environment Agency assessed the impact of climate change on the effective monitoring of chemical standards for health protection (Crane *et al.*, 2005). In the near term, climate change is unlikely to directly cause any exceedances of health and environmental standards. However, unless more samples are taken, changes in climate that lead to an increase in the variability of river flows could lead to an increased likelihood of failure to detect non-compliance with the standards.

Flows in rivers draining impermeable catchment areas decline rapidly when there is little rain, and effluent discharges become an increasingly high proportion of the river flow. In contrast, where natural groundwater inflows sustain river flows, the effect of low rainfall will not be so immediate. However, once groundwater levels become low, the river flow will be depressed and may remain in this state long after rainfall has occurred. If summers become warmer and drier, effluent discharges could remain an important component of the river flow for protracted periods.

In addition to threatening water supplies, low flows reduce effluent dilution. A greater effluent loading in the river will also be reflected in an increased pathogen loading. This could represent an increased challenge to water treatment plants. However, under low flow conditions, transit times between discharge and abstraction will be increased, providing more time for pathogen decay to occur. In addition, if climate change brings warmer and drier summers, river temperatures will be higher, with greater rates of natural purification through biological predation and possibly increased levels of sunlight. An assessment of the dry summer of 2003, when river flows were reduced, found apparent changes in water quality (Senhorst and Zwolsman, 2005). There are also risks of surface water reaching groundwater through routes that are not usually open during periods when the water table is low as a result of a drought.

The most significant consequence of drought would be a failure of the domestic water supply, resulting in a need for standpipes and other methods of water delivery. The potential health effects of this would include infectious intestinal diseases, due to contamination of water and reduced hygiene, but such measures may also lead to civil unrest. Access to sufficient water for the elderly, disabled and less mobile would be a concern. Localised water shortages may be particularly important in South-East England due to population growth and climate change (HPA, 2006).

5.4 Recreational waters and algal blooms

Recreational waters (either inland surface waters or coastal waters) are also an important source of waterborne diseases in bathers (Zmirou *et al.*, 2003). Transmission of waterborne diseases from faecal contamination, as well as from naturally occurring pathogens, may also be affected by warmer temperatures as well as changes in rainfall and run-off (Hunter, 2003; Schijven and de Roda Husman, 2005).

Algal blooms may become more common with increasing temperatures. Several species have been implicated in causing disease in humans. However, there is little direct evidence that *Aeromonas hydrophila* (or other organisms that bloom in distribution) currently cause any significant burden of ill health. There has not been further work on this since the 2001/2002 report. Some risk assessment is needed, both for direct contact and economic implications (since water bodies must be closed), as well as for contaminants in the public water supply (microcystins) (Codd *et al.*, 2005). Blooms of *Aeromonas hydrophila* and coliforms can result from raised organic carbon present in the water in distribution, higher temperatures and reduced chlorine.

There is also evidence that heavy rainfall events can precipitate coliform re-growth in water distribution systems by increasing the nutrient content of water (LeChevallier *et al.*, 1991). Non-faecal coliforms in drinking water do not appear to be associated with disease in the community (Edberg *et al.*, 1986; Zmirou *et al.*, 1987; Hellard *et al.*, 2001). It remains possible that other organisms might take advantage of these changed conditions. Public utilities in charge of recreational waters should therefore be vigilant in checking the organic carbon content of water and should ensure adequate disinfectant levels to prevent these problems.

Cholera is not generally a problem within developed countries. There is a chance that a substantial alteration in world climate could contribute to the triggering of an eighth pandemic of cholera, particularly if there is an increase in sea level. While this might give rise to an increase in the incidence of cholera in people travelling overseas, it is unlikely that indigenous disease would increase with current UK infrastructure. Substantial coastal inundation due to sea level rise might increase population movement and could have a significant impact on immigration and the diseases associated with this.

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6 Direct effects of rising temperatures on mortality in the UK

(See also section 4.1 of 2001/2002 report)

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Summary

- Mean annual heat-related mortality did not rise as summers warmed from 1971 to 2003, implying an increase in population tolerance to heat, while annual cold-related mortality fell by more than 33%.
- Daily mortality in the South of England increases at temperatures above about 27°C, and the effect of several consecutive days combined is much greater than the effect of the same number of separate hot days.
- Improved tolerance to heat in the future will reduce the impact of hotter summers, but increased frequency and intensity of heatwaves are a major concern.
- Extrapolation of current data showed the risk of a 9-day heatwave (averaging 27°C in South-East England, with over 3,000 immediate heat-related deaths and 6,350 heat-related deaths throughout that summer in Britain), as 1 in 40 each year by 2012, or 25% at some time during the 10 years centred on that year.

Recommendations

- Promotion of measures to avoid heat stress and dehydration, on the lines of the current Heatwave Plan, are recommended to reduce heatwave mortality over the next decade.
- In the longer term, improved building design could minimise the need for increased energy use, and the consequent acceleration of climate warming by air conditioning.
- Regular assessments of heatwave impacts will be important as climate warming proceeds.

6.1 Introduction

Heat-related mortalities are substantial throughout Europe, but the hot summers in Southern Europe cause little more mortality than the milder summers of more northerly regions (Keatinge *et al.*, 2000). People in Southern Europe achieve this largely by simple traditional measures, such as use of shade, fans, and avoidance of exercise at hot times of day, rather than by air conditioning as in the United States (Greenberg *et al.*, 1983; Rogot *et al.*, 1992; Taylor and McGwin, 2000; Basu and Samet, 2002; Donaldson *et al.*, 2003; Davis *et al.*, 2003). The time needed for people to adopt effective responses to hotter weather is not known.

There are particular grounds for concern about mortality from occasional heatwaves of unprecedented severity (see Chapter 1). In 2003, an exceptional heatwave in central France caused mean daily temperatures of around 28°C for 10 days with 14,000 deaths (Pirard *et al.*, 2005). Further south, where people were more accustomed to high temperatures, the heatwave caused less mortality. Estimates of the probability of a heatwave approaching that level in Britain, and of its likely effect on mortality, are particularly important.

This chapter estimates heatwave-related mortality using data from 1971 and from extrapolation of this until 2015:

- The level of temperature and frequency of heatwaves, and of heat-related mortality in the absence of intervention.
- The changes in vulnerable population aged 65+, and the response of this population to heat and cold.

Assessments were made separately for South-East England, the rest of England and Wales, and Scotland; data for Northern Ireland were not available. An indication of longer-term problems was based on current predictions of greenhouse gas emissions and climate warming over the next century is described in Chapter 1.

6.2 Observed changes in heat- and cold-related mortality (1971–2003)

Methods and data

The Office for National Statistics (ONS) and the Scottish Office provided populations and daily deaths 1971–2003 (1974–2003 in Scotland). Populations aged 65+ for years 1971, 1976 and 2003 respectively in South-East England (Greater London, Hertfordshire, Essex, Kent, East and West Sussex, Hampshire, Surrey, Berkshire, Oxfordshire, Buckinghamshire and Bedfordshire) were 2.334, 2.467 and 2.693 million; in the rest of England and Wales 4.216, 4.591 and 5.589 million; and in Scotland 0.685 (for 1974), 0.697 (for 1976) and 0.809 (for 2003) million. Mortalities were obtained after dividing daily deaths by estimates of daily population obtained by fitting a third order polynomial to the yearly population, estimated by ONS from census data. Recent mortality data were not available for Northern Ireland in time.

Daily temperatures for Edinburgh (Royal Botanical Gardens), for South-East England (Heathrow) and for the rest of England and Wales ('Central England temperature' – mean of Squires Gate, Lancashire; Manchester Airport; Malvern, Worcestershire; Rothampsted, Hertfordshire) were provided by the Meteorological Office. All temperatures used were 24-hour mean values.

Heat-related mortality starts in the UK when mean daily temperature exceeds about 18°C (Donaldson *et al.*, 2003). Excess mortalities due to heat and cold each year per 10^6 people aged 65+ were estimated respectively as the increase in mortality above and below the 3°C band of temperature at which mortality was lowest in that region that year. No adjustment was made for air pollution (Keatinge and Donaldson, 2006) or for influenza. Cold-related mortality is much larger than heat-related mortality, both in the UK and in the rest of Europe (Keatinge *et al.*, 2000; Eurowinter Group, 1997; Healy, 2003). The band of minimum mortality was obtained from mortalities in 3°C bands calculated at successive 0.1°C increments. Summer temperatures were means for June–August, winter temperatures means for December–February, and temperature of onset of heat-related mortality was the upper end of the 3°C band of minimum mortality. Changes over time (1971 to 2003) were calculated by linear regression with confidence limits.

As described in Chapter 1, the UK has experienced some warming in the last three decades. Figure 6.1 shows that mean summer temperature in South-East England rose significantly ($p<0.05$) from 16.6 to 18°C between 1971 and 2003. It rose non-significantly in the rest of England and Wales from 15.2 to 16.2°C and marginally in Scotland from 14.3°C in 1974 to 14.7°C in 2003.

Despite the increasing temperature, the trend in annual heat-related mortality per million aged 65+ fell significantly in Scotland and non-significantly in other regions:

- South-East England from 258 in 1971 to 193 in 2003
- rest of England and Wales from 188 to 93
- Scotland from 125 (in 1974) to only 8 in 2003 ($p<0.05$).

