Health Protection Agency

Health Effects of Climate Change in the UK 2012

Current evidence, recommendations and research gaps

Sotiris Vardoulakis and Clare Heaviside (Editors)

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Edited by Sotiris Vardoulakis and Clare Heaviside

Preface I

There is substantial evidence that climate change is affecting many aspects of the world around us. Weather patterns are shifting, extreme weather is becoming more commonplace and temperatures in most parts of the world are rising.

For at least ten years now, the UK has been giving serious consideration to the risks climate change could pose to our health.

In 2002 the Department of Health published *The Health Effects of Climate Change in the UK*, one of the first reports of its kind internationally, informed by the UKCIP98 climate projections. In 2008, DH and the Health Protection Agency jointly published an updated version of that study, based on the revised UKCIP02 climate projections.

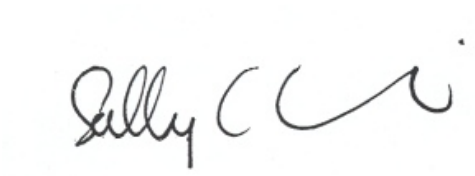
These reports have been highly regarded and helped to shape policies to prepare for the challenges ahead. I am glad that the HPA agreed to produce this timely update as the science around climate change is constantly evolving.

In 2009 the latest long-range climate projections for the UK (UKCP09 from the UK Climate Impacts Programme) were published, updating those produced in 2002, in order to inform the UK's first Climate Change Risk Assessment (CCRA), required by the Climate Change Act (2008), covering 11 sectors across society.

This HPA report complements the Health Sector report of the CCRA by providing scientific evidence of the wider risks to public health from climate change in the UK.

Next year the public health landscape changes, with the HPA moving to Public Health England and more involvement of local authorities in public health decision making. This report will help provide valuable evidence towards local protection of the public's health, with, for example, many actions to combat heatwaves already covered in our National Heatwave Plan.

As well as preparing for the health impacts of climate change, we are also able to help prevent the worst of these impacts as urgent action to reduce individual and corporate carbon footprints continues. We can then also reap the health benefits of a low-carbon society, with cleaner air and more active, healthier lifestyles to help combat obesity, cancer and heart disease. A win-win we can all engage in.



Professor Dame Sally Davies
Chief Medical Officer
Department of Health

Preface II

Human beings are remarkably adaptable. Over the millennia they have spread across the globe to live in virtually every climate our planet has to offer. But during the coming years humans will have to adapt further still as our climate changes.

Floods across the UK in 2007 and the heatwave of 2003 are a stark illustration of the devastating effects that extreme weather events can have. The heatwave during the summer of 2003 resulted in over 2,000 excess deaths across England and Wales, and the 2007 floods caused by heavy rains led to 13 deaths and more than £3 billion pounds worth of damage to the UK infrastructure. Both of these events are covered in this report.

Though it cannot be said with certainty that these events were a direct consequence of climate change; it is clear that events of this kind are becoming more frequent, and they provide a glimpse of what could become even more severe events in the future. For those in health protection, planning for those climate-related changes and, where possible, adapting to their likely effects, is critical.

This is why this new report is so vital – it is an extensive update to reviews published in 2002 and 2008; and it draws on climate projections for the UK published in 2009 (UKCP09), the UK's first Climate Change Risk Assessment, published in January 2012, and recent evidence published by the Intergovernmental Panel on Climate Chance (IPCC) and other organisations.

It gives those in the health and social care sectors the information they need to make informed decisions about the pressures of climate change on public health. It also reminds policy makers of the need to consider how steps to mitigate the effects of climate change may lead to unintended consequences that need other direct action. And, it identifies areas where more research is needed to provide qualitative and quantitative evidence of the direct and indirect effects of climate change, looking in particular at vulnerable populations and regions.

I would like to take this opportunity to thank all those who have lent their considerable expertise to this report. Glancing at the list of chapter titles illustrates the broad range of experts who have contributed to the report – and I am extremely grateful for the work they have done. In addition, I would like to give special thanks to Sotiris Vardoulakis and Clare Heaviside, the editors of the report, without whose tireless work it would not have been completed.

For many years debate has focused on whether our climate is changing. Today the question is no longer whether the climate is changing, but what can be done. My hope is that this report will become the major reference for helping to mitigate and adapt to the impacts climate change will have on UK public health.

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Reviewers' comments have been extremely valuable in improving this report. However, the final report remains the responsibility of the authors.

The editors would like to acknowledge Dr Louise Newport and Agatha Ferrao (Department of Health) for their support and feedback throughout the preparation of this report. The editors also thank Dr Jill Meara, Dr Giovanni Leonardi, Professor Anthony Kessel and Dr John Cooper (HPA) for their encouragement and support in relation to this publication, and Matthew Pardo (HPA Press Office) for help with Communications.

Executive Summary

The original *Health Effects of Climate Change in the UK* report, published by the Department of Health in 2002 was one of the earliest attempts at quantifying the health effects of climate change for the UK. In 2008, a further update was published by the Department of Health and the Health Protection Agency, based on new climate change projections for the UK. The present report has been prepared on the recommendation of the Department of Health, and provides further evidence and analysis, based on the most recent climate change projections for the UK. Individual chapters have been written and peer-reviewed by a wide range of experts from academia, industry and government as well as within the Health Protection Agency.

The latest UK climate change projections have provided clear indications of the future climate in the UK over the coming decades based on probabilistic outcomes and a range of future emissions scenarios. Where possible, and taking into account the wide range of uncertainties in both climate projections and health effects, quantitative analyses have been performed. For each chapter, the analysis focuses on regional differences in possible future health impacts and discusses vulnerable populations and adaptation effects in the UK. This report follows on from the first UK Climate Change Risk Assessment (published in 2012) and can be used to inform the National Adaptation Programme.

The global scientific consensus is that climate change is unequivocal, with high confidence that the net effect of anthropogenic activity since 1750 has been that of warming the planet. In the UK, temperatures have been increasing by around 0.25^{o}C per decade since the 1960s, summer rainfall has decreased and winter rainfall has increased. Climate projections indicate that annual mean temperatures will be around 2 to 5^{o}C higher than present in the UK by 2080. Heatwaves are likely to become more frequent in the future in the UK. At present, the health burden due to low temperature exceeds that of high temperature. However, heat-related mortality, which is currently around 2,000 premature deaths per year, is projected to increase steeply in the UK throughout the 21st century, from around a 70% increase in the 2020s to around 540% in the 2080s[1]. Southern, central and eastern England appear to be most vulnerable to current and future effects of hot weather compared with other UK regions. Cold is still likely to contribute to the majority of temperature related health effects over the coming decades, although the health burden due to the cold is projected to decline by the 2080s compared with the present day levels. The elderly are more vulnerable to extreme heat and cold than younger people, so future health burdens are likely to be amplified by an ageing population.

The future health impacts of air pollution due to climate change are difficult to project, since air pollution levels are largely controlled by man-made atmospheric emissions of chemicals, as well as weather and climate. We have focused our quantitative assessment on the future impacts of ground level ozone pollution on health for a range of emission scenarios for the 2030s. Ozone is a respiratory irritant strongly affected by the climate, and background levels of ozone are increasing across much of Europe. As well as future emissions scenarios, we have included a temperature sensitivity analysis to test changes in ozone related to increased temperatures in the UK. The extent of health impacts of future ozone levels depends on whether or not a threshold effect for ozone is assumed, and the type of future emissions scenario for ozone precursors and greenhouse gases.

[1] in the absence of any physiological or behavioural adaptation of the population to higher temperatures.

Present day ozone-related mortality is estimated to be up to around 11,900 premature deaths per year[2], and the assessment shows increases of up to between 14,000 and 15,000 for the 2030s depending on future ozone precursor emissions. Increasing temperatures by 5^{o}C is projected to lead to an increased ozone related health burden of 4% (around 500 premature deaths per year) compared with the baseline and assuming no threshold effect, with the south east of England seeing the largest increases.

A new chapter in this report concerns aeroallergens associated with pollen grains and fungal spores in the context of climate change. It is thought that changes in seasonality, temperature and weather patterns in the UK, related to climate change may have an effect on human exposure to pollen grains, as well as affecting the potency of aeroallergens. Existing allergy sufferers may suffer from longer- pollen seasons and more rapid symptom development. There is also likely to be a longer term indirect effect on the UK population through changes in plant and fungal distributions. This chapter reviews links between aeroallergens and the climate, and motivates the need for further research on the likely effects of climate change on the health impacts of pollen exposure in future.

Effects of climate change in the indoor environment should not be overlooked, as the population of the UK typically spends 90% of their time indoors. Another new chapter discusses the way in which climate change may exacerbate health risks associated with building overheating, indoor air pollution, flood damage and water and biological contamination of buildings. Hospitals, health centres and care homes may be adversely affected by high temperatures during heatwaves and flooding. The potential health effects of climate change adaptation and mitigation options are discussed in this context.

Climate change may have an effect on ambient levels of Ultraviolet (UV) radiation in the UK, but human exposure to UV radiation is also strongly influenced by lifestyle and behaviour. For example, warmer summers in the UK may increase population exposure to UV radiation due to increased time spent outdoors. This could increase health risks associated with UV including some skin cancers. However, moderate exposure to the sun is beneficial for the production of vitamin D. Climate change is also thought to be delaying the recovery of the stratospheric ozone layer, which affects the amount of UV radiation reaching the surface of the Earth.

The effects of climate change on floods and droughts have been investigated in terms of health impact, although this is difficult to quantify. Understanding of the health implications of flooding, particularly impacts on mental health and impacts from disruption to critical supplies of utilities such as electricity and water has increased in recent years, but knowledge gaps still remain. It is likely that climate change will increase river and coastal flood risk in the coming decades, particularly in South Wales, Northwest Scotland, East Anglia, the Thames Estuary and Yorkshire and Humberside regions.

Vector-borne diseases are influenced in complex ways by the climate, land use changes and human activities, and as such it is difficult to make quantitative predictions of future changes due to climate change. However, it is likely that the range, activity and vector potential of many ticks and mosquitoes will increase across the UK by the 2080s. There is also the potential for introduction of exotic species and pathogens. Potential drivers of these changes include milder winters and warmer

[2] assuming that there is no threshold effect for ozone.

summers. Climate change adaptation strategies such as those to mitigate flooding and sea level rise may have more effect on vector-borne disease exposure than the direct effects of climate change.

Climate change can influence the incidence of certain water and food-borne diseases, which show seasonal variation. Climate change is also likely to affect the risk from water and food-borne disease through changes in human behaviour associated, for example, with food hygiene. Increased temperature will allow pathogens such as Salmonella to grow more readily in food. However, interventions to prevent this are likely to have more of an effect in reducing numbers of cases than climate change will have on increasing them. Climate change may also lead to reductions in the availability of certain food groups, which may lead to reductions in the nutritional quality of dietary intake in some population groups.

The final chapter of this report discusses the health co-benefits of measures to reduce greenhouse gas emissions. Examples include a decline in air pollution from measures to reduce anthropogenic greenhouse gas emissions (e.g. from coal combustion), increased physical activity as a result of reduced car use in urban centres, and health benefits from reduced dietary saturated fat consumption from animal products. When taking into account these types of health co-benefits, climate change mitigation policies become more attractive. However, certain climate change mitigation policies, such as sealing buildings to increase energy efficiency, may lead to increased exposure to indoor air pollution (unless adequate ventilation is maintained). This highlights the need for climate change mitigation policies to be subject to health impact assessment.

Public health recommendations and research needs have been identified for each of the specific health effects of climate change in the UK covered in this report.

Scope and Background

Sotiris Vardoulakis (Health Protection Agency) and Clare Heaviside (Health Protection Agency)

This is the third report on the health effects of climate change in the UK published by the Health Protection Agency in partnership with the Department of Health. The Health Protection Agency established a programme on Climate Change and Extreme Events in 2010 with the aim of enabling the UK to respond to the public health effects of climate change by delivering evidence-based effective interventions. A workshop on "Climate Change and Health Protection: Looking Forward" with key stakeholders was organised by the HPA in October 2010 to inform this process (HPA, 2010).

This report has been written by a number of experts from the Health Protection Agency and other UK academic and research institutions covering a range of disciplines related to climate change and public health. Each chapter has also been independently peer-reviewed by at least three experts. Although it is an update of two earlier reports (DH, 2002; HPA, 2008), it can be used as a stand-alone document providing a comprehensive review, analysis and discussion of the currently available scientific evidence on climate-sensitive environmental stressors, population exposure patterns, exposure-response relationships and associated health impacts in the UK.