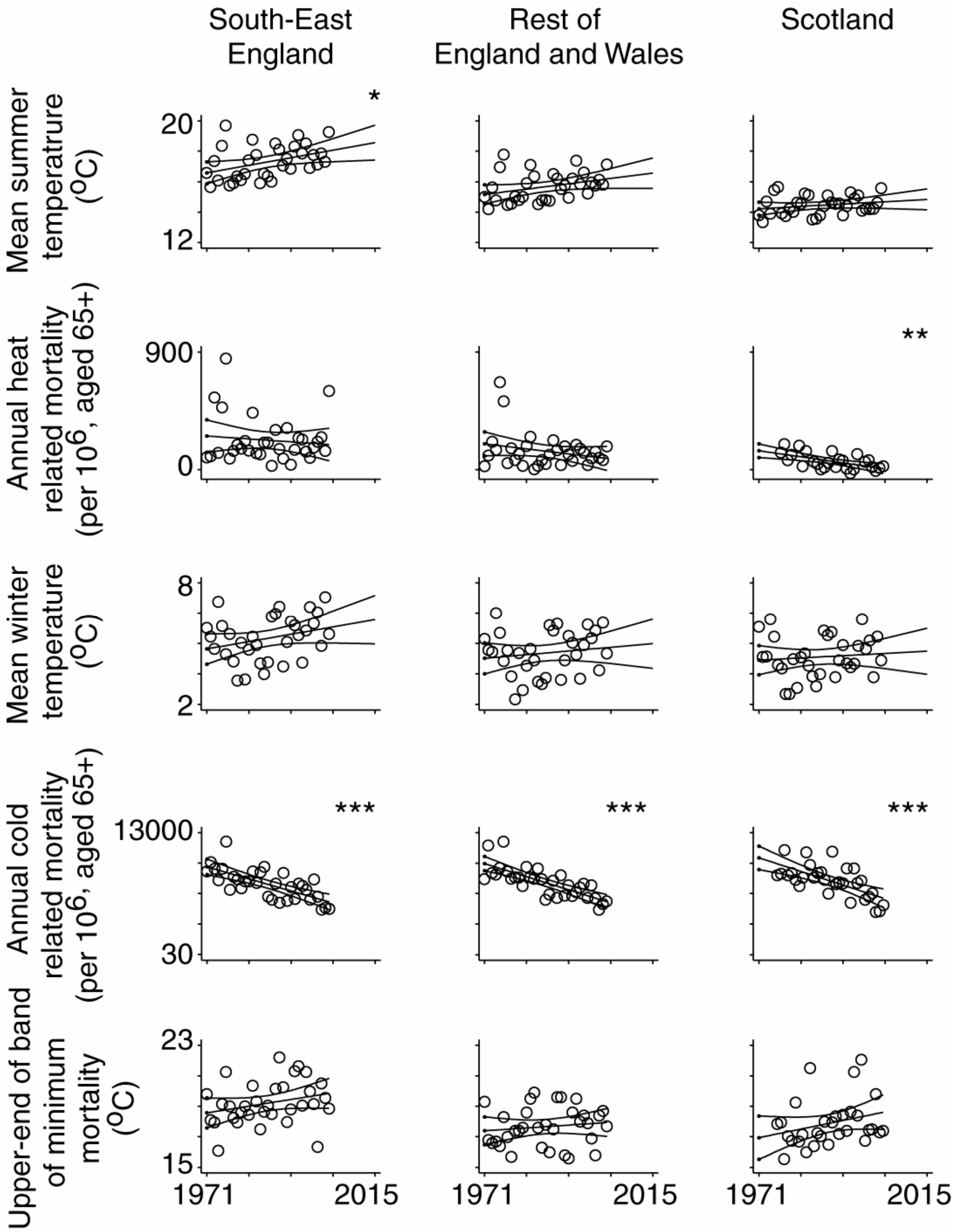
Winter temperatures tended to rise and the trend in cold-related mortality per million aged 65+ fell in all regions ($p<0.001$):

- South-East England from 9,174 to 5,903
- rest of England and Wales from 9,222 to 6,088
- Scotland from 9,751 in 1974 to 6,166 in 2003.

The bottom row of graphs in Figure 6.1 shows that the temperature of the upper limit of the band of minimum mortality, above which mortality starts to rise with temperature, tended to increase in all regions. This, as well as the decline in heat-related mortality despite warmer summers, provides evidence of improving tolerance of the population to hot weather, especially in Scotland. The figure also shows that mean summer temperatures in South-East England in 1976 and 2003 were higher than those of neighbouring years, and produced higher heat-related mortalities than these neighbouring years.

Heat-related deaths in 1976 (actual, not trend and not as mortality per 10^6) totalled 4,651 in all regions of Britain; 2,101 were in South-East England, 2,392 in the rest of England and Wales, and 158 in Scotland. Linear regression of annual heat-related deaths in South-East England showed that these tended to fall (by 69 to 548), although summer temperature rose between 1971 and 2003 and the vulnerable population aged ≥65 increased (from 2.334 to 2.693 million).

Figure 6.1 Mean summer and winter temperatures, heat- and cold-related mortalities, and upper limit of 3°C band of minimum mortality each year. Means and 95% confidence limits of the mean



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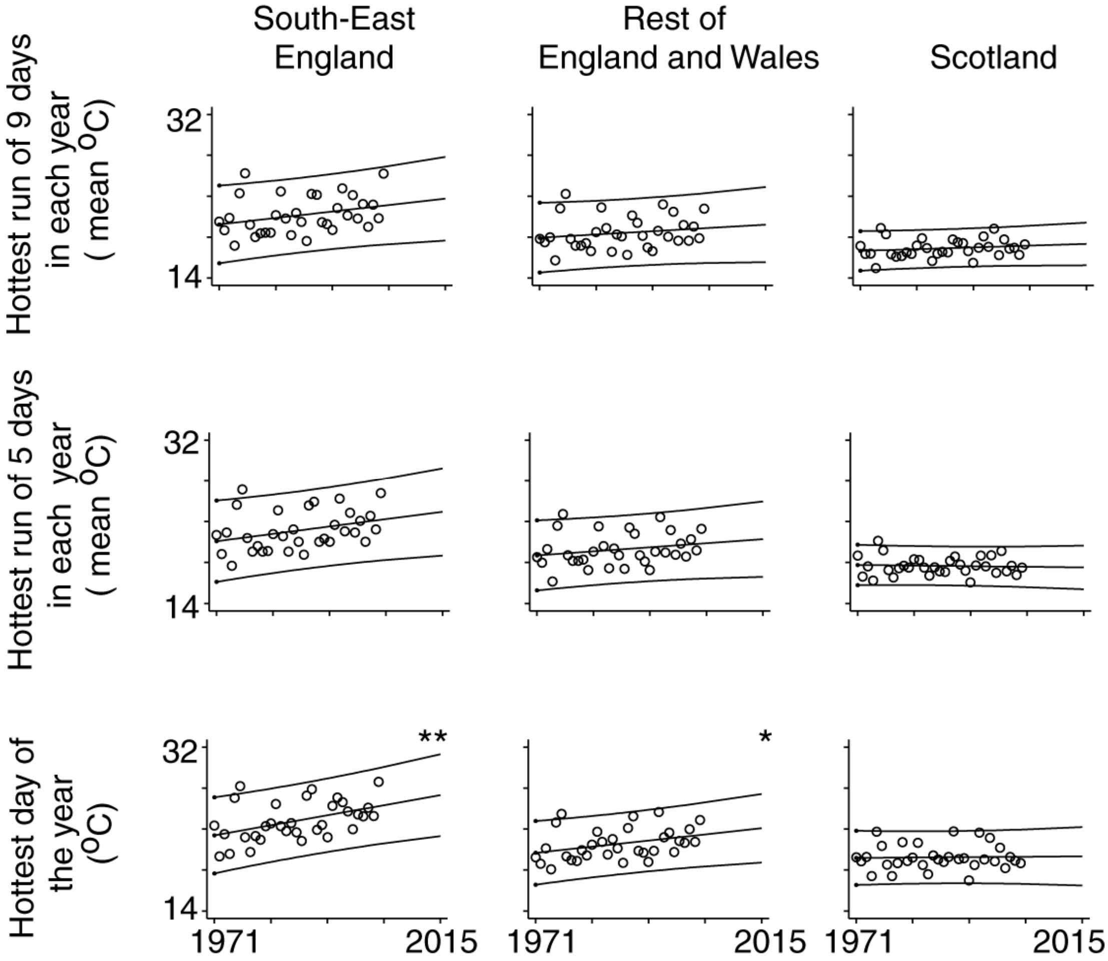
Key
Significance of slope:
* = p<0.05
** = p<0.01
*** = p<0.001

Figure 6.2 Hottest day and hottest runs of 5 and 9 days each year. Means and 95% confidence limits for individual years



Key
Significance of slope:
* = p<0.05
** = p<0.01

6.3 Observed and future changes in heatwaves and in heatwave mortality

Figure 6.2 shows that the temperature of the hottest day each year, and of the hottest 5 and 9 consecutive days each year in South-East England and in the rest of England and Wales, all tended to increase at approximately double the rate of increase of mean summer temperature, as variability in the daily temperatures increased (see also Schar *et al.*, 2004). Changes in Scotland were too small to assess.

Figure 6.3 shows daily data for the 1976 and 2003 heatwaves. Mortality in the population aged ≥55 rose sharply when mean daily Central England temperature exceeded 25°C for a few days, as it did in South-East England in 1976 with one day at 25.7°C followed by three at 27.45–27.7°C (mean 27.1°C over the successive 4 days above 25°C). During this time daily mortality continued to rise, with approximately equal increments, and fell on the day the temperature fell. The heatwave of 2003 was both briefer and less intensive, producing a clear rise in mortality mostly in South-East England.

Figure 6.4 shows that deaths per day (not adjusted for the progressive rise in population aged 65+) rose sharply in the South-East when daily mean temperature (on the same day) (Heathrow) exceeded 25°C. Even with the increase in the population aged ≥65, heat-related deaths were a little lower in the years after than before 1986, particularly at the higher temperatures.

The 95% confidence limits in Figure 6.2 show the probability of a 9-day heatwave averaging 27°C in South-East England as 1 in 40 each year by year 2012, or of 1 in 4 (25%) at some time during the 10 years from mid-2007. The potential mortality from such a heatwave can be estimated as follows.

There were 854 heat-related deaths in South-East England during the 4-day heatwave in 1976, estimated as excess deaths above the 328 mean daily deaths in the 3°C band of minimum mortality that year. During those 4 days (when daily temperature averaged just over 27°C), daily deaths increased each day by a mean of 80.2 from a baseline of 341 mean daily deaths on the previous 14 days. If deaths had continued to increase at that rate, 9 days averaging 27°C in South-East England would have caused 3,726 heat-related deaths there, that is, 2,382 more than actual heat-related deaths in the 9-day heatwave starting 25 June 1976.

For 2012, this estimate of heat-related deaths during a 9-day heatwave in South-East England can be reduced a little, since Figure 6.4 shows that daily deaths at such temperatures were tending to decline, by around 2.1 each year, as tolerance to heat improved. This reduces the estimate to 3,046, or 1,702 more heat-related deaths than on the 9 days starting 25 June 1976. Taking heat-related deaths outside those days in the South-East, and all year in the rest of Britain, as unchanged from 1976, with increasing tolerance to heat offsetting rising temperatures outside the 9-day heatwave in the South-East, total heat-related deaths in Britain throughout 2012 would be 6,353.