Much of the information on methods that was included in the original report (DH, 2002) remains valid and therefore has not been repeated here. However, new evidence on direct and indirect effects of climate change on human health has become available through the first UK Climate Change Risk Assessment (a requirement of the Climate Change Act 2008) released in January 2012 (DEFRA, 2012), and other independent research studies. The main focus of the present report is on public health, although implications for specific health services are briefly discussed in some of the chapters. A comprehensive assessment of the risks of climate change for the UK health sector, including public health and health services was presented in the first UK Climate Change Risk Assessment (Hames and Vardoulakis, 2012). The present report does not attempt to scope or prioritise health effects; it rather investigates a predefined list of impacts in detail, providing a summary of relevant health outcomes, public health recommendations and research needs. The analyses included in this report are based on the latest available climate projections for the UK released in 2009 (UKCP09: ukclimateprojections.defra.gov.uk), which have superseded earlier projections published in 2002. The current scientific evidence on climate change in the UK, and the climate projections used in this report are discussed in Chapter 1.

Chapters 2-4 and 6-9 focus on the specific health effects of climate change in relation to temperature, air pollution, aeroallergens (included as a separate chapter for the first time), floods, vector-borne diseases, water and food-borne diseases, and UV radiation exposure. The following aspects are also discussed in each chapter as far as possible: (a) the geographical variability of health impacts (are any UK regions at higher risk?); (b) vulnerable populations (are any population sub-groups at higher risk?); (c) adaptation to climate change in relation to the health impacts identified (what is the extent of physiological, behavioural and planned adaptation that may occur in the future?)

Two more new chapters have been included: Chapter 5 which reviews the impacts of climate change in the indoor environment, including the trade-offs between indoor air quality and energy efficiency and other climate change mitigation and adaptation measures; and Chapter 10, which discusses the

health co-benefits from policies to reduce greenhouse gas emissions with examples from the household energy, urban transport, electricity generation, and food and agriculture sectors. Detailed assessments of climate related health risks and benefits from mitigation policies in these sectors were reported in the LANCET series "Public health benefits of strategies to reduce greenhouse-gas emissions" (Haines *et al.*, 2009). Although it was not possible to provide full quantitative estimates of all impacts covered mainly due to the lack of reliable exposure-response relationships, semi-quantitative or qualitative estimates are provided. Formal quantitative health impact assessment methods were used to estimate the effects of current and future temperatures (Chapter 2) and air pollution (Chapter 3) on population health under different scenarios. In these two chapters, population growth at regional level was also explicitly taken into account. In chapters where a full quantitative analysis was not possible, baseline incidence rates (e.g. cause specific mortality and hospitalisation rates) are reported to give an indication of the number of people that could be affected by climate-related diseases. Uncertainties associated with impact estimates are also discussed and quantified where possible.

It is recognised that climate change may have a wider range of indirect effects on health, aggravating on certain occasions existing public health problems related to water availability, nutrition, mental health and well-being, displacement and migration, and health equity. For example, ground level ozone, which is sensitive to changes in climate, has direct effects on respiratory health (Chapter 3) but is also responsible for reducing crop yields affecting food security (UNEP, 2011). Increasing temperature and CO_2 levels in the atmosphere and declining precipitation can also affect agricultural production (Brown and Funk, 2008). Interactions between climate change and the global food system have been discussed in the Foresight (2011a) report "The Future of Food and Farming: Challenges and choices for global sustainability". The present report focuses mainly on the direct health effects, although indirect impacts are also acknowledged and discussed to some extent (e.g. Chapter 7 on floods). Wider impacts of climate change related to global conflicts and population displacement are covered in the Foresight (2011b) report "International Dimensions of Climate Change".

Finally, the target audience of this report is health practitioners, managers and decision-makers who may not have a detailed technical knowledge of the topics covered. Therefore, explanatory notes are provided to help the reader, and in some cases technical information is placed in appendices or provided in the form of references for further reading.

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Contents

1 Climate change in the UK: current evidence and projections

Clare Heaviside, Health Protection Agency
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Summary

- The scientific consensus is that warming of the climate system is unequivocal and there is very high confidence that the net effect of anthropogenic activity since 1750 has led to warming of the climate.
- The most recent decade (2002-2011) was warmer than any previous decade on record (e.g. 1992-2001, 1982-1991).
- Natural variability in the climate system means that weather can vary greatly over space and time, for example a global warming trend does not rule out exceptionally cold winters locally.
- In the UK, temperatures have been increasing since preindustrial times, and at a rate of around 0.25^{o}C per decade since the 1960s.
- There is no clear trend in annual mean rainfall in the UK, but over England and Wales summer rainfall has decreased and winter rainfall has increased since pre-industrial times.
- The UKCP09 climate projections use a probabilistic rather than deterministic approach for their outcomes, which goes some way to address uncertainty due to natural climate variability and the uncertainty associated with modelling the complexities of the climate system.
- UKCP09 projections indicate increases in annual mean temperatures of around 2 to 5^{o}C under a medium emissions scenario for the UK by 2080 depending on geography, with the largest increases expected in the south of the UK and the smallest in the north.
- Projected precipitation levels vary geographically and by season, with central estimates showing winter rainfall increasing in general, and summer rainfall decreasing.
- Heatwaves are likely to become more frequent in the UK in the future due to anthropogenic influences.

Research needs

- The continued increase in spatial resolution of climate models may help to increase the reliability of climate change projections in the future.
- Improvements in the modelling of extreme events would increase understanding of potential health impacts.
- Improvements to regional modelling of urban centres may provide more realistic projections of local climate in cities, under climate change conditions.

1.1 Introduction

This report provides an update to the 'Health Effects of Climate Change in the UK' report (HPA, 2008), which was based on an earlier Department of Health report (DH, 2002). It has been prepared in response to the publication of the UKCP09 climate projections (Murphy *et al.*, 2009), which differ from previous projections by presenting a probabilistic approach to future climate that takes into account uncertainty due to natural climate variability, our incomplete understanding of the climate system, and its imperfect representation in climate models.

The most recent publication from the Intergovernmental Panel on Climate Change (IPCC), the Fourth Assessment Report Summary for Policymakers states:

"Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level" (IPCC, 2007, page 5).

The report also states that there is:

"… very high confidence that the global average net effect of human activities since 1750 has been one of warming." (IPCC, 2007, page 3).

The global temperature record reveals that the 13 hottest years have all occurred in the 15 years between 1997 and 2011 according to the World Meteorological Office (WMO, 2011). Global annual mean temperatures are heavily influenced by the El Niño Southern Oscillation (ENSO), which is associated with increased ocean temperatures (during the El Niño phase) or decreased ocean temperatures (during the La Niña phase) in the tropical Pacific. A strong La Niña event meant that temperatures in 2011 were not as high as in 2010, which was the 2nd hottest year ever. However, even with one of the strongest La Niña events for 60 years, 2011 is still the 11th warmest year on record. The overall hottest year was 1998, which coincided with a record breaking El Niño. Figure 1.1 shows globally averaged temperature anomalies[1] from the 1961-1990 mean, from the period 1850 to the present day. Even accounting for inter-annual variability, there is a clear upward trend in the temperature anomalies since pre-industrial times.

Climate is defined as a long-term average of meteorological conditions (i.e. weather) and as such can not easily be experienced directly. Climate variability means that the weather can vary greatly over geographical distances or time. For instance, even though 2010 was a record breaking year in terms of global mean temperature, the UK experienced a particularly cold winter (Seager *et al.*, 2010). Climate change manifests itself in a change in average conditions as well as changes in the frequency and severity of extreme weather events (e.g. heatwaves, flooding and cold winters). In a changing climate it is likely that previous extreme records (e.g., high temperatures) will be more frequently exceeded (Rahmstorf and Coumou, 2011).

In the last few years, significant progress has been made to assess the influence of human activities on the risk of the occurrence of extreme events, for example, heatwaves (Stott *et al.*, 2004). There were high numbers of excess deaths associated with the European heatwave during August 2003: in

[1] Global temperature anomalies represent global mean temperature relative to a baseline period. In this case the baseline period is the average temperature for 1961-1990.

England and Wales, approximately 2,000 excess deaths were recorded (Johnson *et al.*, 2004), and France recorded approximately 15,000 (Fouillet *et al.*, 2006). It has been suggested that it is 90% likely that human activity has doubled the risk of the occurrence of a heatwave in Europe of the same order as the one in 2003 (Stott *et al.*, 2004) and that we can expect more frequent heatwaves in the future (Jones *et al.*, 2008). Similar studies have focused on flood risk in the UK (Pall *et al.*, 2011) and extremes of intense precipitation globally (Min *et al.*, 2011). A recent special report by the IPCC on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation provides a comprehensive assessment of the role of climate change in altering characteristics of extreme events and assesses options to reduce exposure and vulnerability (IPCC, 2012).

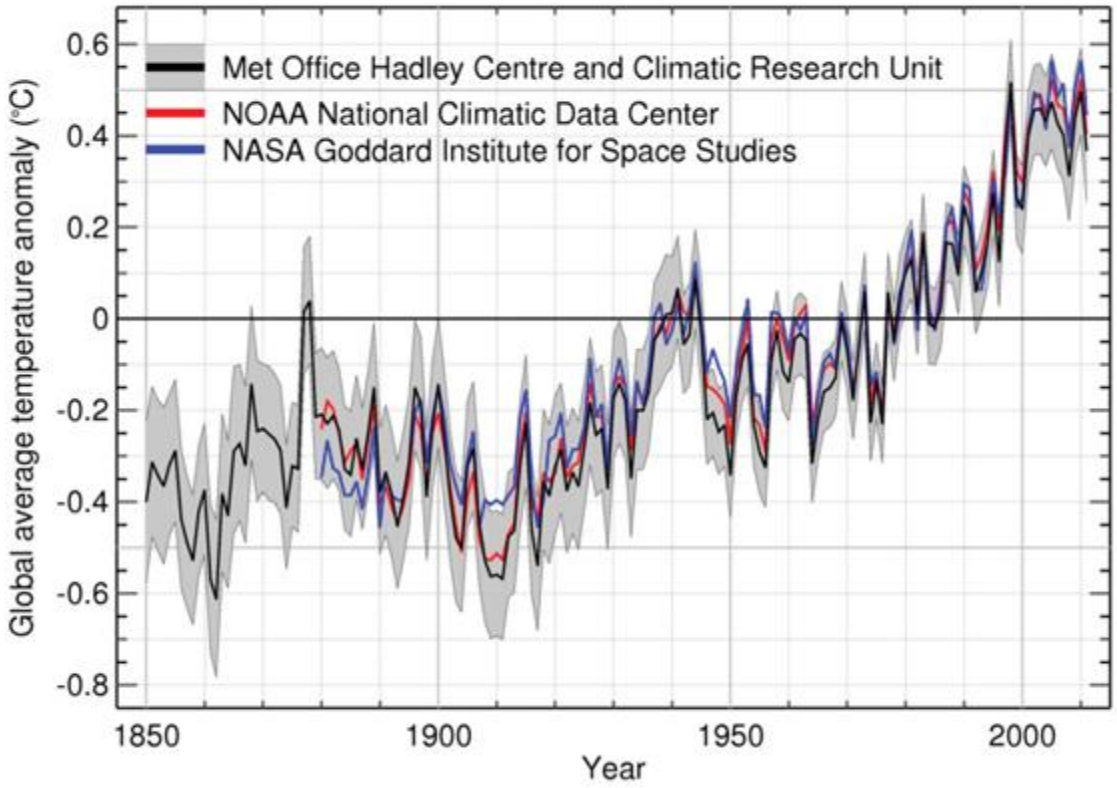

Figure 1.1. Global average temperature anomaly (from 1960-1991) from 1850 to 2011, based on 3 observational datasets. (Source: Met Office http://www.metoffice.gov.uk/media/image/g/8/temp-anomaly-large.jpg).

This chapter discusses the scientific consensus on climate change and investigates historical evidence for climatic trends globally and for the UK. The basis of the UKCP09 climate projections from the UK Climate Impacts Programme is explained and some key predictions for future UK climate based on UKCP09 are discussed.

1.2 Observed trends in UK climate

1.2.1 Mean temperature

The Central England Temperature (CET) record provides a series of surface air temperature measurements for a roughly triangular area of England enclosed by London, Lancashire and Bristol.