Figure 6.3 Temperature and mortality each day in two major heatwaves in South-East England

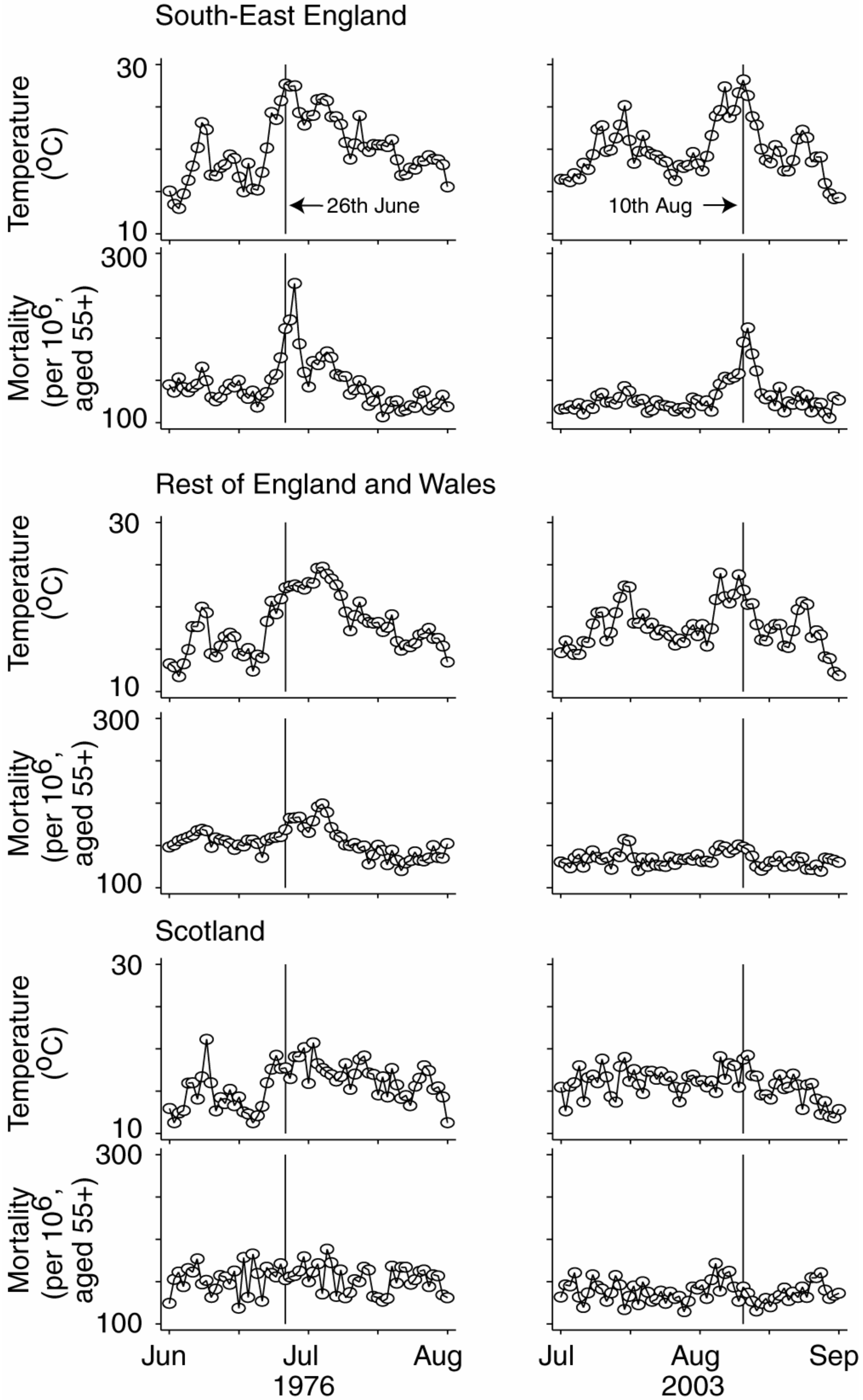


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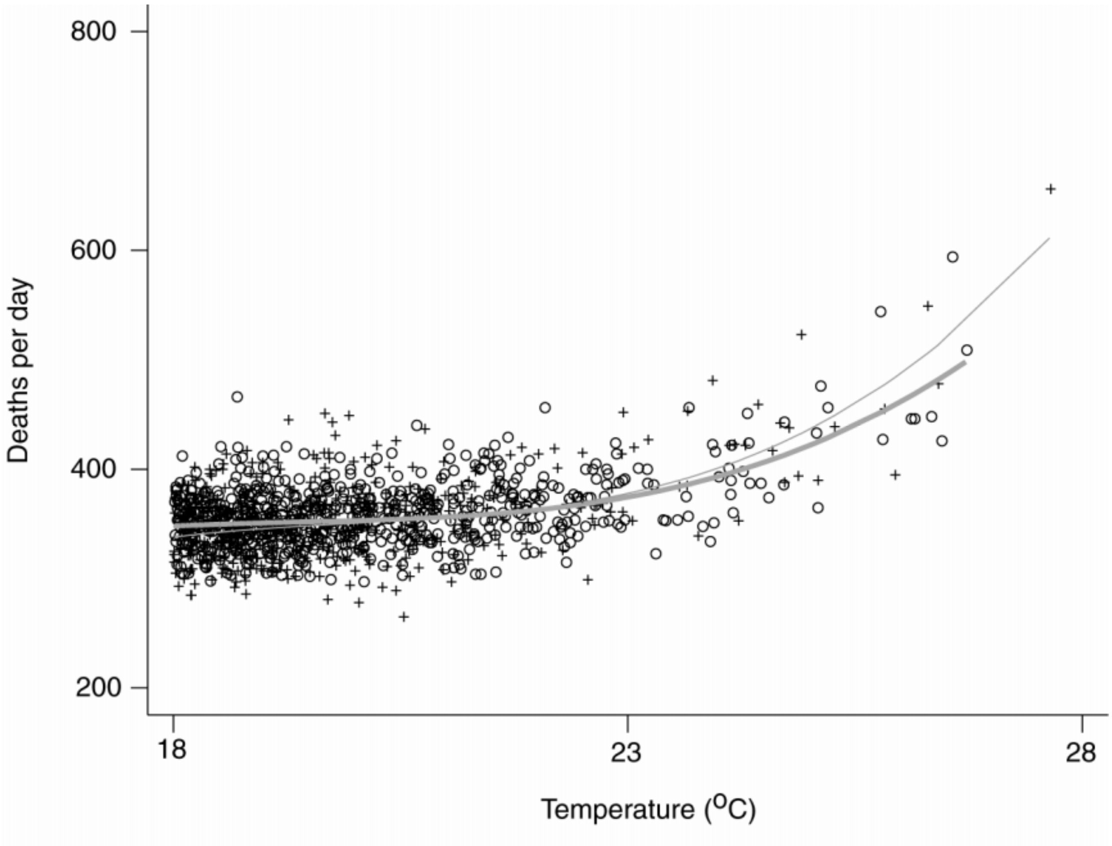
Figure 6.4 Crude relationship between daily deaths and mean daily temperature in South-East England. Temperatures are means of values on days 0, -1, -2 relative to mortality

Key

\+ —— 1971–86   o ━━ 1987–2003



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6.4 Discussion

Increasing tolerance to heat has so far prevented rising temperature from increasing mean heat-related mortality, even in South-East England where summer temperatures have risen 1.4°C since 1971. Together with falls by more than a third in cold-related mortality in all regions as winters grew warmer, the overall trend in combined heat- and cold-related mortality during climatic warming from 1971 to 2002 was beneficial.

The increasing tolerance to heat probably resulted as much from lifestyle changes, such as greater readiness to wear informal clothing and less need for physical exertion, as from physiological adaptation to heat stress, which is relatively short term. However, we estimate that the increasingly variable as well as higher summer temperatures will create, by 2012, a 1 in 40 risk every year (a 1 in 4 risk in the decade centred on 2012) of a 9-day heatwave at 27°C in South-East England. Without preventive action, this could cause more than 3,000 immediate deaths with more than 6,350 heat-related deaths throughout that summer.

6.5 Actions to reduce heatwave mortality as summers become hotter

The most obvious need at this level of risk is for elderly and ill people and their carers to be aware that these people are particularly vulnerable to heat stress (Flynn *et al.*, 2005), and to adopt protective measures that are common in Southern Europe in hot weather. The Heatwave Plan for England already incorporates several of the following points. We recommend that, at the start of summer, the first forecast of mean daily temperature approaching 17°C in any region should trigger initial printed and broadcast warnings, and that the broadcast warnings be repeated with any forecast of mean daily temperature above 25°C.

Important components of advice are to have an electric fan available and check that windows can be opened. Shading of windows from direct sunshine, for example by outside shutters, will prevent greenhouse heating. If shading is impractical, the use of thick curtains can reduce heating of the indoor environment. Windows should be opened in the early morning, and shut if the outdoor temperature rises above indoor temperature. If the indoor temperature rises enough to cause heat discomfort, a fan will need to be started. Water can be sprinkled on the face, arms and clothing if necessary to reinforce evaporative cooling by sweat, particularly in people taking medical drugs that suppress sweating. If indoor humidity rises enough to prevent evaporation and cause heat discomfort, windows will need to be opened again to provide air unsaturated with water vapour. In emergencies, a cool bath or shower will provide rapid cooling. It is important for people to continue to eat meals, preferably of carbohydrate and with at least normal amounts of salt, and to drink plenty of water to maintain osmotic balance. Loss of salt and water in sweat can otherwise cause dehydration with haemoconcentration and increased risk of coronary and cerebral thrombosis (Keatinge *et al.*, 1986), as well as accelerating body heating by impairing vasodilatation and sweating.

It is essential that the warnings stress the importance of immediate cooling at home, rather than waiting for admission to hospital. Overall hospital admissions in England rose by only 1% in the 2003 heatwave, but among people in London aged >75 they rose 16% (Johnson *et al.*, 2005). Many of the deaths in the more severe 2003 French heatwave occurred in hospitals (Pirard *et al.*, 2005).

Unlike air conditioning, these measures do not involve high energy consumption. Air conditioning does, and so can accelerate global warming. It can be kept to a minimum by effective use of these simple measures, although it will sometimes be needed where these cannot be implemented adequately, as in hospitals or old people's homes when only small numbers of carers are available to attend to large numbers of incapacitated people.

Scenarios of climate change beyond 2012 take into account some of the uncertainty about future levels of greenhouse gas emissions (Chapter 1), and suggest increases in the frequency of heatwaves over the next 100 years in the South-East of the UK, and less in other regions. Such temperatures have led to extensive installation of air conditioning in the United States. Despite the adverse effect of air conditioning on carbon dioxide emissions, policy on its use in Britain, together with the use of other protective measures against heat stress, needs to be reviewed regularly as further temperature and mortality data become available.

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7 The health impact of climate change due to changes in air pollution

(See also section 4.7 of 2001/2002 report)

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Summary

- Future ambient concentrations of air pollutants which are hazardous to health will depend both on trends in emissions of primary and precursor pollutants and on trends in meteorological factors which affect dispersal of pollutants and secondary chemical atmospheric processes.
- The weather conditions associated with winter episodes will become less common, while over the same time there will be a decrease in the ambient concentrations of particulate matter (PM_{10}), sulphur dioxide (SO_2) and nitrogen dioxide (NO_2) should an episode occur. Ozone (O_3) concentrations are already low in winter episodes and will remain so in any future episodes. Thus the health impact of winter episodes, which is already low, will become even less.
- Weather conditions associated with summer episodes will increase in frequency and intensity. However, because the European emissions of ozone precursors such as volatile organic compounds (VOCs) and oxides of nitrogen (NOx) are predicted to fall, episodic peak ozone concentrations should continue to fall over the period to 2030. The frequency and intensity of summer NO_2 episodes is unlikely to change. PM_{10} usually increases during summer episodes, but the intensity of this is likely to fall in the future because of falling emissions. SO_2 episodes, already rare, will not increase.
- Longer-term mean concentrations of particles, NO_2 and SO_2 are unlikely to increase in the future. However, annual mean and annual mean daily maximum 8-hour ozone concentrations are likely to increase in both the short term until 2030 and over the long term until 2100 as part of a more general increase in ozone occurring in the hemisphere as a result of both increases in precursor emissions and climate change.
- Without the assumption of a threshold, the increase in estimated annual ozone concentrations between 2003 and 2020 will result in a 15% increase in attributable deaths and hospital admissions for respiratory diseases. When threshold assumptions of 35ppb and 50ppb (8-hour average) are assumed, the respective increases are 51% and 53%. Estimates holding climate at 2003 levels show increases of 8%, 14% and -5% for the no threshold, and 35ppb and 50ppb thresholds respectively. Thus, in the no threshold model, about half of the increase in health impact is due to changes in UK and European emissions rather than climate change. In the threshold models, however, most of the increase is attributable to climate change.

Recommendations

- Maintain and strengthen measures that reduce outdoor air pollution.

7.1 Introduction

Urban air quality in the UK has been extensively reviewed in recent years, together with its public health consequences. Understanding has also grown concerning the important linkages between urban air quality and global climate change. There is growing concern that some of the steps taken to tackle urban air quality may either exacerbate or ameliorate climate change. Equally well, climate change and the global-scale population and economic growth that drives it may make urban air quality goals more difficult to achieve in the medium term (Air Quality Expert Group, 2006).

Here we look at the period up to 2030 and beyond and consider how the emissions of the classic air pollutants may change in the UK. We use a global climate model to understand how climate change may influence the frequency and intensity of the meteorological conditions associated with pollution episodes. By combining these two elements, we can estimate future levels of ambient air pollutant concentrations. Public health impacts have been assessed using risk coefficients based on recent epidemiological evidence. The air pollutants of particular interest are PM_{10}, SO_2, NO_2, and O_3.

In the previous report on climate change and public health in the UK, we presented estimates of the human health impacts of air pollution through to the year 2100 (Anderson *et al.*, 2001). In the intervening period, several aspects of our methodology and approach have been subject to review and updating. Furthermore, the policy focus has shifted more towards the period up to the year 2030. A reassessment of the human health impacts of air pollution and climate change in the UK is therefore timely.

7.2 Meteorological factors, emissions and future urban air pollution episodes

7.2.1 Meteorological factors

As explained in our previous report, 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 (IPCC, 1996). 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.

We have looked at the simultaneous occurrence of low wind speed with freezing conditions that is associated with episodes of poor urban air quality. There are isolated days with low wind speeds and below-freezing temperatures during the decades up to the 2030s, but their frequency is reduced from the 2050s onwards. The number of days with temperatures just below zero and low wind speeds also declines dramatically through to the year 2100. The conditions of low wind speeds and below-freezing temperatures that have occurred with a frequency of about once per decade during the second half of the 20th century appear much less frequently as winters gradually become warmer and windier. On this basis, we concluded that wintertime pollution episodes were likely to become less frequent and less intense in the future.

From time to time during warm, sunny anticyclonic conditions, 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. To address the occurrence of the meteorological conditions which drive these summertime air pollution episodes, we have again examined the daily meteorological parameters produced by the HadCM3. It is the simultaneous occurrence of daily maximum temperatures above 25°C and low wind speed conditions which favour the occurrence of summertime air pollution episodes and so the joint distribution of elevated temperatures and low wind speed conditions has been investigated.

There are an increasing number of days with low wind speeds and daily temperatures above the 25°C threshold for elevated ozone levels for each of the decades through to the year 2100. They might triple in frequency by the 2030s and increase by an order of magnitude by the 2080s. An increasing number of these low wind speed days have maximum temperatures above 35°C by the 2050s and above 40°C by the 2070s. Conditions of low wind speeds and elevated daily temperatures appear to occur with increasing frequency throughout the period up to 2030 and beyond, driving up the frequency of conditions associated with summertime air pollution episodes. On this basis, we asserted that ozone episodes had the potential to become more frequent and more intense in the future.

Since the previous study, high-resolution data have become available from a regional climate model HadRM3P and this has been used as a basis for the UKCIP02 climate scenarios (UKCIP02, 2002). These data are available at a spatial resolution of 50km x 50km and this represents a significant improvement on the single grid point data provided by the global model HadCM3. However, we have not updated our assessments of the frequency and intensity of wintertime and summertime air pollution episodes from those based on the global model to those based on the regional model. This is because of the poor performance of the HadRM3P model during the control period from 1960 to 1991 for the parameters required in the evaluation of urban air quality. Due to the excessive drying out of soil surfaces, almost one in every two summers in South-East England were found to have maximum temperatures in excess of 35°C with a maximum temperature of over 41°C (Moberg and Jones, 2004). Such behaviour would not provide a satisfactory base case for a regional air quality model.

7.2.2 Future urban air pollution episodes

Emissions of primary pollutants in urban areas from road traffic are expected to decline steadily from current levels over the period to 2030 and beyond due to the continuing tightening of both fuel and vehicle emission legislation. Figures 7.1–7.3 show the anticipated falls in traffic emissions of PM_{10}, NOx and VOCs, respectively, from their peak levels in the 1990s by 2025. If this were the only factor operating, then urban PM_{10} air quality would steadily improve through to 2025. Taken together with the tendency for winters to become warmer and windier, then both the frequency and intensity of wintertime PM_{10} pollution episodes should decrease during the period up to 2025.

Wintertime episodes of elevated SO_2 and black smoke concentrations have in the past been confined to the areas where coal has been the most important domestic fuel. But because this use of coal has declined markedly in British cities, such episodes are of historic importance only. Summertime episodes of SO_2 are generally associated with plumes from individual major industrial plants and have not been considered in any detail here. However, the current trend towards tighter regulation, cleaner fuels and the implementation of cleaner technologies in industries such as power generation should lead to a reduction in the frequency of summertime episodes of SO_2 by 2025.

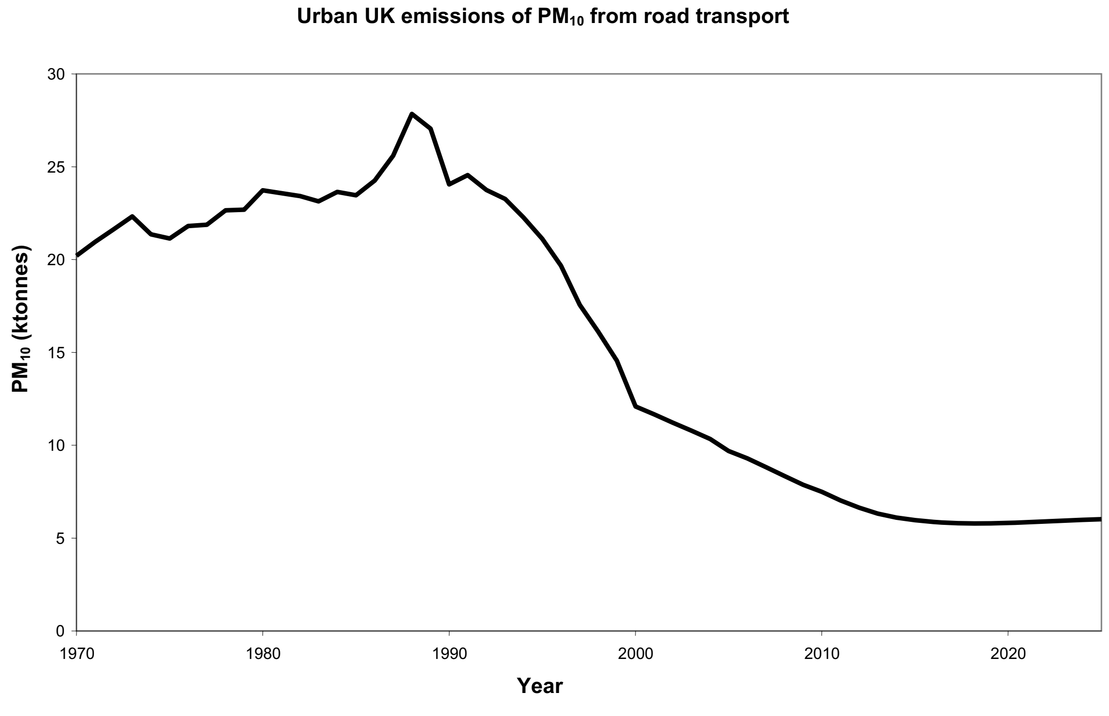
Wintertime episodes of NO_2 depend for their occurrence upon the chemical reaction:

$$NO + NO + O_2 = NO_2 + NO_2$$

Because this mechanism depends on the square of the nitric oxide (NO) concentration, wintertime episodes are expected to become increasingly rare as NOx emissions decline steadily (see Figure 7.2) from their peak in the early 1990s and as the frequency of wintertime stagnant conditions declines with climate change.