The observations date back to 1659, with daily data available since 1772 (Parker *et al.*, 1992). Figure 1.2 shows the annual mean CET temperature anomalies relative to the 1961-1990 average[2]. There is an increasing trend in the temperature anomalies, and there has been a series of warm years since the late 1980s. 2006 is currently the warmest year on record in the CET.

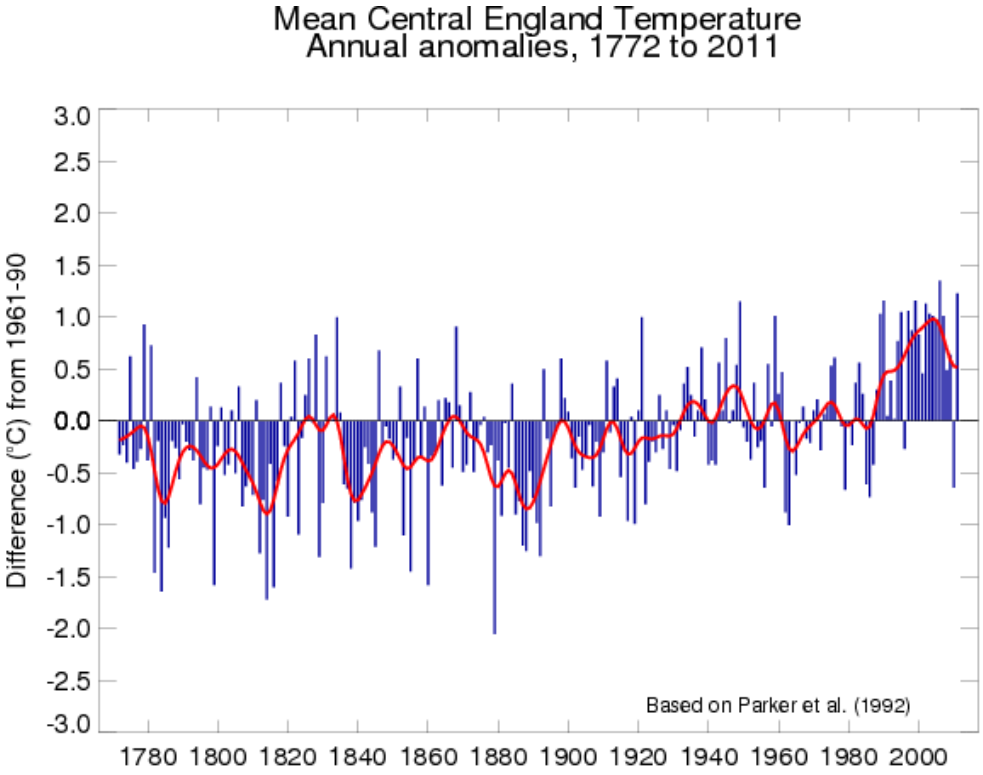

Figure 1.2. Annual CET anomalies relative to the 1961-1990 mean. The red line represents a 10 year running mean. (Source: Met Office http://www.metoffice.gov.uk/hadobs/hadcet/).

As part of a recent series of country-specific reports, observations, projections and a range of impacts of climate for the UK have been reported (Met Office, 2011). Observations show a warming over the UK since 1960, which is greater during summer (0.28°C per decade) compared with winter (0.23°C per decade) according to CRUTEM3 data, a collaborative product of the Met Office and the University of East Anglia (Brohan *et al.*, 2006).

1.2.2 Changes in frequency of hot and cold days

As well as changes in mean temperatures, there have been decreasing numbers of cool, and increasing numbers of warm, days and nights between 1960 and 2010. According to the CET, the number of cold days (mean temperature below 0 °C) has decreased from nearly 20 per year in the late 18th century to fewer than 10 per year currently (Figure 1.3). However, very high variability in the number of cold days exists – for example, compare the winters of 2009 and 2010 with 2005 and 2006.

[2] taken from the Hadley Centre HadCET observations dataset (http://www.metoffice.gov.uk/hadobs/hadcet/)

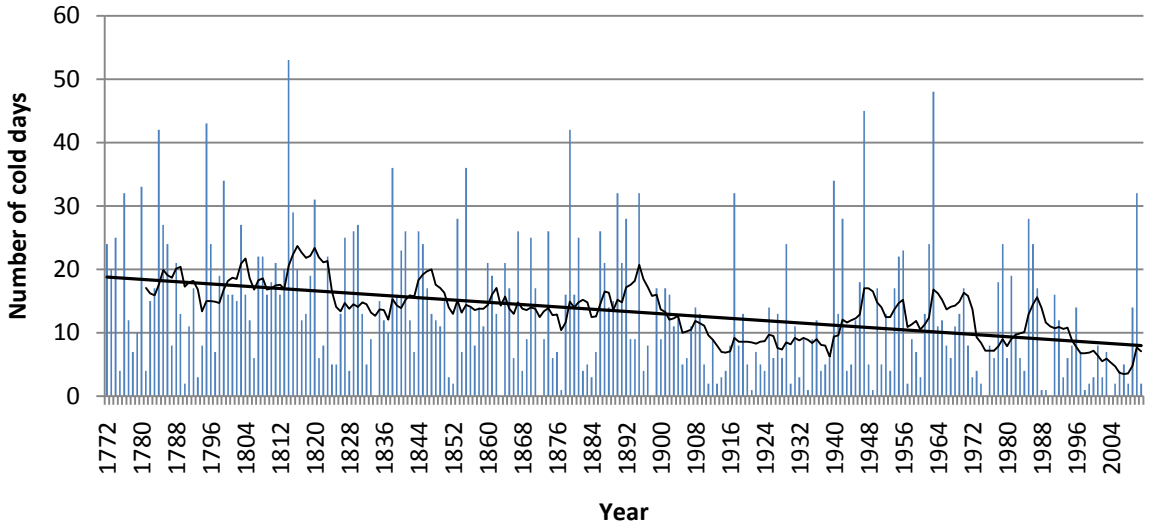

Figure 1.3. Number of cold days (with mean temperature below 0°C) per year calculated from daily mean CET from 1772-2011. The straight black line shows the linear trend and the other black line shows the 10-year moving average.

According to the CET, the number of hot days (daily mean temperature above 20 °C) has increased from fewer than 2 per year in the late 18th century to nearly 5 per year in the present climate. As with cold days, large variability exists, with some years exhibiting over 10 hot days (for example, 1995 had 26 hot days and 2006 had 19 hot days).

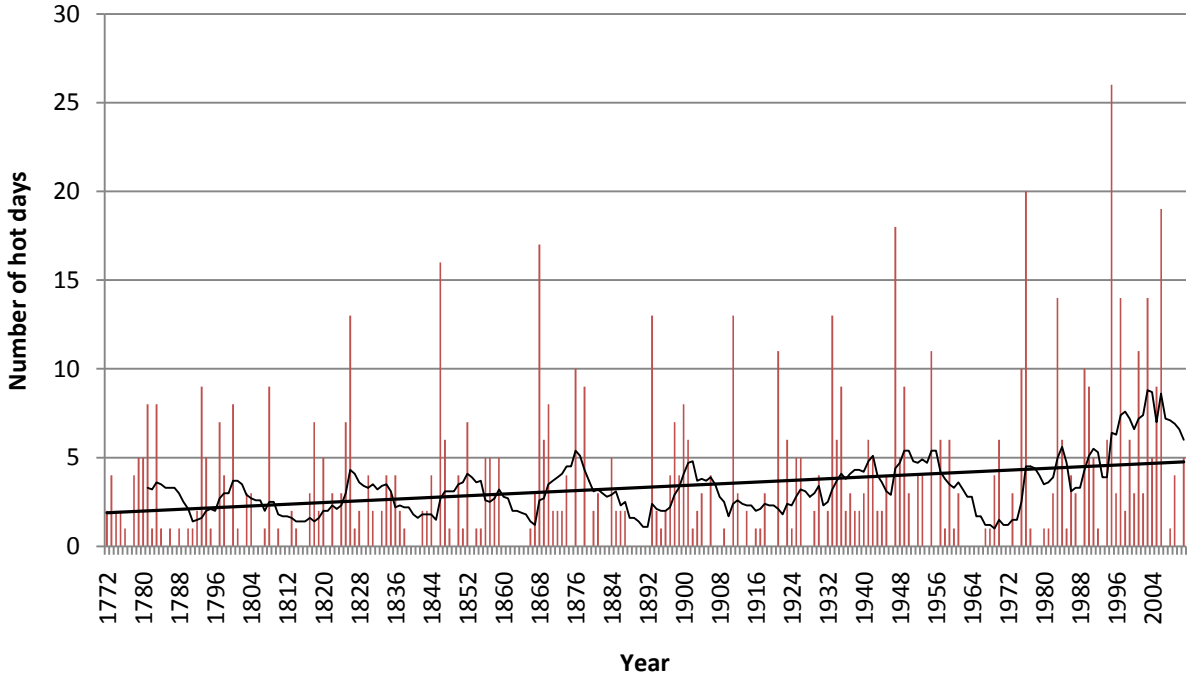

Figure 1.4. Number of hot days (with mean temperature over 20°C) per year from daily mean CET from 1772-2011. The straight black line shows the linear trend and the other black line shows the 10-year moving average.

1.2.3 Trends in rainfall

The UKCIP trends report (Jenkins *et al.*, 2008) states that rainfall over the UK shows large variations between years, with no overall *annual* trend over England and Wales since records began in 1766. Seasonal rainfall is highly variable, but has decreased during summer and increased during winter, although there has been little change in winter rainfall over the last 50 years. In terms of extreme rainfall, over a similar time-scale, all regions of the UK have seen increases in the contribution of heavy rainfall events for winter, and all regions apart from north east England and western Scotland have seen decreases in heavy rainfall events during summer (Mauraun *et al.,* 2008). However, interannual variability means that droughts due to low rainfall in winter can still occur, for example, low rainfall over winter 2011/12 led to widespread water shortages in the UK in spring 2012.

Figure 1.5 shows percentage changes in seasonal precipitation, highlighting a general increase in winter and a decrease in summer precipitation for England and Wales since the late 1800s, based on the England and Wales Precipitation series (Alexander and Jones, 2001) which dates back to 1776.[3] Autumn and winter tend to be the wettest seasons in the UK, with rainfall associated with frontal systems brought in mainly from westerly airflows across the Atlantic Ocean. In the summer, much of the rainfall comes from heavy convective rain showers. Although flooding most often occurs during winter, June 2007 saw major flooding across much of the UK. With increases in air temperature, convective storms, especially in the southern parts of the UK which are closest to the continent are likely to become more frequent (Fowler *et al.*, 2005).

In winter, soils tend to contain large amounts of moisture, as this period tends to be wet and evaporation is reduced owing to the low temperatures. Rain falling onto such saturated soils can not be absorbed and hence heavy rain events in winter can lead to flooding. However dry soils in summer can also cause increased runoff and summer flooding, as the soils cannot absorb the rainfall quickly and so most of the rainfall flows away. Under summer drought conditions, the soil contains very little moisture which could partly offset, through evaporation, high temperatures; hence, heatwaves are more likely to occur under such circumstances (Fischer *et al.*, 2007).

[3] The series is held by the Met Office: (http://www.metoffice.gov.uk/hadobs/hadukp/).