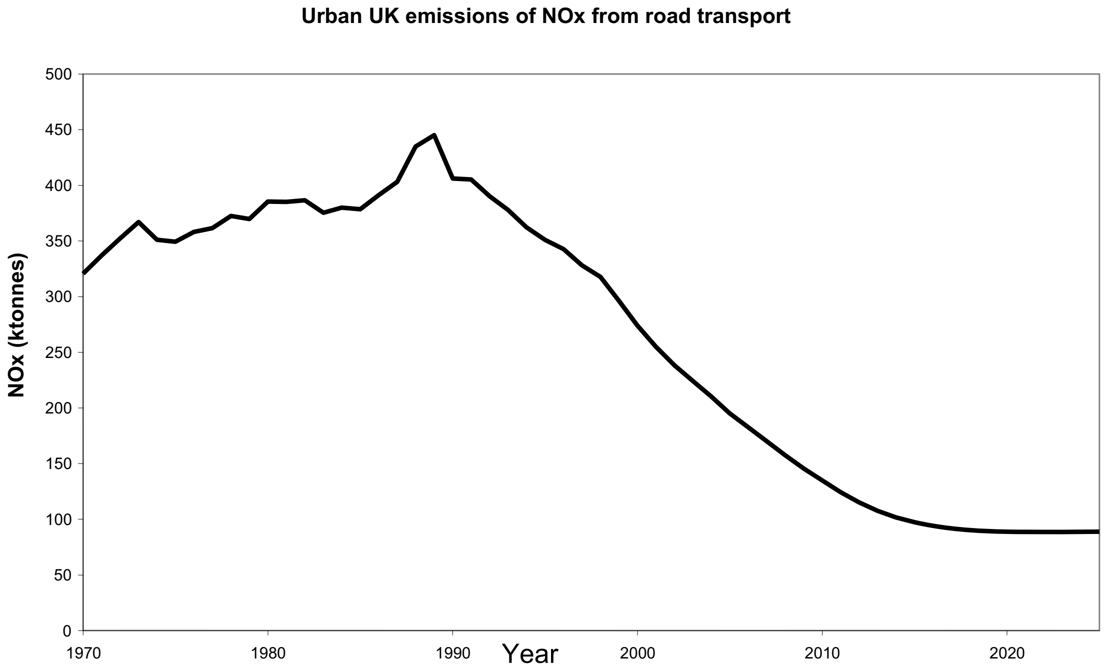
Episodes of elevated NO_2 concentrations occur also in the summertime when photochemical episodes occur simultaneously with episodes of poor dispersion of NOx emissions. The intensity of summertime NO_2 episodes is expected to decline over the period up to 2025 as a result of both the reductions in urban NOx emissions from road traffic (see Figure 7.2) and the expected decline in episodic ozone concentrations resulting from reductions in European regional emissions of ozone precursors. However, the frequency of summertime episodes may increase at the same time due to climate change. Furthermore, there is also the impact of the increase in the global ozone baseline to consider, as well as the increasing direct emissions of NO_2 into urban atmospheres from diesel vehicles fitted with catalytically regenerating particle traps and filters. At present, these factors are finely balanced and so it is likely that there will be little change in the intensity and frequency of summertime NO_2 episodes for the present. A detailed study of future NO_2 concentrations in the UK is available elsewhere (Air Quality Expert Group, 2004).

Figure 7.1 UK urban road traffic PM_{10} emissions up to 2030



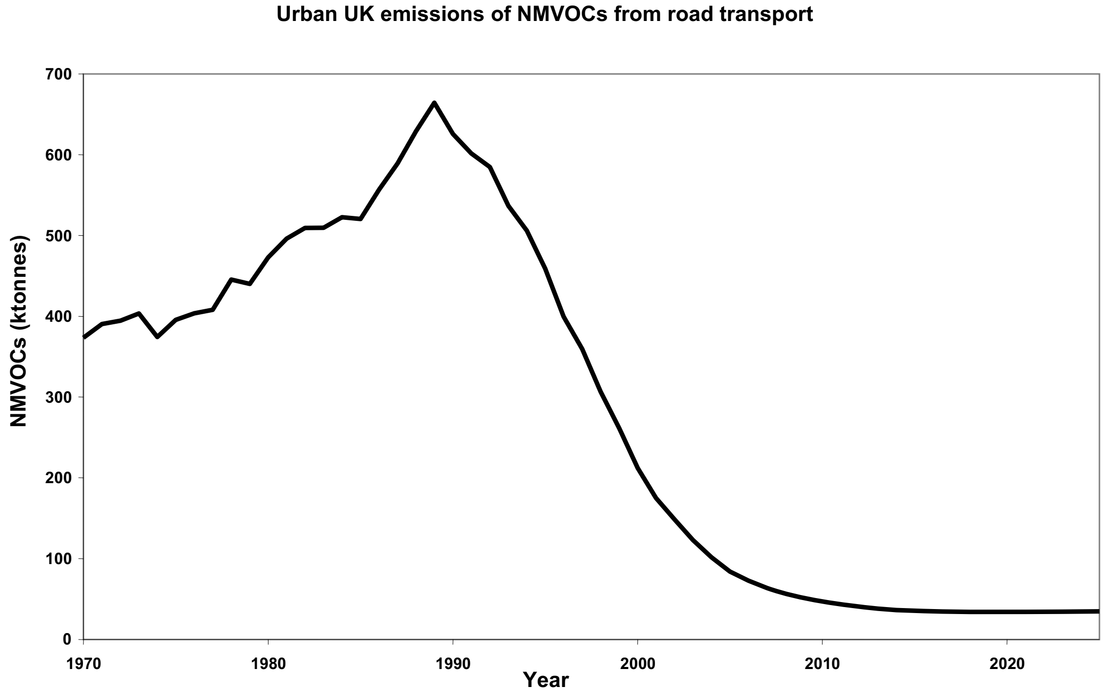
Source: NAEI © AEA Technology plc

Figure 7.2 UK urban road traffic NO_x emissions up to 2030



Source: NAEI © AEA Technology plc

Figure 7.3 UK urban road traffic VOC emissions up to 2030



Source: NAEI © AEA Technology plc

7.2.3 Future ozone episodes

It is recognised that the summertime European regional-scale photochemical ozone episodes sit on top of an ozone baseline which is itself global in scale. 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 (Volz and Kley, 1988). 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 (CH_4), CO and NOx from human activities (IPCC, 2001). Furthermore, these computer modelling studies suggest that this ozone increase should continue into the future. In our previous report, the need was recognised for further modelling at the global and regional scale of the combined effects of climate change and changes in the emissions of the precursors of both the background and regional ozone in the period up to 2030.

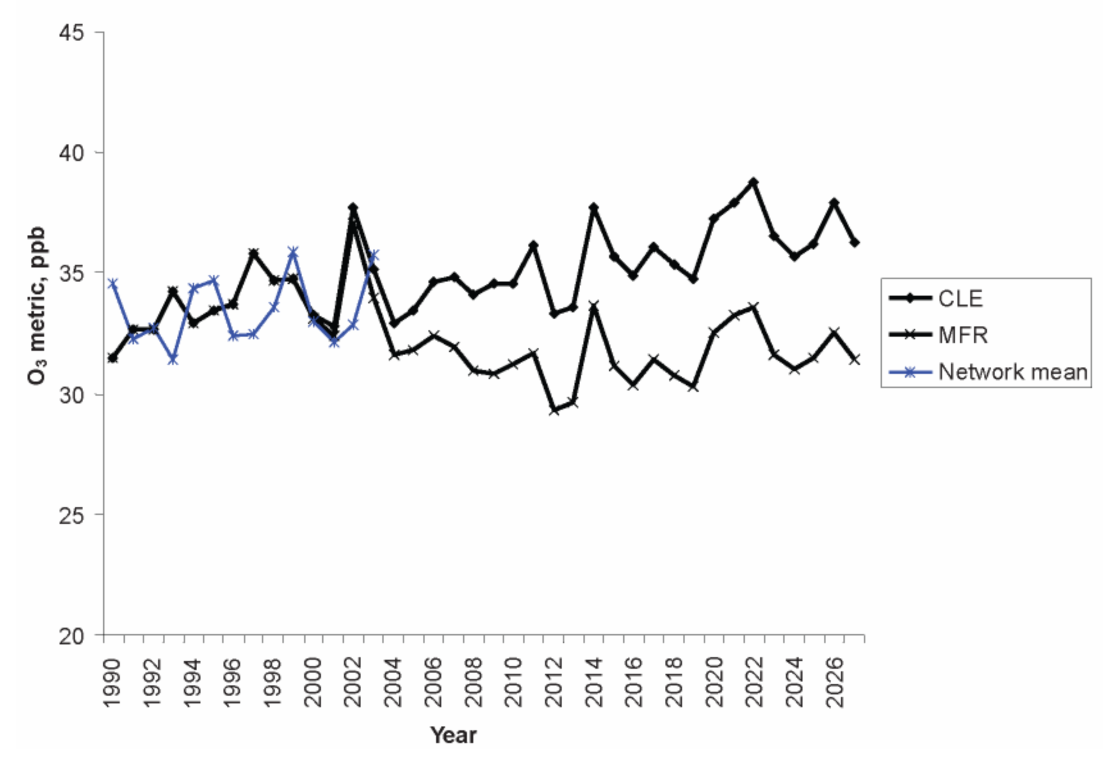
More recently, further global emission scenarios have been developed for the tropospheric ozone precursor gases, in addition to those used previously and promulgated by the Intergovernmental Panel on Climate Change in their SRES scenarios. These new global emission scenarios have prompted a further consideration of the combined influence of ozone precursor emission controls on both global and regional ozone within Europe. They address the global emissions of man-made sources of SO_2, NOx, CH_4, CO and VOCs annually through to 2030 in two scenarios: CLE, current legislation and MFR, maximum feasible reduction. In the CLE scenario, each country applies the pollution controls that have already been agreed with their current policies, whereas in the MFR scenario, all technically and economically feasible ozone precursor emission reductions are put in place by 2030.

Figure 7.4 presents the annual mean ozone concentrations for South-East England calculated with the global three-dimensional Lagrangian chemistry-transport model STOCHEM from 1990 through to 2028 (Derwent *et al.*, 2006). Model results are shown as solid black lines and the available observations are taken from the Defra Rural Ozone Network. The observations are presented as the annual average of the daily maximum 8-hour mean ozone concentrations. Over the period from 1990 through to 2003, the model and observations agree well both in relative magnitudes and trends. The observations show a small downwards trend of -0.03ppb/year and the model results between +0.27 and -0.10ppb/year depending on the climate dataset employed. In the global scenario with all countries, both within Europe and globally, implementing their current legislation CLE, ozone levels increase steadily over the period to 2030 by +0.10 to +0.13ppb/year. When all countries adopt maximum feasible reductions, ozone levels decline in South-East England by -0.04ppb/year. Relative to 2000 levels, ozone concentrations rise by about 3.0ppb by 2030 in the CLE scenario and decline by about 1.4ppb in the MFR scenario.

The ozone concentration changes anticipated in the CLE and MFR scenarios in Figure 7.4 by the year 2030 are somewhat smaller than the 3.7ppb increase reported in our previous assessment using the IPCC SRES A2 scenario. This reflects a change in perceptions of the growth in Asian emissions and the take-up of ozone precursor emission controls in the same region that have been built into the new emission scenarios. However, on the longer timescale, the ozone increases projected in our previous report with the IPCC SRES A2 scenario by 2060 and 2100 still remain a distinct possibility. Furthermore, there is no guarantee that the countries of the world will embrace the concept of maximum feasible reductions and fully implement them and so bring down both global and regional ozone concentrations as shown in Figure 7.4. Currently, therefore, the CLE curves in Figure 7.4 represent our best estimate of where future ozone concentrations will be over the period to 2030.