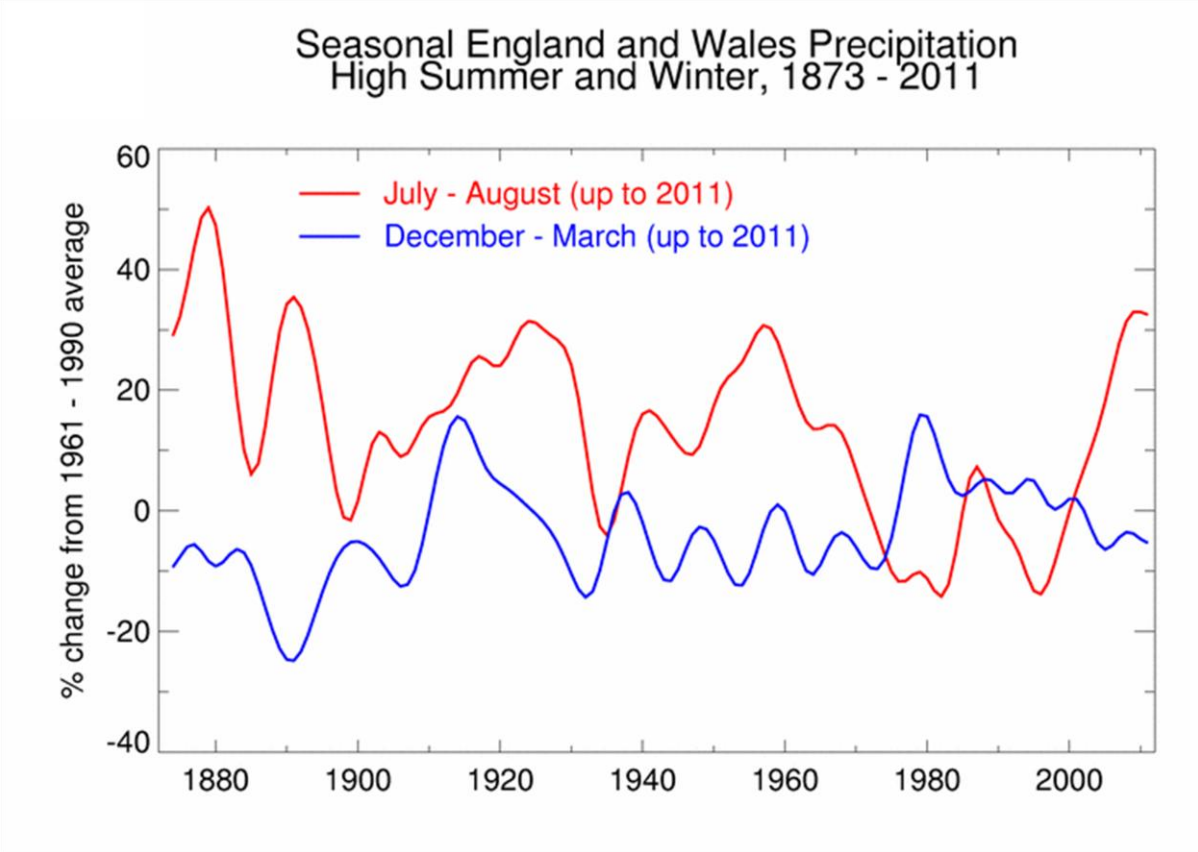

Figure 1.5. Long-term smoothed seasonal precipitation changes (with respect to 1961-90 climatology) for summer (red line) and winter (blue line). (Source: Met Office http://www.metoffice.gov.uk/hadobs/indicators/reports/EWP_seasonal1.gif).

1.3 Future climate change in the UK: the UKCP09 projections

1.3.1 The UKCP09 projections and changes since UKCIP02

The UKCP09 climate projections are the latest in a series of climate change projections for the UK presented by the UK Climate Impacts Programme (UKCIP). The first set of projections was published in 1991, and UKCP09 represent the 5th generation of projections. The first version of 'Climate Change and Health in the UK' (DH, 2002) addressed the possible impacts of climate change on health in the UK based on the UKCIP98 climate change projections. Since then, an updated report was published in 2008 (HPA, 2008) which used the UKCIP02 projections (Hulme *et al.*, 2002).

The latest UKCP09 projections are based on 3 possible future emissions scenarios: high, medium and low, which correspond to the Special Report on Emissions Scenarios (SRES) scenarios A1FI, A1B and B1, respectively that are among the scenarios used for the IPCC (Nakicenovic *et al.*, 2000). The main difference of the UKCP09 projections compared with the UKCIP02 projections is that they are probabilistic, rather than deterministic. This means that a range of climate change outcomes are taken into account, and probability values are ascribed to a range of projections rather than a single outcome. The projections are available at 25 km square grid cells across the UK (the UKCIP02 projections were at 50 km resolution).

1.3.2 Probabilistic projections and the representation of uncertainty in UKCP09

For UKCIP02, the climate model was run only once, to give a deterministic result. The UKCP09 projections (Murphy *et al*., 2009) were constructed using nearly 300 simulations made with the UK Met Office Global Climate Model HadSM3. This model is very similar to the global climate model HadCM3 (Gordon *et al*., 2000) except that it uses a 'slab' ocean model which only includes the near-surface of the ocean and uses prescribed mixing terms. A large number of different parameters within this model were perturbed away from their standard values to create many different variants of the HadSM3 model, and each variant was used to simulate climate for the period 1950 to 2100. Eleven additional simulations were made using the regional climate model HadRM3 and a system was built to establish the relationship between meteorological data produced by the regional and global climate models. The quality of each of the 300 model runs is assessed by how well it simulates recent climate. The weighting of each model version is then altered based on the outcome from this test which means that outcomes are produced as probability density functions (PDFs).

In order to include models apart from the Met Office global climate model in the projections, another 12 climate model single runs were included in UKCP09. These single runs from different climate models such as those from the Coupled Model Intercomparison Project, CMIP-3 (Covey *et al.*, 2003; Meehl *et al.*, 2005) can increase the range of output and modify the shape of the PDF.

Outcomes are then provided based on probability of occurrence, from 1 to 99% for each of the 3 emissions scenarios, rather than a single deterministic projection for each emission scenario. For example, the 10% and 90% probability levels indicate there is only a 10% chance that future conditions will be below the 10% estimate or above the 90% estimate and the 50% level represents a central estimate. The range of probability reflects natural climate variability and model uncertainty, whereas the uncertainty in future emissions is reflected in the three discrete scenarios used. The probabilistic nature of the projections provides information on the estimated relative likelihood of the smallest or largest changes in climate variables we might expect in the future.

It is not straightforward to directly compare the 2002 and 2009 projections, since the UKCP09 covers a range of probabilities and UKCIP02 has a single deterministic output, and each set of projections is based on different emissions scenarios. However, a comparison of seasonal mean temperature changes for the 2080s between the UKCIP02 and UKCP09 projections is shown in Figure 1.6. The high emissions scenario used was the same in both projections. The UKCIP02 projections are compared with the 10, 50 and 90% probability levels of UKCP09. For the summer and winter temperatures, the UKCIP02 projections are similar to the central estimate from the UKCP09 projections. However, a comparison of rainfall changes for summer shows that the UKCIP02 projections lie at the extreme dry end of the UKCP09 projections, and closely resemble the changes at the 10% probability level.

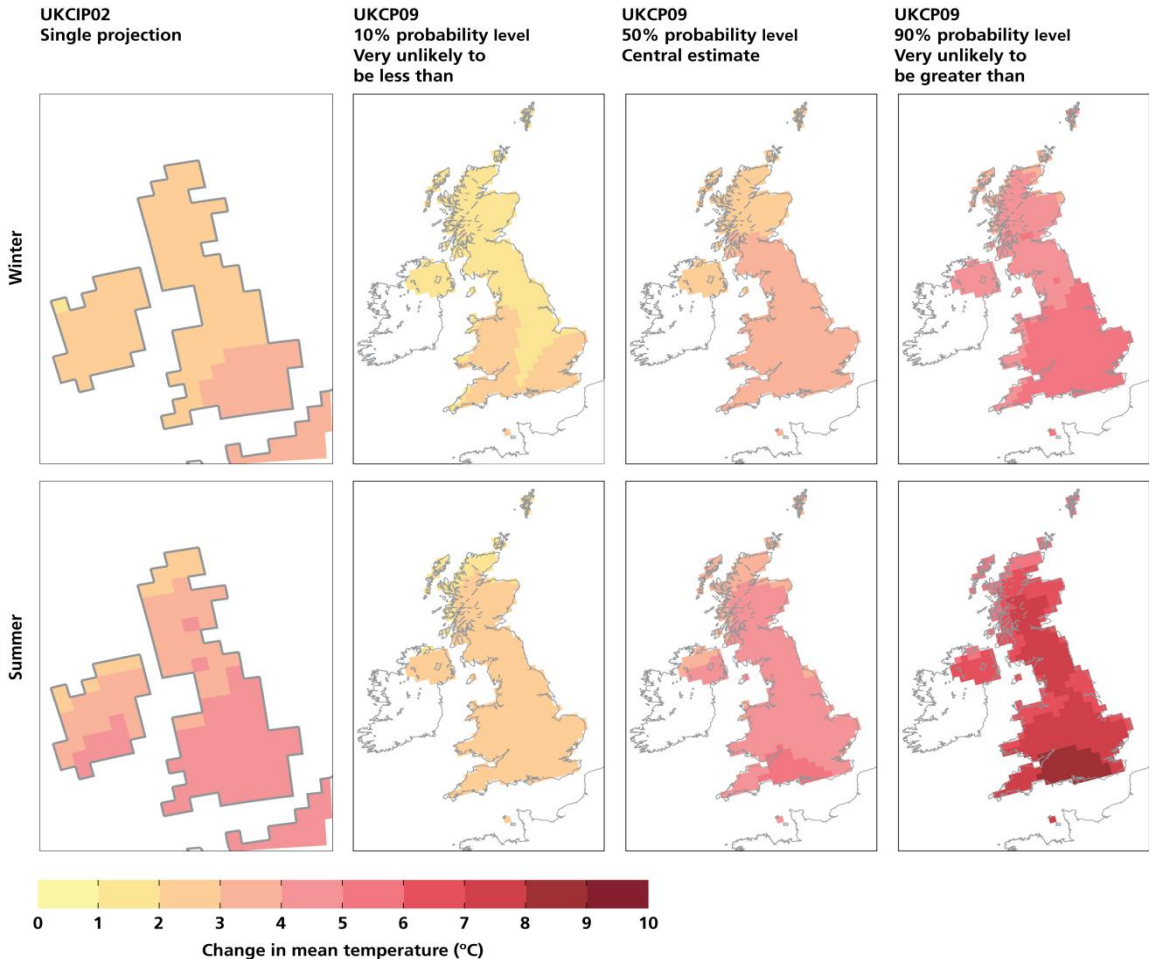

Figure 1.6. A comparison of changes in seasonal mean temperature in summer and winter for the 2080s under a high emissions scenario for UKCIP02 (left) and UKCP09 for 10%, 50% and 90% probability levels. (Source: Jenkins *et al*. 2009).

1.3.3 What is not included in the UKCP09 projections

The global thermohaline circulation or meridional overturning circulation is an ocean current which is driven by gradients in temperature and salinity. It is considered very unlikely that the meridional overturning circulation in the North Atlantic Ocean (of which the Gulf Stream is a component) will change abruptly or 'switch off' within the next century (IPCC, 2007) and this eventuality is therefore not considered in the UKCP09 projections. However, a gradual weakening of the global thermohaline circulation, associated with increased greenhouse gases, and the consequent melting of arctic ice is thought to be more likely (IPCC, 2007) and this effect is included in UKCP09 projections (Jenkins *et al.*, 2009).

The Urban Heat Island (UHI) effect describes the effect that cities and urban areas have on local temperatures (Oke, 1982). Due to the properties of urban building materials, heat sources from human activity, reduced sky-view factor and a lack of moisture in urban areas, temperatures are often a few degrees (around 5-10^{o}C) higher in urban areas than in surrounding countryside, particularly at night (Bohnenstengel *et al.*, 2011). This can have an important effect on the health of urban populations, especially during heat waves. The surface scheme used in the regional climate

model does not include the influence of urban surfaces on climate, and heat storage and release by urban materials is not modelled, since most urban areas are small compared to the model's grid cell size (with the exception of London). Therefore the UKCP09 projections do not include urban effects on climate. It is however possible to estimate future temperatures in urban areas by using baseline temperatures for urban areas and adding the future change in temperature projected by UKCP09 (Jenkins *et al.*, 2009). The Hadley Centre has run some regional climate model simulations exploring the effect of the Urban Heat Island on climate (e.g. McCarthy *et al.,* 2011).

1.3.4 Future climate change projections for the UK

The UKCP09 climate projections provide a set of estimates of changes in temperature, rainfall, and many other meteorological variables for the UK during the 21st century, along with the probability of a range of outcomes. The projections are grouped into seven overlapping 30 year periods, beginning with the 2020s (2010 – 2039) and ending with the 2080s (2070 – 2099). The variables in the projections include a range of temperature metrics such as average and extreme values, precipitation, specific and relative humidity, total cloud, sea level pressure, surface long wave and short wave radiation flux and total downward short wave flux. Here we present temperature and precipitation projections, and discuss possible sea level rise, incoming shortwave radiation at the surface, total cloud amount and relative humidity since these have the most direct relevance to possible health impacts.

Change in seasonal mean, maximum and minimum temperatures

Changes in winter and summer mean temperature have been projected for the 2080s under a medium emissions scenario at a range of 3 different probabilities: 10%, 50% and 90%, where 50% is the central probability estimate and the outside estimates represent the upper and lower 10% probabilities. Summer mean temperatures are expected to increase more than winter temperatures, and southern England temperatures are expected to increase more than those of Scotland and the North. For the central estimate (middle panels), projected temperature increases range from about 2 to 5^{o}C (Figure 1.7).

Furthermore, projected changes in winter mean minimum and summer mean maximum temperatures have been calculated. For a medium emissions scenario, we can expect an increase in winter minimum temperatures of up to 4^{o}C (less further north). However, for summer, the increase in maximum temperature is likely to be up to 6^{o}C based on the same scenario. Again, this reflects the increases in summer temperatures being larger than increases in winter temperatures (Figure 1.8).

Changes in precipitation

Figure 1.9 illustrates the geographical and seasonal variability in precipitation projected for the 2080s under a medium emissions scenario. For example, the annual mean central estimate shows changes within a few percent of zero for the majority of the UK (Jenkins *et al.*, 2009). When looking at seasonal changes, different patterns emerge. For winter mean precipitation, there is a general increase over most of the UK of up to about 30% (using the central estimate), with slightly smaller increases over higher ground (Figure 1.9). In contrast, summer mean precipitation shows decreases of a similar magnitude to the winter mean increases at the 50% probability level. However, note that at the 90% probability level, the projections for summer mean precipitation show a small increase in

most areas. Projections for changes in the wettest days (99th percentile of daily precipitation rate) in winter range from zero in Scotland to up to +29% in England and changes in the wettest days in summer range from -9% in England and up to +25% in Scotland, for the 2080s under a medium emissions scenario (Jenkins *et al.*, 2009).

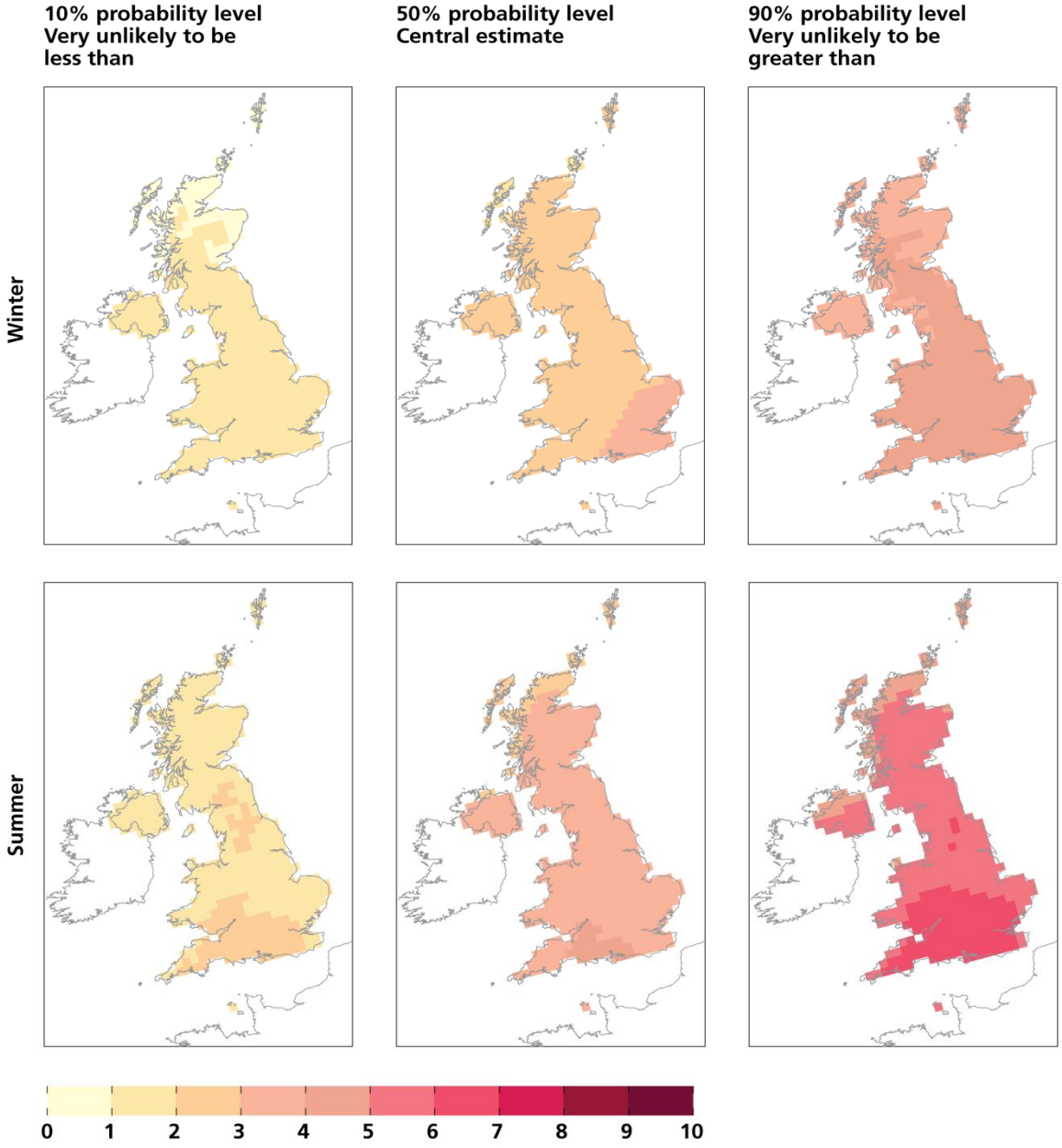

Figure 1.7. Change in winter mean temperature (upper) and summer mean temperature (lower) under a medium emissions scenario for the 2080s in ^{o}C. (Source: Jenkins *et al.*, 2009).

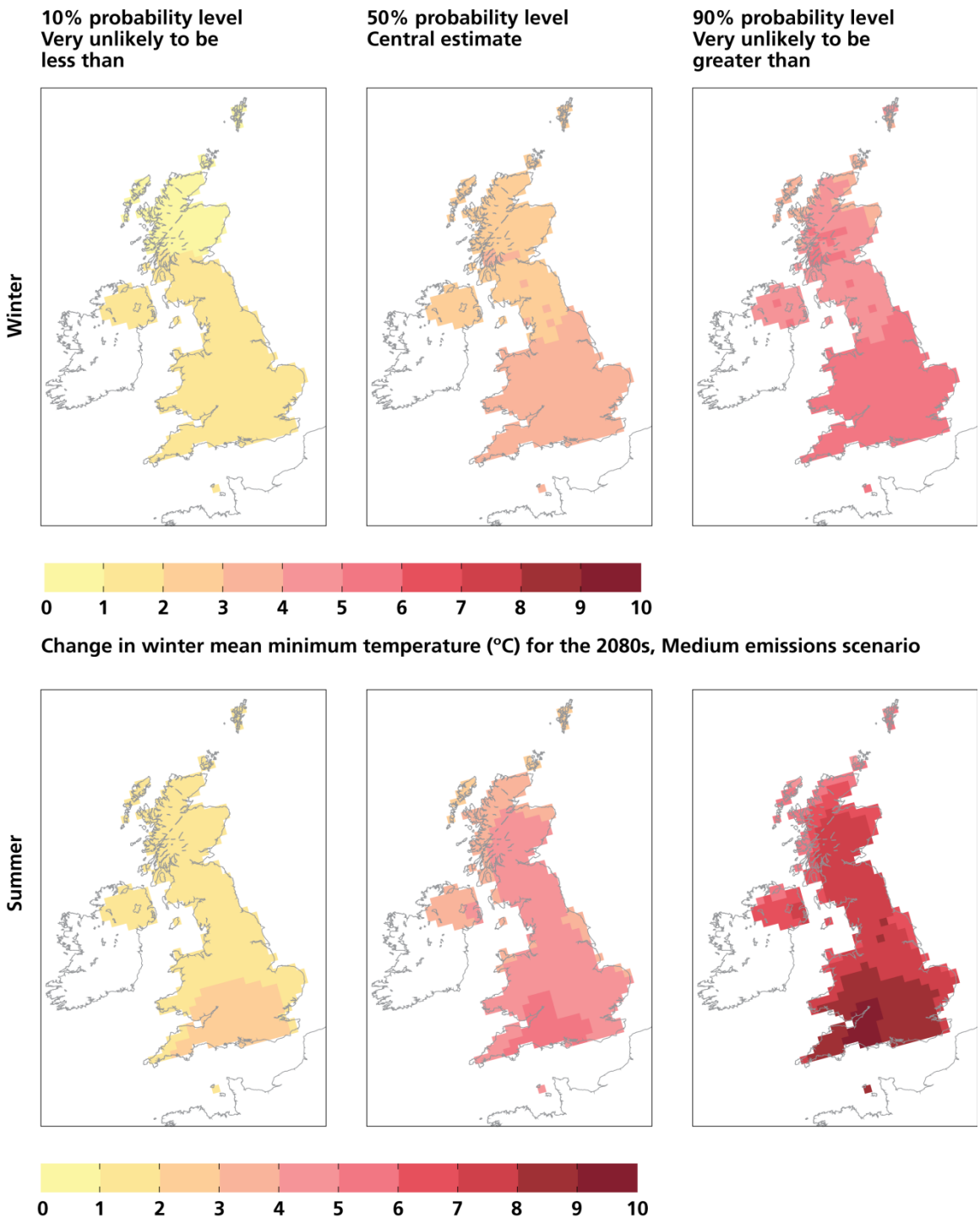

Figure 1.8. Change in winter mean minimum temperature (upper) and summer mean maximum temperature (lower) for the 2080s under a medium emissions scenario. (Source: Jenkins *et al.*, 2009).

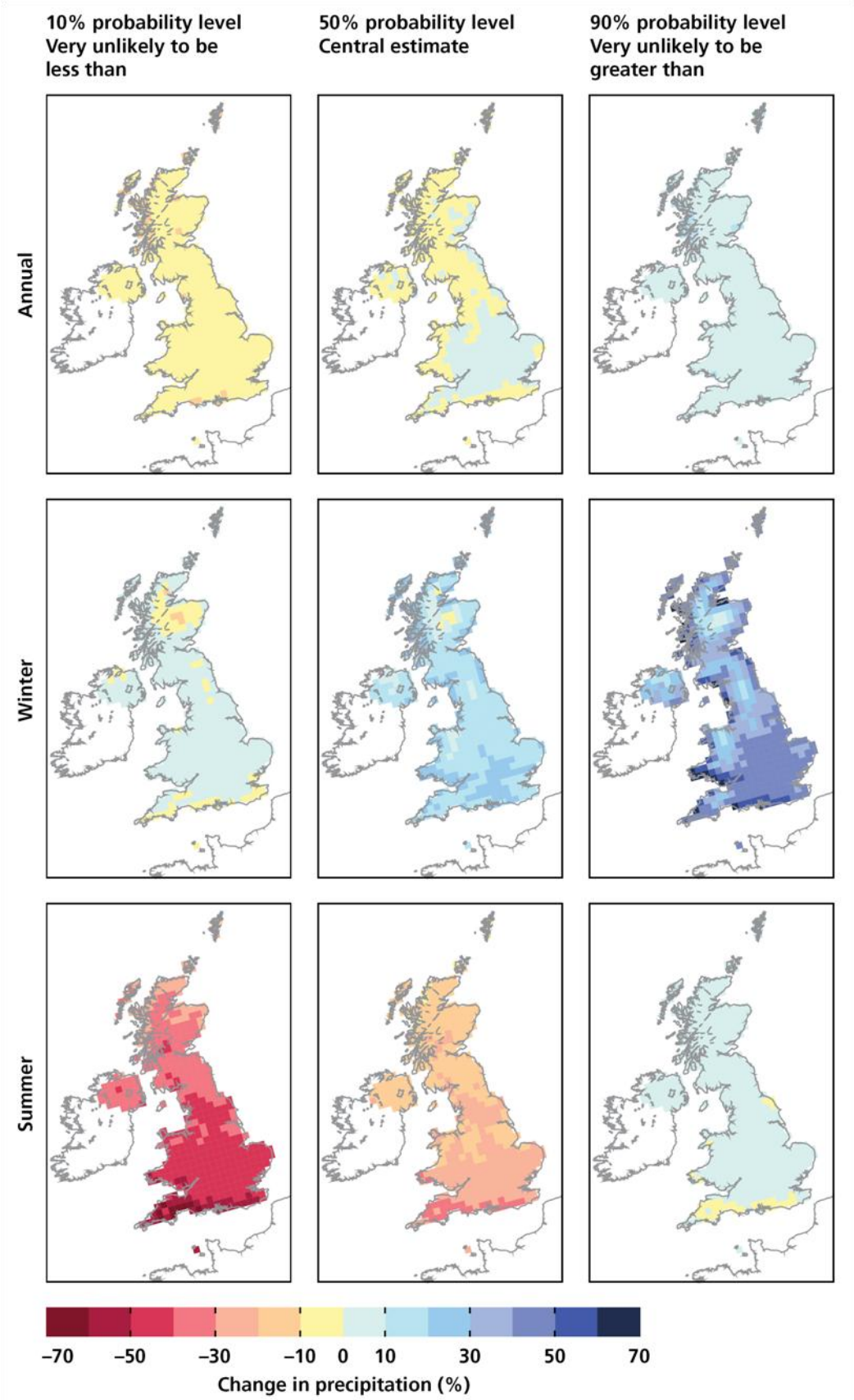

Figure 1.9. Change in annual, winter and summer precipitation for the 2080s under a medium emissions scenario. (Source: Jenkins *et al*., 2009).