In the IPCC SRES A2 scenario, ozone concentrations are projected to rise throughout the 21st century. There is an important question as to the extent to which these ozone increases are the direct consequences of climate change or the consequences of the increasing global emissions of the radiatively active trace gases that drive climate change. Because of the close coupling between the climate processes, atmospheric chemistry and the biogeographical cycles of the radiatively active trace gases, it is difficult to give a simple answer to these questions. Broadly speaking, ozone concentrations over the time horizon up to 2030 and 2050 are more strongly influenced by the increasing emissions of CH_4, NOx, CO and VOCs that drive climate change. In contrast, over the time horizon from 2030 onwards, climate change processes themselves start to exert a more dominant influence on future ozone concentrations. Nevertheless, in a given snapshot in time or over a given timescale, it is difficult to discern whether climate change itself or increasing global emissions of methane are responsible for the ozone changes from the present day, because the global systems are so closely coupled.

Figure 7.4 Model calculated monthly mean ozone concentrations for Southern England from 1990 through to 2026 in two global emissions scenarios: diamonds, on current emission control policies (CLE) and crosses, with maximum feasible emission reductions in methane, CO, NOx and VOCs (MFR). The blue trace shows the observed annual means of the daily 8-hour mean ozone concentrations from the rural site network also in Southern England



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7.3 Health impacts: episodes

We have not attempted to quantify the changes in health impact associated with the trends in the frequency and atmospheric characteristics of winter and summer episodes described above. One reason is that there is uncertainty about what concentrations might occur. Another reason is that there is little firm evidence concerning the appropriate exposure response coefficients to apply during episode conditions. Finally, since episodes account for such a small proportion of days, their impact is far outweighed by the effects of day-to-day exposure to air pollution during the rest of the year. Nevertheless, air pollution episodes are important public health threats and as such are associated with publicity and the issuing of advice to the public. Qualitatively the following predictions can be made.

The weather conditions associated with winter episodes will become less common, while over the same time there will be a decrease in the ambient concentrations of PM_{10}, SO_2 and NO_2 should an episode occur. O_3 concentrations are already low in winter episodes and will remain so in any future episodes. Thus the health impact of winter episodes, which is already low, will become even less due to the combined effects of climate change and reduced emissions.

In contrast, the weather conditions associated with intense summertime photochemical ozone episodes will increase in frequency. However, these future episodes will be accompanied by lower concentrations of ozone than already occur under similar circumstances, because European emissions of VOCs and NOx precursors are predicted to fall.

We have concluded that the frequency and intensity of summer NO_2 episodes are unlikely to change. The implications of this for health impact are uncertain partly because there is more doubt about the direct health effects of NO_2 than for particles and ozone (WHO, 2004). PM_{10} usually increases during summer episodes, but the intensity of this is likely to fall in the future. SO_2 episodes, already rare, will not increase.

7.4 Quantitative health impact assessment

The main pollutant of concern is O_3, concentrations of which are predicted to rise in the long term, largely due to increases in hemispheric ozone. In this section we estimate changes in attributable deaths and emergency respiratory hospital admissions attributable to this trend up to 2020. This was done in the previous report but needs repeating because of changes in the various parameters required to estimate health impact (predicted exposure to O_3, risk coefficients, baseline rates and population estimates). The choice of exposure response coefficients is not clear cut. Since the first climate change report, there have been important refinements in epidemiological methods (Health Effects Institute, 2003) and an expansion in the body of evidence associating ozone with health effects, including several multi-city studies (Department of Health, 2008 – in preparation).

7.4.1 Choice of mortality coefficient for ozone

Unlike the case of particles, for ozone there is insufficient evidence for an effect of chronic exposure on mortality to justify estimating health impacts in terms of shortened life-expectancy. However, mortality associations have been found in a large number of short-term exposure studies using daily time-series. These enable the estimation of attributable deaths ‘brought forward’, but the life lost cannot be quantified. A variety of averaging times (1-hour, 8-hour and 24-hour) have been used in these studies, but we shall confine our estimates to the 8-hour maximum ozone. This has been used in many European time-series studies, and was recently adopted by the WHO in its forthcoming update of guidelines. The previous climate change report used a coefficient of 0.6% increase in daily deaths per 10µg/m^3 8-hour ozone. This was taken from the QUARK 1 report (Department of Health Committee on the Medical Effects of Air Pollutants, 1998) and was based on unpublished results from the European multi-city study (APHEA 1) which had combined results from five cities (Athens, Barcelona, London, Lyon and Paris) (Touloumi *et al.*, 1997). Many new studies have been reported as well as several meta-analyses.

A meta-analysis of 15 European cities carried out by the WHO (2004) has been used to estimate mortality impacts of ozone by Clean Air For Europe (CAFE) for the European Commission (Commission of the European Communities, 2005). This estimate was 0.3% (95% confidence interval (CI) 0.1 to 0.4). It did not incorporate the more recently published results from 23 European cities as reported from APHEA 2 (Gryparis *et al.*, 2004). While there was overlap between the cities included in the APHEA 2 and WHO meta-analyses, the APHEA 2 analysis had the advantage of newer datasets and a standardised and more refined approach to the analysis. To obtain the most recent and comprehensive meta-analysis of European cities, we combined these new European results with those from four additional European cities (27 cities in total) and obtained a random effects estimate of 0.3% (95% CI -0.05 to 0.74), the same as that obtained by the WHO meta-analysis. This is also what was obtained by the Committee on the Medical Effects of Air Pollutants review of ozone (Department of Health Committee on the Medical Effects of Air Pollutants, 2008 – in preparation) in a meta-analysis based on 22 cities world-wide (0.3%, 95% CI 0.2 to 0.4). Since three independent meta-analyses with different mixes of cities all agree, we decided to use the all-year coefficient for 8-hour ozone of (0.3% 95% CI 0.1 to 0.4) based on European cities published by the WHO and used by CAFE in its health impact assessment for the European Commission (WHO, 2004). It is within the range of estimates provided by three recent meta-analyses reported from the US based on 1-hour and 24-hour averaging times (Bell *et al.*, 2005; Ito *et al.*, 2005; Levy *et al.*, 2005). This coefficient is about half of that used in the previous climate change report.

7.4.2 Choice of morbidity coefficient for ozone

Ozone has been associated with a range of morbidity outcomes, including emergency hospital admissions for respiratory disease, increased respiratory symptoms in asthmatics and reduced lung function (WHO, 2003). Notably, however, there is little evidence of an association with hospital admissions for heart disease or stroke admissions (Department of Health Committee on the Medical Effects of Air Pollutants, 2006). Hospital admission is the only morbidity outcome for which there is adequate baseline data and we have therefore confined our morbidity impact assessment of ozone to emergency respiratory admissions.

The previous report estimated the impact of ozone on emergency respiratory admissions using a coefficient of 0.7%, based on a rounded estimate from unpublished results from four European cities in the APHEA 1 study (Spix *et al.*, 1998). No results for 8-hour ozone and all-age all respiratory admissions are yet available from APHEA 2. However, newer estimates are available from individual city studies. We combined the results of all available European cities (Birmingham, London, Paris and Rome) and obtained an estimate of 0.1% (95% CI -0.3 to 0.6). The WHO meta-analysis of European cities obtained age-specific estimates for the 15–64 age group (1.001, 0.991 to 1.012) and 65+ age group (1.005, 0.998 to 1.012). These age-specific coefficients provide an alternative for estimating attributable admissions which has the advantage of being derived from the same WHO meta-analysis as the mortality coefficient. We shall estimate impacts using both the coefficient for all ages and the WHO age-specific coefficients.

Most studies show higher coefficients in the warm half than in the cool half of the year. For this reason, health impacts are frequently estimated for the warm half of the year only

(Stedman *et al.*, 1997). This approach was also followed by QUARK 1 and the previous climate change report, using the all-year coefficients, which is likely to have underestimated the exposure response. In contrast, the APHEIS/ENHIS project used larger, warm-season-specific coefficients for estimating health impacts of ozone (ENHIS, 2005). The argument against using all-year coefficients is based mainly on the belief that there is likely to be a threshold for ozone effects, together with the possibility that negative confounding with traffic pollution in the cool season may artificially depress ozone coefficients based on cool season analyses. Another argument is that individual ozone exposure is greater in the summer because more time is spent outdoors and there is an increased outdoor to indoor ratio. Against this argument is the general lack of epidemiological evidence of a threshold where this has been looked for in time-series analyses. Having considered these arguments, we decided to estimate the health impacts using all-year ozone estimates as was also recommended by UNECE (UNECE, 2004).

Because the question of a threshold for ozone remains open, it is usual to examine the sensitivity of the results to a threshold assumption. This was done in a study of the effect of ozone in the summer of 1995 (Stedman *et al.*, 1997), in the previous climate change report (Anderson *et al.*, 2001) and in Quark 1 (Department of Health Committee on the Medical Effects of Air Pollutants, 1998). In these analyses, a threshold of 50ppb 8-hour ozone was used to estimate health effects on days at or above that level. More recently, the question of a threshold for ozone was discussed by the Joint Task Force on the Health Aspects of Air Pollution (UNECE, 2004). While it was recognised that current evidence was insufficient to derive a threshold, it was also thought that uncertainty about exposure response increased at lower levels. This led to the decision to estimate effects only in relation to days over 35ppb, this being about the background level in Europe. This cut-off was adopted by the CAFE impact assessment. The same group also recommended that effects should be estimated over the whole year using all-year coefficients. Recognising that this approach might underestimate effects, it was also recommended that a sensitivity analysis using no threshold should be also done. Since urban monitors had been used to generate exposure response relationships, urban levels of ozone should be used to estimate urban health effects. We estimated impacts with no threshold, a threshold of 35ppb and a threshold of 50ppb (as was done in the previous climate change report).

7.4.3 Ozone modelling

The Ozone Source Receptor Model (OSRM) has also been used to generate UK scale maps on a 10km x 10km grid. The OSRM is a recently developed model to describe photochemical ozone production in the UK (Hayman *et al.*, 2006; Hayman *et al.*, 2005; Hayman *et al.*, 2002). The OSRM covers the EMEP model domain and uses global meteorological datasets provided by the Met Office to derive 96-hour back trajectories. The chemical scheme is based on that used in the STOCHEM model (Collins *et al.,* 1997). The mechanism has approximately 70 chemical species involved in approximately 180 thermal and photochemical reactions. The mechanism represents ozone formation using 10 VOCs, which provides an appropriate description of ozone formation on the regional scale. The emission inventories are taken from EMEP for Europe with the option to use NAEI emission inventories for the UK, which have been aggregated to 10km x 10km and into eight key sectors.

The OSRM describes the boundary layer by a single box and assumes that this is well mixed. While this is a reasonable assumption for rural areas, it is less valid in urban areas with high NOx emissions. In such areas, there will inevitably be a gradient in the NOx concentration profile, with higher concentrations at the surface. This will lead to lower ozone concentrations at the surface through reaction with NO.

An algorithm has been developed and implemented in the OSRM post-processor to convert the mid-boundary layer concentrations to surface concentrations on a hour-by-hour basis. This algorithm uses the local meteorological parameters characterising the boundary layer, surface roughness appropriate for the surface types considered, resistance parameters for O_3 and NO_2, the local NOx emission rates and a simple $NO-NO_2-O_3$ photostationary state chemistry.

The OSRM calculates ozone concentration on an hourly basis and can thus be used to calculate a wide range of ozone metrics, including the annual means of the daily maximum running 8-hour mean concentrations with cut-offs at 0, 35 and 50ppb used here. A comparison of the OSRM results for these metrics with monitoring data and empirical modelling methods has been provided by Kent *et al.* (Kent *et al.*, 2005).

7.4.5 Estimation of attributable deaths and admissions

In calculating the effects of pollutants on health, the following sequence of steps has been adopted. These steps are described in more detail in earlier reports (Department of Health Committee on the Medical Effects of Air Pollutants, 1998; Stedman *et al.*, 2002).

a) The country has been divided into 1km grid squares and the concentration of pollutants and resident population has been estimated for each. The former has been derived from the 10km square OSRM results and the latter from 2001 Census data. Population-weighted mean concentrations are then calculated by region or for the whole of the UK.

b) A baseline level of the given health-related and pollution-affected events, e.g. daily deaths and hospital admissions for the treatment of respiratory diseases, was obtained from the Office for National Statistics and the Hospital Episode System (England only).

c) By combining the data from (a) and (b) and applying the chosen coefficient linking the pollutant concentration with the relevant effects, the expected health effects were derived under various threshold assumptions (none, 35ppb and 50ppb).

d) To distinguish the effects of climate and hemispheric emissions from those of trends in UK emissions, estimates were made for 2020 under the climate change scenario, and under the UK and European emissions scenario holding the climate and hemispheric emissions at 2003 levels.

7.4.6 Results

Table 7.1 shows the results of modelling the health impacts of predicted changes in ozone using the above approach. Table 7.2 summarises these results and also presents the qualitative conclusions concerning other pollutants and winter and summer episodes.

The percentage change in ozone concentration, and thus the health impact between 2003 and 2020, is dependent on both the ozone metric chosen and the assumptions about the composition of the atmosphere. The ozone metric with no threshold shows a 15% increase to 2020 for the baseline and an 8% increase to 2020 for the 2003 atmosphere calculation. Thus, about half of the expected change is due to the changing atmosphere (hemispheric emissions and climate change) and half is due to changes in UK emissions, specifically the control of NOx emissions, which is expected to lead to an increase in ozone concentration in urban areas to more closely resemble those in rural areas. There is a much larger expected increase of about 50% in the 35ppb and 50ppb ozone metrics to 2020 for the baseline. Most of this is due to the changing atmosphere. Reductions in emissions lead to a decrease in the 50ppb ozone metric for the 2020 baseline with the 2003 atmosphere. For this metric, the reduction in the emission of the precursors of photochemical episodes between 2003 and 2020 outweighs the increase in ozone concentration in urban areas (Hayman *et al.*, 2006).

Table 7.1 2003 baseline mortality and emergency hospital admissions and predictions for 2020 under (1) model for climate change including UK emissions and (2) model for UK and European emissions without climate change

	2003 (base year)	2020 baseline (climate change and UK emissions)	2020 baseline (2003 climate, 2020 UK and European emissions)
No threshold			
Deaths (0.3%) (95% CI 0.1 to 0.4)	**11272 (3757 to 15029)**	**12930 (4310 to 17240)**	**12140 (4047 to 16186)**
Resp Ads (0.1%) (95% CI -0.3 to 0.6)	**3664 (-10991 to 21983)**	**4203 (-12608 to 25216)**	**3946 (-11838 to 23675)**
Resp Ads (sum of age-specific)	**9280 (-12875 to 32501)**	**10645 (-14769 to 37282)**	**9995 (-13867 to 35004)**
35ppb threshold			
Deaths (0.3%) (95% CI 0.1 to 0.4)	**1582 (527 to 2109)**	**2391 (797 to 3189)**	**1802 (601 to 2402)**
Resp Ads (0.1%) (95% CI -0.3 to 0.6)	**514 (-1542 to 3085)**	**777 (-2332 to 4664)**	**586 (-1757 to 3513)**
Resp Ads (sum of age-specific)	**1302 (-1807 to 4561)**	**1969 (-2732 to 6896)**	**1483 (-2058 to 5195)**
50ppb threshold			
Deaths (0.3%) (95% CI 0.1 to 0.4)	**333 (111 to 444)**	**511 (170 to 681)**	**317 (106 to 423)**
Resp Ads (0.1%) (95% CI -0.3 to 0.6)	**108 (-325 to 650)**	**166 (-498 to 996)**	**103 (-309 to 619)**
Resp Ads (sum of age-specific)	**274 (-381 to 961)**	**420 (-583 to 1472)**	**261 (-362 to 915)**

Table 7.2 Summary of predictions: the range against hospital admissions refers to the two coefficients used

	2020. Climate change model (climate, hemispheric emissions and UK emissions)	2020. UK emissions but 2003 climate	Winter episodes	Summer episodes
Pollutant	% change in deaths from 2003 (n)	% change in deaths from 2003 (n)		
Particles			Reduction	Reduction
Ozone (no threshold)			Not applicable	Increase in frequency. Lower intensity
Deaths	**15% (1658)**	**8% (868)**		
Respiratory admissions	**15% (539 to 1365)**	**8% (282 to 715)**		
Ozone (35ppb threshold)				
Deaths	**51% (810)**	**14% (220)**		
Respiratory admissions	**51% (77 to 667)**	**14% (263 to 667)**		
Ozone (50ppb threshold)				
Deaths	**53% (177)**	**-5% (-16)**		
Respiratory admissions	**53% (58 to 146)**	**-5% (-5 to -13)**		
Nitrogen dioxide			Reduction	No change in frequency or intensity
Sulphur dioxide			Reduction	Reduction

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8 Climate change, ground level ultraviolet radiation (UVR) and health

(See also section 4.8 of 2001/2002 report)

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Summary

- Further epidemiological studies have confirmed the role of ultraviolet radiation (UVR) in skin cancers, and new evidence suggests that UVR exposure is a cause of some types of cataract.
- There is growing evidence of important health benefits from adequate levels of vitamin D. Sunlight exposure is an important factor in maintaining adequate vitamin D levels, but only modest exposures are needed.
- The ozone layer is expected to recover by 2050, but climate change may delay that recovery.
- Longer summers and changes in cloud cover may lead to changes in behaviour that are probably more important for personal UVR exposure.

Recommendations

- There is a continuing need to maintain health promotion campaigns to limit personal exposure to damaging UVR.
- Clearer advice is needed on how the public can maintain adequate vitamin D status and at the same time avoid the adverse consequences of exposure to sunlight.

8.1 Introduction

The previous review outlined the ways in which stratospheric ozone depletion was increasing the amounts of solar ultraviolet radiation (UVR) reaching the surface. Greenhouse-gas-induced climate change may also increase the surface level of ultraviolet radiation by mechanisms such as decreases in cloud cover during spring and summer. If there were no changes in behaviour, increases in environmental UVR would lead to increases in the exposures received by the population and increases in the health effects associated with such exposures.

8.2 Health impacts of UVR

Apart from an enhanced potential for sunburn, the most important impact is likely to be an increase in the risk of skin cancers. Another potential effect would be an increase in the incidence of cataracts, which are a major cause of blindness. There are also concerns about the ability of UVB radiation to cause suppression of the immune response, and this could adversely affect the course of some infectious diseases in humans and reduce the effectiveness of vaccinations. However, there are health benefits in UVR exposure. The most obvious of these is that exposure to sunlight, at adequate intensity, leads to synthesis of vitamin D, which is known to be important for skeletal health and calcium metabolism. There are also geographical studies that link vitamin D status to other chronic diseases, including some cancers. More research is needed to investigate these associations and define the optimum level of vitamin D for individuals. The evidence on skin cancer and cataracts is considered strong enough to provide quantitative estimates of the potential adverse health effects of the anticipated increases in the surface level of UVR. The independent Advisory Group on Non-Ionising Radiation (AGNIR) published a thorough review of the health effects of UVR in 2002 (AGNIR, 2002) and subsequently the National Radiological Protection Board published advice on protection against UVR (McKinlay *et al.*, 2002). The role of UVR in maintaining vitamin D levels and the clinical importance of vitamin D have recently been reviewed (ICNIRP, 2006).

Studies continue to confirm the crucial role of exposure to sunlight in the aetiology of skin cancers (UNEP, 2003). New animal models have been developed for cutaneous melanoma and for basal cell carcinoma that point to an important role for UVB and especially to exposure early in life.

At the time of the last review, some uncertainties remained about the role of sunlight exposure in the formation of cataract, which is the leading cause of blindness in the world. New studies from Australia (Neale *et al.*, 2003) and from France (Delcourt *et al.*, 2000) and a review of 22 published studies (McCarty and Taylor, 2002) all support an association between sun exposure and cataract with animal models (UNEP, 2003) particularly implicating UVB. Knowledge continues to accumulate on the mechanisms by which exposure to UVR causes immune suppression but direct evidence on what the implications are for human health remains elusive (UNEP, 2003).

In summary, some laboratory and population studies suggest that vitamin D may protect against some cancers. Some of these have used vitamin D supplements, while others have tried to estimate the amount of sun exposure people have had. However, the research results are inconsistent and it is too early to say how much vitamin D people need and how levels can best be increased. Holick (2004) provides a review of work linking vitamin D protection against cancer and other diseases.

8.3 Changing exposures due to changes in behaviour, climate and ozone layer

As well as affecting surface levels of UVR by changes in cloud cover, it was noted that climate change might have important effects on patterns of behaviour that in turn could have consequences for health. The health effects of solar UVR are related to the exposure received by the population and these depend on both the UV irradiance in the environment and patterns of behaviour that bring about exposure. 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 on the UVR exposures received by the population and the associated health effects. Unfortunately, very little empirical evidence is available on the possible links between climate, outdoor activity and UVR exposure in the UK which would allow a quantification of the risks that might be involved.

Since the last review there has been a large volume of published work on trends in stratospheric ozone and associated changes in surface levels of UVR. An active research effort has also yielded new information on the potential health impacts of enhanced exposure to UVB. A comprehensive review of this large body of new evidence lies beyond the scope of this report but major reviews have been published on ozone depletion, its causes (WMO, 2003) and its potential impacts on human health (UNEP, 2003).