Sea level rise

Sea level rise is driven mainly by thermal expansion of the upper layer of the ocean, together with melting of ice on land and smaller contributions from other sources. The sea level around the UK, corrected for land movement, rose by about 1 mm per year during the 20th century. Since the 1990s the rate has accelerated. Observations around the English Channel show rises in extreme sea levels at all 16 sites studied, at around the same rate as the observed rise in mean sea level (Haigh *et al.*, 2011). The same study used UKCP09 projections for low, medium and high emissions scenarios and suggested that by 2100, the frequency of extreme high sea level events along the south coast of England would increase by factors of 10, 100 and 1800, respectively. There is a lively scientific debate about how much global sea level will change in the course of the 21st century and some researchers argue that we could see more than double the values quoted in the latest IPCC (2007) report, depending on factors such as ice sheet dynamics which were not well understood when the IPCC Fourth Assessment Report was published (Rahmstorf, 2007; Pfeffer *et al.*, 2008; Vermeer and Rahmstorf, 2009). The UKCP09 projections contain scenarios for sea level rise that give estimates of UK coastal absolute sea level rise (not including land movement) for 2095 that range from approximately 13–76 cm. Furthermore, a low probability, high impact sea level range has been defined for vulnerability testing; for the UK this absolute sea level rise estimate ranges from 93 cm to 1.9 m by 2100 (Jenkins *et al*., 2008; Lowe, 2009).

Total cloud, radiation and relative humidity

Other climate variables which have potential relevance to human health (particularly in terms of UV exposure) are total cloud amount, downward shortwave radiation and relative humidity. Changes in cloud amount and shortwave radiation flux have implications for both detrimental health impacts associated with increased exposure to UV radiation such as skin cancer, as well as the possible beneficial effects of sunlight on vitamin D production (see Chapter 6). Variations in relative humidity may affect respiratory illnesses through the spread of infections and mould growth, especially in indoor environments. Changes in these variables are dependent on season and location within the UK and are consistent with temperature and precipitation changes. Total cloud amount decreases by 18% in parts of southern England, but changes by only a few percent in winter for the same scenario. Relative humidity is projected to decrease in summer in southern England by around 10% but with smaller changes in the North, and in winter in the 2080s (Jenkins *et al.*, 2008).

1.4 Climate variability and climate projection related uncertainty

The UKCP09 projections are based on some of the most sophisticated climate model simulations that were available at the beginning of the 21st century. Yet like all models, they fall some way short of a full description of natural processes, in particular, limited resolution in space and time and incomplete descriptions of atmospheric and other processes. An ensemble approach and advanced statistical techniques have been used to explore some of the inherent uncertainties in the climate system and in climate models.

One major topic that is outside the ensemble approach and which is covered by having several scenarios is that of greenhouse gas (GHG) emissions. Different scenarios in UKCP09 assume different rates in GHG emissions, depending on a range of global socio-economic factors (which do not include mitigation scenarios). In recent years, GHG emissions have tended to be near the top-end of the SRES scenarios (Friedlingstein *et al.*, 2011; Peters *et al.*, 2012) and it may be necessary to

consider new scenarios with even higher emissions and larger associated changes in climate to explore likely impacts.

Recent modelling efforts using climate models with "higher ceilings", i.e. extending much further into the stratosphere than previously thought necessary, indicate that under climate change northern Europe could experience much greater rainfall during winter than is projected by models which do not resolve the stratosphere (Scaife *et al.*, 2011a). Results from high resolution climate models that can resolve convection explicitly are just becoming available. Despite general projections of drier UK summers, there is a potential for increased numbers of heavy rainfall events which can lead to localised flooding. Such models have improved spatio-temporal characteristics of heavy rainfall events (Kendon *et al.*, 2012).

Results from climate models which include the influence of variations of the sun's UV radiation output suggest colder northern European winters when the sun is at a solar minimum, as was the case in winters of 2009/2010 (Ineson *et al.*, 2011). Results from model simulations with diminishing arctic ice cover also suggest higher frequency of colder north European winters, though it is not clear yet how these two effects interact. More research is required to understand the links between variations in solar output and northern hemisphere winters.

Another area of ongoing research is that of "blocking events" (Sillmann and Croci-Maspoli, 2009; Sillmann *et al.*, 2011). Blocking events are caused by near-stationary large high pressure areas which can temporarily (over the course of a few days or weeks) block the normal air flow (typically mild and wet westerlies for the UK). Of relevance to health, blocking is often associated with increased air pollution and heatwaves in summer and anomalously cold winter temperatures in Europe. Blocking events are still not resolved satisfactorily by many climate models. Current research indicates that removing biases in the model's climatology or increasing the resolution improve the simulation of blocking events (Scaife *et al*., 2011b) during winter. Some model projections indicate that cold winters could still be expected in a warmer climate (Sillmann and Croci-Maspoli, 2009).

The large-scale atmospheric phenomenon known as the North Atlantic Oscillation (NAO) is the dominant mode of winter climate variability over the North Atlantic region, North America and Europe. The NAO is defined as the difference in atmospheric pressure at sea level between the Icelandic low and the Azores high. Variations in the polar low pressure and the subtropical high pressure influence the strength and direction of westerly winds and storm tracks across the North Atlantic. A positive NAO phase often results in warm, wet and stormy winters in the UK, and a negative phase tends to draw cold air into northern Europe. The NAO is difficult to predict and long term seasonal forecasting of the NAO has very limited accuracy (Kushnir *et al.*, 2006; Folland *et al.*, 2011).

When physical climate impacts are used to model the effect on human population (e.g. of a country or region), it is important to consider that future climate impacts are complicated by changes in population demographics and other socio-economic characteristics. Changes in particular climate related health burdens in the future may also be affected by changes in the size and geographical distribution of vulnerable population groups (e.g. elderly populations). While projections of population are available (e.g. for the UK up to 2110), one needs to bear in mind that through migration and policy changes such projections have an uncertainty range that is comparable to (if not exceeding) uncertainties in climate projections (ONS, 2012).

The UKCP09 results have provided, for the first time, probabilistic data which bound the uncertainty range in climate projections. Climate science and model development have continued to advance and give improved understanding and better description of the Earth's climate system. This process is by no means near its end and while it is unlikely that new results will change the current view dramatically, some moderate alterations will be possible. In that sense, UKCP09, as well as the latest IPCC fourth Assessment Report (AR4) should not be seen as "the final word", but as "good work in progress". The IPCC fifth Assessment Report is currently in preparation and is due to be published in 2013.

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- UKCP09 Climate Change Projections from UKCIP http://ukclimateprojections.defra.gov.uk/
- The Central England Temperature series compiled by the Met Office and available from the British Atmospheric Data Centre (BADC) http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_CET
- The England and Wales Precipitation series compiled at the Met Office http://www.metoffice.gov.uk/hadobs/hadukp/
- Population statistics from the Office for National Statistics http://www.statistics.gov.uk/hub/population/index.html

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2 Temperature effects of climate change on human health

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Summary

- National-level percent changes in mortality from exposure to current patterns of hot and cold weather are approximately 2.1% and 2.0% per 1°C change in temperature above/below the respective temperature thresholds.
- Attributable burdens from cold weather are currently substantially larger than from heat exposure due to the UK experiencing more cold days than hot days.
- Heat-related mortality is projected to increase steeply in the UK in the 21st century. We estimate this increase to be approximately 70% in the 2020s, 260% in the 2050s, and 540% in the 2080s, compared with the 2000s heat-related mortality baseline of around 2,000 premature deaths, in the absence of any physiological or behavioural adaptation of the population to higher temperatures.
- Cold-related mortality is projected to remain substantially higher than heat-related mortality in the first half of the 21st century. However, it is estimated to decline by 2% in the 2050s and by 12% in the 2080s, compared with the 2000s baseline.
- The South East, London, East and West Midlands, the East of England and the South West appear to be most vulnerable to current and future effects of hot weather.
- The elderly, particularly those over 85 years of age, are much more vulnerable to extreme heat and cold compared with younger age groups. Future health burdens may be amplified by an aging population in the UK.
- Physiological, behavioural and planned adaptations to a changing climate are likely to play a key role in determining future burdens to health of hot and cold weather in the UK.

Public health recommendations

- Promotion of measures to avoid heat stress and dehydration during periods of hot weather. Planning for hotter weather and heatwaves in the health care sector.
- Climate change adaptation policies aiming to support adaptation to rising temperatures on public health should focus on elderly and other vulnerable populations such as those with pre-existing illnesses.
- Additional advice should be directed to residents of urban areas as they are likely to be more heavily affected by hot weather due to the urban heat island effect.
- Promotion of affordable household interventions aiming to maintain thermal comfort during periods of extreme heat and cold weather, particularly for the elderly.
- Support for seasonal flu vaccination programmes.

Research needs

- Quantification of preventable heat- and cold-related morbidity, focusing on vulnerable population groups.

- Evaluation of the effectiveness of public health measures to reduce the impact of heat and cold on population health.
- Improved understanding of the role that planned adaptation strategies and long-term physiological changes may play in determining future temperature-related health burdens. Advanced modelling of such adaptations to rising mean temperatures and higher frequency of heatwaves in health impact assessments.
- Improved urban surface modelling schemes and inclusion of these in regional climate models in order to capture the additional effects of urban heat islands on temperature when investigating climate change impacts on health.

2.1 Introduction

Ecological studies show that current patterns of weather are associated with appreciable adverse health burdens in many cities and countries around the world (Basu, 2009; Basu and Samet, 2002; McMichael *et al*., 2008). In general, a U-shaped relationship exists between temperature and the risk of death in a population, with an increased risk when temperatures begin to rise or fall (Hajat *et al*., 2007; Carder *et al*., 2005). Very few of these deaths will arise as a direct result of hyperthermia or hypothermia, but rather from temperature effects on disease, especially cardiovascular and respiratory.

Currently, the UK experiences a large health burden from cold weather, with many thousands of preventable deaths occurring during the winter months each year (Donaldson *et al.,* 2002). Heat-related deaths also pose a significant problem to public health, especially during extreme heatwave periods, such as that experienced in Western Europe during the summer of 2003. In England and Wales alone, approximately 2000 excess deaths occurred during the 2003 heatwave (Johnson *et al.,* 2005).

Future changes in the climate system will likely alter such risks. In the UK, the number of heat-related deaths is expected to increase in future due to warmer summers, and the number of cold-related deaths will likely decrease due to milder winters. The projected change in mean summer and mean winter temperatures in the 2020s, 2050s and 2080s, relative to the 1961-1990 baselines, is presented in Figure 2.1. Extremes of hot weather are likely to become much more common in future (Jones *et al*., 2008), although models predict that extreme cold weather events are still likely to occur over continental areas even under 21st century warming scenarios (Kodra *et al*., 2011).

Information on the likely future health impacts of such changes is needed in order to inform UK public health policy on climate-change. Central to this is characterisation of the direct health impacts of current patterns of local climate, and identification of the sub-groups of the population most at risk. This information can then be used to estimate future health burdens based on climate change scenarios. This chapter models health impacts of current patterns of weather variability in the UK and applies these to climate projections to estimate future temperature-related health burdens in the UK due to climate change.