The World Meteorological Organization (WMO) review of ozone depletion confirms that a slow recovery of stratospheric ozone is likely as the atmospheric burden of halogens decreases with values reaching pre-Antarctic-ozone-hole value by about mid-century. This means that enhanced levels of surface UVB radiation as a result of ozone depletion are likely to persist until approximately 2050. Up to then there will be a period when any effects on human health due to ozone depletion will overlap with those that may be caused by climate change. An important issue on which there is some new data is whether stratospheric cooling related to global warming could delay recovery (McKenzie *et al.*, 2003). It has been calculated that a delay of 15 to 20 years would increase the peak excess incidence of skin cancer in North-West Europe attributable to ozone depletion from 9% above baseline to 15%, with the peak year shifting from 2055 to 2065 (UNEP, 2003).

8.4 Future impacts on health

Sunburn is perhaps the most obvious health consequence of increased acute exposure to UVR and the previous review (2001/2002) noted that particular risks might result from springtime episodes of ozone depletion acting on a population with largely un-acclimatised skin. An interesting study from an area of Southern Chile periodically affected by the Antarctic ozone hole confirms a large increase in the incidence of sunburn during an episode of ozone depletion that coincided with sunny weather at a weekend (Abarca *et al.*, 2002). It should be noted that such episodic changes in ozone and the resultant UVR exposure will have little impact on the cumulative risk over the year at UK latitudes, the main risk factor being people's behaviour.

Because of the overriding importance of people's behaviour in determining their solar UVR exposure, the World Health Organization, in collaboration with other agencies, has developed the Global Solar UV Index (UVI) (WHO, 2002). This provides a simple measure of the UVR level at the Earth's surface and an indicator of the potential for skin damage. It serves as an important vehicle to raise public awareness and to alert people about the need to adopt protective measures when exposed to UVR. It is used extensively by the news media in weather forecasts to indicate possible high UVR levels.

Solar UVR has been monitored at various sites within the UK for many years, covering latitudes from the South of England to the Shetland Islands (HPA, 2007). The monitoring data are available live online from both the Health Protection Agency and Met Office websites. The data are reported in both graphical form and in terms of the prevailing Global Solar UV Index.

The carcinogenic potential of exposure to sunlight may be enhanced by increases in temperature (van der Leun and de Gruijl, 2002) although the evidence is speculative. This study estimates that a 2°C increase in ambient temperature might result in 21% increase in the incidence of skin cancer, which is substantially greater than any anticipated effects of ozone depletion alone. However, this is based on extrapolation from the results of experiments on mice and there is, as yet, no direct evidence for humans.

The previous review (2001/2002) emphasised that any health effects will depend on the exposures of UVR received by the population, and this will depend on a combination of levels in the environment and patterns of behaviour. Climate change can be expected to effect both of these. The UKCIP02 climate change scenarios point to larger changes in summer cloud cover than the UKCIP98 scenarios that were the basis of the previous review. The UKCIP02 scenarios for the 2080s point to decreases in summer cloud cover for much of England: of 9–12% for medium–low scenario (see Chapter 1) and 12–15% for medium–high scenario which, other things being equal, would be associated with increases in UVB radiation of ~5% and ~7% respectively. Previously it was argued that changes in climate such as increases in sunshine, reductions in precipitation and higher temperatures would be likely to favour patterns of behaviour involving more outdoor activity, lighter clothing and greater exposure to the sun.

The likelihood of such changes is supported by evidence from a recently completed study of factors influencing the sun exposure of beach users in East Anglia (Horton, 2004). This showed that the length of time spent on the beach and the estimated UVB exposures received were strongly positively associated with ambient temperatures, whereas the proportion of the body covered by clothing showed a significant negative association. The odds ratio per 1°C for receipt of >1 minimal UVR erythemal dose (MED) was 1.34 (95% CI 1.21 to 1.48) which underlines the strong influence of ambient temperature on patterns of behaviour involving potentially risky UVB exposure. These findings support the view that, over this century, behaviour associated with climate change, rather than ozone depletion, may be the largest determinant of sun exposure and consequent impact on skin cancer (and other health effects) in the UK population (Diffey, 2004).

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Appendix

Response to public comment on this report

1. This report was published for comment on Friday 4 May 2007. Fifteen responses were reviewed; these have been collated and may be viewed on the Department of Health website: www.dh.gov.uk. The comments received were, in general, supportive of the work of the expert group that compiled this report and were in general agreement with its conclusions. The authors of the report wish to thank all those who took the time and trouble to make comments.

2. A number of commentators noted that the report did not discuss either how climate change might be abated (mitigation) or how its effects might be reduced (adaptation). These are important comments, but it should be noted that to consider these aspects of the problem of climate change was not the purpose of the report. This report deals only with the possible or likely effects of climate change on health in the UK. That such effects might be reduced if appropriate measures are taken is accepted. It is also accepted, with concern, that the effects of climate change on health might be greater in some other countries than in the UK: this, too, was not within the remit of the expert group.

We now turn to specific comments.

3.i It is agreed that the report should be of interest to a wider audience than climate change scientists. We see it as a detailed but accessible report that should be of interest to policy-makers, to health professionals and, indeed, to the public. The report was prepared at the request of the UK Department of Health and will play an important part in guiding the development of policy initiatives such as the Department of Health's Heatwave Plan.

ii One commentator pointed out that no recommendations regarding an upper limit for safe temperatures at work could be made. This is correct. We see this as a subject for the Health and Safety Executive.

iii Comments on the preface of the report are noted. We feel that the responsibility for the contents of the prefaces must lie with their authors and that it is not for us to comment on this.

iv We did not deal with the NHS response to flooding. This was outside our remit.

v We note a comment on the possible effects of climate change on ambient levels of allergens – caused by changes in the seasonal pollen abundance associated with the earlier onset of spring in Europe. We accept that this is an omission and recommend that it be rectified in any further reports in this area.

vi We note the comment from the Environment Agency: 'there is a need to clarify who in Government is leading on the health aspects of climate change'. We agree with this and recommend that this be addressed by officials in the Department of Health.

vii We note the comment by the Environment Agency regarding the need for a strategic approach to coastal flooding. We accept that management of the risk of coastal flooding necessarily implies more than improved flood defences. The details of this area are clearly a matter for the Environment Agency rather than for us.

viii We note the Environment Agency's comments regarding drought events and water supplies and agree that this needs to be considered in more detail. A note to this effect has been added on page 78 of our report.

ix We recognise that increasing ambient temperatures may cause problems if collection of domestic waste is made more infrequent. We recommend that this point should be considered by local authorities.

x We note comments regarding the possible effects of climate change on food production on a world-wide scale. We accept that increasing grain prices could have 'knock-on' effects in the UK.

xi We accept that we did not look at the possible effects of changes in weather patterns on road traffic accidents. This, and a more detailed examination of urban heat-island effects, might be considered in future reports.

xii We note with concern and regret that flooding events that have occurred since this report was written have claimed four lives. The need for a sharper focus on flood warnings and preparedness is clear.

xiii We have considered a comment regarding tick-borne disease. Professor Sarah Randolph has responded as follows:

There is no doubt that complex tick-borne disease systems are affected by climate, but no reason to suppose that climate change will strengthen rather than weaken or disrupt the delicate balance between wildlife hosts, vectors, pathogens and humans. Lyme borreliosis systems are very robust (and better able to withstand disruption than TBE virus cycles), and the risk to humans depends principally on the abundance of infected ticks and the exposure of humans to those ticks. There is no evidence that tick survival will improve in warmer wetter winters (ticks are adaptively cold-hardy), especially if the insulating effects of snow cover are reduced, but ticks are likely to become active earlier in the spring. Hotter drier summers, however, are likely to impose higher mortality. The balance between the positive and negative effects of climate change on tick abundance has not yet been estimated. Host availability has an equally two-pronged impact on the abundance of the hungry infected ticks that pose risks to humans: more hosts allow ticks to feed more easily, with a potentially positive effect on overall tick populations, but therefore a negative effect on the time that ticks must remain on the vegetation questing for hosts (and thereby accidentally contacting humans).

The response of humans to opportunities for outdoor activities in more clement weather at times of the year when ticks are also active is highly significant. Human response to improved awareness and perceived greater risk is more complex, and is the subject of a new multi-disciplinary research project (sociology, psychology, environmental science and zoology), jointly awarded to Forest Research and the Universities of Surrey and Oxford by the ESRC within the RELU programme.

xiv We note comments regarding our predictions of the effects of climate change on ambient concentrations of nitrogen dioxide and particulate matter. Our predictions are based on current estimates provided by Defra and we think that questions regarding the likely accuracy of these should be directed to Defra rather than to us. As we understand it, emissions of pollutants such as nitrogen oxides and particles are likely to decline as a result of measures proposed in the Air Quality Strategy. We are unable to undertake further detailed work in this area but recognise that this and appropriate sensitivity analysis might usefully be undertaken in further reports on this subject.

xv We note the comments from the Nottingham Energy Partnership regarding the UKICP02 scenarios used as a basis for our work. We note that updated scenarios will be available in 2008 (UKCIP08).

xvi We also note the comment from the same source that we might have paid more attention to the implications for the UK of climate change impact abroad, including travel-associated infections and migration patterns. The return to the UK of citizens now living abroad may place an additional burden on the NHS – but we feel that hard data on this may be difficult to acquire.

xvii We note the comments from the Campaign for Clean Air in London:

a. The question regarding current trends in NO_2 concentrations in London will be dealt with in a report from the Defra Air Quality Expert Group. It remains our view that if motor vehicle emissions are controlled as planned, NO_2 concentrations will fall in the period to 2030 and beyond.

b. It is not possible to arrive at a firm position regarding the question of a threshold for the effects on health of ozone. For this reason a sensitivity analysis was undertaken. All estimates of effects of air pollutants on health depend on models and these are likely to be imperfect. An 'objective' analysis of deaths caused by exposure to ozone during the heatwave of 2003 is not possible because of the impossibility of distinguishing between deaths due to ozone and those due to other reasons. The latter will be the majority. Attempts to separate the effects of ozone from those of high temperatures have been made and the reader is referred to a paper by Stedman (2004).[1]

c. We have noted the work of the World Health Organization; a number of the authors of the present report were involved in that work.

4. In conclusion, we thank, again, all those who have commented on our report. Important points have been raised. These and others should be addressed in any further reports on this subject.

Health Protection Agency
Department of Health
2007

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[1] Stedman, J.R. (2004) The predicted number of air pollution related deaths in the UK during the August 2003 heatwave. *Atmos.Environ.* **38**, 1087–1090.

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