2.2 Methods

The methods to estimate future numbers of temperature-related deaths due to climate change in the UK had two components: (i) an epidemiologic analysis of weather and health data to characterise and quantify mortality associations with current patterns of climate and, (ii) a risk assessment, whereby the temperature-health relationships estimated from stage (i) were applied to projections of future climate.

2.2.1 Epidemiologic analysis

Health data

All deaths occurring in England & Wales over a 14 year time-period (1993-2006) were obtained from the Office for National Statistics (http://www.ons.gov.uk). Deaths were aggregated by date of death to create a time-series of the daily number of deaths occurring during the 14 year study period. As

weather can contribute to mortality from many causes, the series were based on deaths occurring from all causes (including external causes) and were created separately by age group (0-64 years, 65-74, 75-84, 85+) and also by the 10 government regions of England & Wales. Mortality data for Scotland and Northern Ireland are obtained from different sources and were not readily available for the purposes of this assessment.

Morbidity impacts of temperature are not as consistent or extensively characterised as mortality outcomes, especially in relation to hot weather, and therefore are not considered in this assessment (Kovats and Hajat, 2008).

Weather data

Outdoor measurements of temperature and relative humidity data were obtained from the British Atmospheric Data Centre (BADC) using the large network of Met Office surface monitoring stations in the UK (http://badc.nerc.ac.uk). The data were processed to create a 14 year series of daily mean temperature and daily relative humidity representative of each region. Details of the averaging process of weather measurements within each region and handling of missing values have been published elsewhere (Armstrong *et al.,* 2010). The study period included the notable hot summers of 1995, 2003 and 2006.

Statistical model

Regression analyses of daily time-series data were conducted to assess the short-term relationship between the daily number of deaths and day-to-day fluctuations in ambient temperature. Poisson variation with scale overdispersion was assumed in all regression models. Based on previous work (Armstrong *et al.,* 2010), heat effects were assessed using models restricted to just the summer months (June – September). Broad seasonal patterns were controlled for using natural cubic splines (NCS) of time with 4 degrees of freedom (df) within each summer season. Any trends in the 14 year series were modelled using linear and quadratic terms for time. NCS were used to control for confounding from relative humidity, and day-of-week effects were also modelled.

For cold-related mortality assessment, all year models were used as cold effects may not be restricted to just the winter season in the UK. Similar control for confounding was used as with the heat models, but with additional seasonal control and also inclusion of counts of daily deaths from influenza to control for confounding of cold impacts by influenza epidemics.

It was not possible to control for the possible confounding effects of outdoor air pollution as variations in concentrations would have been too large between monitoring sites to obtain a series that would be adequately representative of each region. However, a sensitivity analysis on air pollution control was conducted in the London region, where it was possible to create a representative series for PM_{10} (particulate matter with aerodynamic diameter <10 μm) and ground level ozone (O_3). Daily concentrations of each pollutant, based on an average measurement for lags 0-1 days, were therefore added to the London model.

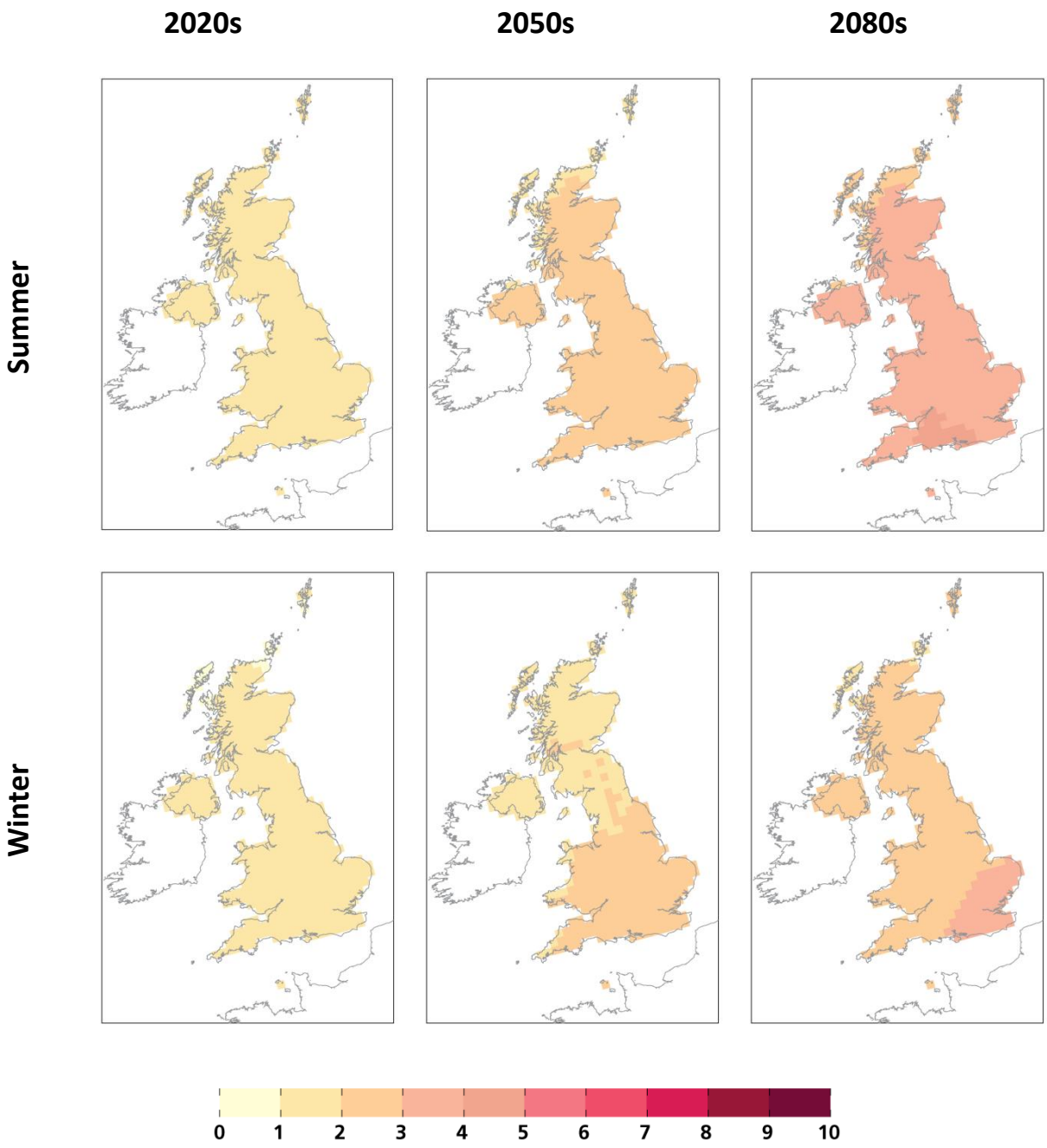

Figure 2.1. Change in summer mean temperature (top) and winter mean temperature (bottom) for the 2020s (left), 2050s (middle) and 2080s (right) under a medium emissions scenario (50% probability level). (Source: Jenkins *et al.*, 2009).

Characterisation of temperature effects

After creating the core model described above, the relationship with temperature was first assessed graphically using NCS of temperature within each region. For the summer months, this indicated a fairly well defined value of temperature (a so-called heat threshold) above which risk of death increased in a log-linear fashion with high temperature, but with no increased risk in death below

the threshold. Therefore, to quantify the effect of heat on mortality, the NCS terms were replaced with a linear-threshold model.

Previous evidence shows that heat impacts are mostly immediate, i.e. occurring on the same day as the day of exposure (lag 0) and the following day (lag 1), but little raised risk beyond then (Armstrong, 2006). In a previous mortality assessment in England & Wales, the heat threshold was identified by statistical model fit as broadly occurring at the 93rd percentile of the all-year daily maximum temperature distribution within each region (Armstrong *et al.,* 2010). As our analysis also assesses cold effects, we use daily mean temperature rather than maximum temperature, but at the same percentile. For example, the 93rd percentile heat threshold for London corresponds to a daily mean temperature of 19.6°C, whilst for the North East this is 16.6°C over the same period (1993-2006).

An equivalent cold threshold is not as obvious, indicating that an increased risk of death for a unit drop in temperature can occur throughout much of the year. To reflect this, a cold threshold was assumed at the 60th percentile of the all-year temperature distribution within each region. The thresholds broadly correspond to the maximum daily mean temperature value in the 4 coldest months of the year (December-March), excluding outliers. For example, the 60th percentile cold threshold for London corresponds to a daily mean temperature of 13.2°C, whilst for the North East this is 10.9°C over the same period (1993-2006). Cold impacts are modelled here using temperature measures lagged by up to 28 days, as previous work has indicated that cold impacts can be distributed over a number of weeks following initial exposure (Bhaskaran *et al.,* 2010).

In addition, in the summer months a separate indicator term to represent individual periods of exceptionally hot weather (heatwaves) was simultaneously modelled with the general heat effect to quantify any *additional* health impact conferred upon risk due to the more extreme temperatures occurring during a heatwave, and also that due to the cumulative effects of heat exposure over successive hot days. In other words, there may be greater than expected risk at the very extreme end of the exposure-response function which may be underestimated if the assumption of a log-linear relationship is no longer valid here. This is important as more frequent, more intense, and longer lasting heatwaves are expected to occur in future due to climate change (Meehl and Tebaldi, 2004; Fischer and Schär, 2010). Assessing additional impacts of such events is often therefore based on identifying periods of high heat intensity and duration (Anderson and Bell, 2011). For this analysis, a heatwave was defined as a period when daily mean temperatures on the current day and at least the previous 2 days was above the 98th percentile of the all-year temperature distribution. This definition was used to provide a balance between distinguishing such days from the more general heat effect and to provide sufficient statistical power to quantify the contribution of such periods. For example, the 98th percentile heatwave threshold for London corresponds to a daily mean temperature of 22.6°C, while for the North East this is 19.0°C over the period of 1993-2006. The heatwave term is modelled as an indicator variable, and so represents whether there is any additional heatwave effect over and above that predicted from the general log-linear heat-mortality relationship.

In contrast to heatwave effects, there is little evidence to suggest that cold-waves defined in a similar fashion have additional impacts over and above the general cold related risk (Barnett *et al.,*

2012), although it is recognised that prolonged icy conditions will probably increase the number of deaths and injuries from car accidents and hip fractures from slips outdoors.

For the general models, heat (and cold) risks are presented as the relative risk of death for every 1°C increase (decrease) in temperatures above (below) the heat (cold) threshold (Figures 2.2 and 2.3). Figure 2.4 shows any additional heatwave effect. All relative risks are estimated separately for each region, as well as a mean national effect from a random effects meta-analysis.

2.2.2 Risk assessment

Projections of future climate and population data

Projected daily mean temperatures for the periods 2000-2009, 2020-2029, 2050-2059 and 2080-2089 were obtained from the British Atmospheric Data Centre (BADC). This dataset contains daily output from 1950 to 2100 from an ensemble of eleven variants of the Met Office Hadley Centre Regional Climate Model (HadRM3) used to dynamically downscale global climate model (GCM) results for the medium emissions scenario (SRES A1B) to a horizontal resolution of 25km for use in the UKCP09 climate projections. A subset of nine regional climate model variants, corresponding to climate sensitivity[1] in the range of 2.6-4.9°C, was used in the analyses presented in this chapter. Regional daily mean temperatures for each model variant were calculated by averaging the daily mean temperatures of all the grid cells within the boundaries of each UK region.

Recent population data and health statistics at regional levels, as well as future projections, were obtained from the Office for National Statistics (ONS, 2011).

Health impact analysis

The heat- and cold-related mortality in UK regions were calculated for the last decade 2000-2009 (2000s) and the future decades 2020-2029 (2020s), 2050-2059 (2050s) and 2080-2089 (2080s) using regional daily mean temperatures, relative risks, regional population data and baseline mortality rates for all-cause deaths based on a methodology proposed by Knowlton *et al.* (2007). As exposure-risk relationships for Scotland and Northern Ireland were not available, regression coefficients from the adjacent regions of North East and North West, respectively, were used.

It should be noted that relative risks, temperature thresholds and baseline mortality rates in each region were held constant over the decades included in the analysis (although daily mortality rates were assumed to follow a seasonal pattern within each year). However, baseline mortality rates will change in the future as a result of changes in the age structure of the population, as well as due to changes in socioeconomic and environmental determinants of health, and in the provision of health care services. Relative risks will also change to some extent in the future as the population will acclimatise and adapt to generally higher temperatures. Although not possible to address in this assessment, it is acknowledged that future adaptation to hot weather is likely to be a key driver in determining future vulnerability. Options for modelling adaptation are discussed more fully elsewhere (Kinney *et al.,* 2008). Predicting future changes in baseline mortality rates and relative risks was not possible within the scope of this chapter.

[1] Climate sensitivity (also refer to as 'Rate of Global Warming') is the global average warming in response to a doubling of the atmospheric CO_2 concentration from 280 ppm (pre-industrial level) to 560 ppm.

The above analysis was initially carried out for the total population in each region (all ages), and then repeated for four specific age groups (0-64, 65-74, 75-84, and over 85 years of age) in each region.

Regional heat- and cold-related mortality per year was separately calculated with each one of the nine regional climate model (HadRM3) variants and then aggregated over the whole of the UK. Finally, the mean, minimum and maximum excess mortality estimates were extracted from the ensemble of nine model realisations for each region and for the UK as a whole.

2.3 Results and discussion

2.3.1 Epidemiologic analyses

In every region, there was a statistically significant raised risk in mortality associated with both heat and cold exposure (i.e. relative risk greater than 1). National-level percent changes in mortality from exposure to heat and cold were 2.1% (95% CI 1.5, 2.7) and 2.0% (95% CI 1.8, 2.2) respectively, indicating a 2.1% increase in mortality for every 1°C rise in temperature above the heat threshold and a 2.0% increase in mortality per 1°C drop in temperature below the cold threshold. Although heat and cold risk were similar, there were many more days below the cold threshold than above the heat threshold, leading to a much larger number of deaths attributable to cold weather than to hot weather. At the national level, there was a 1.4% (95% CI -0.7, 3.4) increase in mortality on heat-wave days compared to other days after controlling for general heat effects; this increase was not statistically significant at the 5% level.

London, the South East, East and West Midlands and East of England were most vulnerable to heat effects (Figure 2.2), and the greatest cold risk was in the southern regions, the East of England and Wales (Figure 2.3). A significant additional heatwave effect was only apparent in London (Figure 2.4). In London, control for PM_{10} and O_3 changed the heat risk from 1.039 (95% CI 1.033, 1.044) to 1.034 (1.028, 1.040), the heatwave risk from 1.074 (1.034, 1.117) to 1.073 (1.033, 1.115), and the cold risk was left unchanged.

Heat, cold and heatwave estimates for separate age groups are detailed in Appendix A. In general, heat and cold risk increased with successive age groups, with the greatest heat risk in those aged 85 years and above.

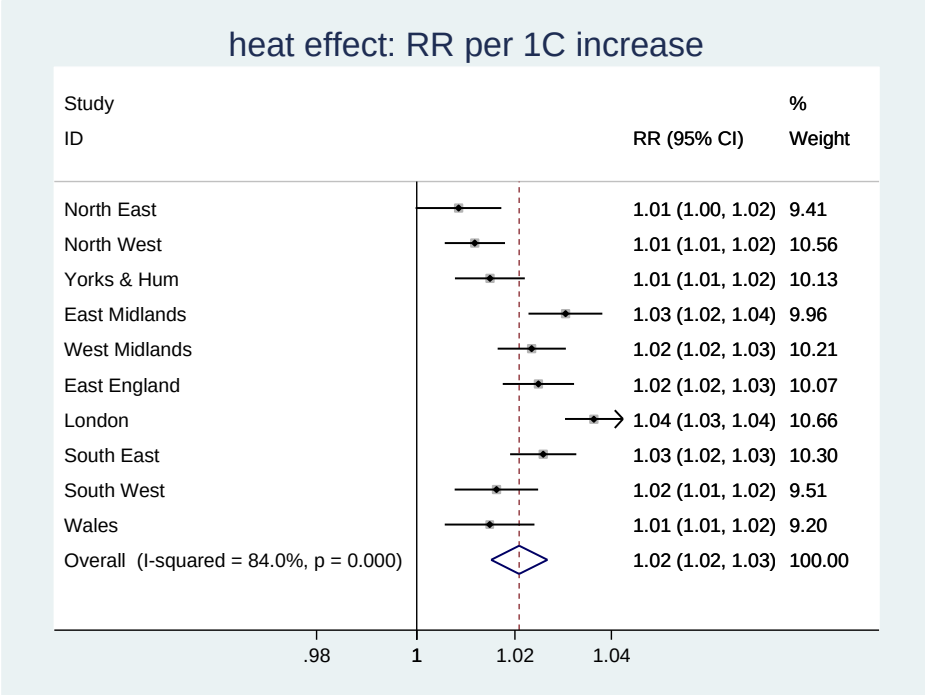

Figure 2.2. Region-specific and national-level relative risk (95% CI) of mortality due to hot weather. Daily mean temperature 93rd percentiles: North East (16.6°C), North West (17.3°C), Yorks & Hum (17.5°C), East Midlands (17.8°C), West Midlands (17.7°C), East England (18.5°C), London (19.6°C), South East (18.3°C), South West (17.6°C), Wales (17.2°C).

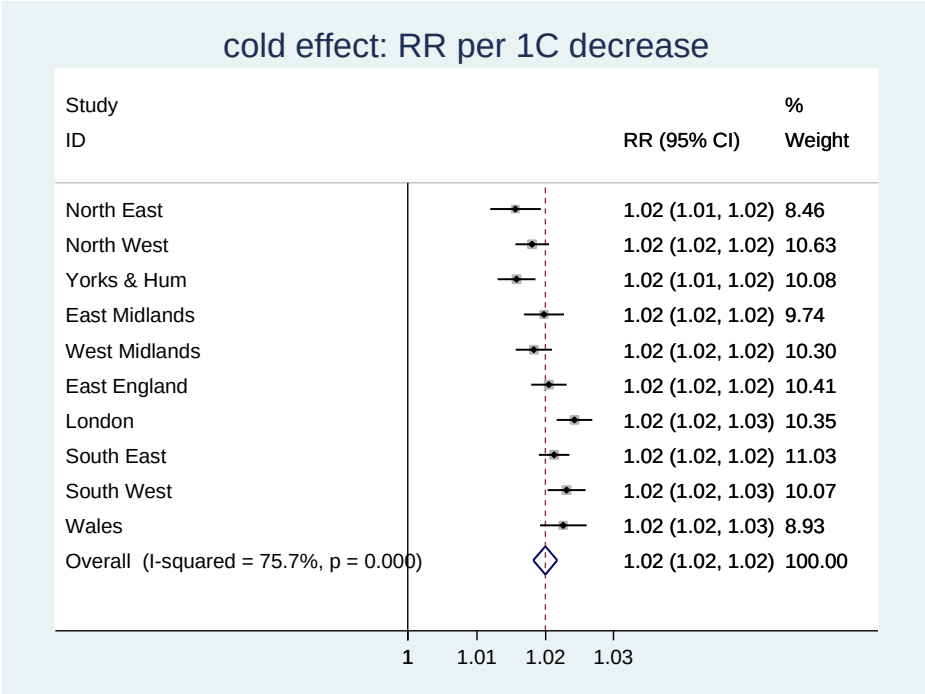

Figure 2.3. Region-specific and national-level relative risk (95% CI) of mortality due to cold weather. Daily mean temperature 60th percentiles: North East (10.9°C), North West (11.9°C), Yorks & Hum (11.5°C), East Midlands (11.7°C), West Midlands (11.6°C), East England (12.2°C), London (13.2°C), South East (12.4°C), South West (12.1°C), Wales (11.9°C).

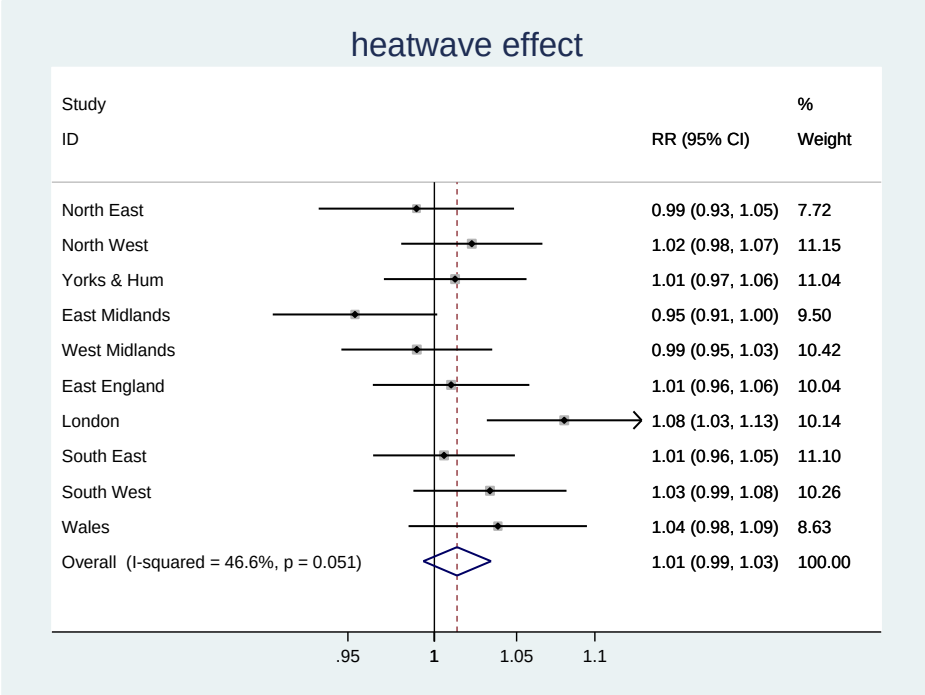

Figure 2.4. Region-specific and national-level relative risk (95% CI) of a heatwave effect. Daily mean temperature 98th percentiles: North East (19.0°C), North West (19.8°C), Yorks & Hum (20.1°C), East Midlands (20.5°C), West Midlands (20.2°C), East England (20.9°C), London (22.6°C), South East (20.7°C), South West (19.6°C), Wales (19.3°C).

2.3.2 Risk assessment

The estimated heat and cold-related excess deaths per year in the UK (taking population projections into account) during the 2000s, 2020s, 2050s and 2080s are summarised in Figures 2.5 and 2.6. It can be observed that the mean estimate of heat-related mortality increases by approximately 66%, 257%, and 535% in the 2020s, 2050s and 2080s, respectively, compared with the 2000s baseline. In the same period, the mean estimate of cold-related mortality will slightly increase by approximately 3% in the 2020s, and then decreases by 2% in the 2050s and by 12% in the 2080s, compared with the 2000s baseline. These projected changes in total heat and cold-related mortality reflect the pattern of increasing mean daily temperatures in following decades, but also the increasing size of the population in most UK regions during the 21st century. It should be noted that the UK population is projected to increase at a higher rate in the first three decades of the current century compared with following decades (ONS, 2011). This increase in population size more than offsets the expected reduction in cold-related mortality due to climate change in the 2020s (Figure 2.6). If we keep the size of the population constant, the national-wide heat-related mortality is projected to increase by approximately 46%, 169%, and 329% in the 2020s, 2050s and 2080s respectively, while the cold-related mortality is projected to decrease by approximately 9%, 26% and 40% over the same decades compared with the 2000s baseline.

In the present analysis, we have used the 93rd, 98th and 60th percentiles of daily mean temperatures in each region to estimate heat-related deaths, additional heatwave deaths, and cold-related deaths, respectively. It should be noted that the annual burdens for the 2000s presented in Figure 2.5 are

generally higher than the heat-related mortality (1,142 excess deaths per year for the baseline period of 1993-2006) reported in the Climate Change Risk Assessment for the UK health sector (Hames and Vardoulakis, 2012). This is mainly due to the use of lower temperature thresholds for heat effects (93rd instead of 95th percentile) and the inclusion of all-cause deaths (including external causes) in the present analysis.

It should also be noted that the cold-related burdens reported in Figure 2.6 would be much reduced had a cold threshold at lower values of temperature been assumed. A sensitivity analysis on temperature thresholds for cold effects included in the Climate Change Risk Assessment for the UK health sector indicated that current cold-related mortality in the UK ranges between 26,000 and 57,000 excess deaths per year (Hames and Vardoulakis, 2012).

Regarding future burdens, the present analysis shows a generally larger increase in heat-related deaths and a smaller decrease in cold-related deaths during the 21st century compared with the estimates presented in the Climate Change Risk Assessment for the UK health sector. This is mainly due to the use of time-series of modelled daily mean temperatures for future decades, which take into account an increased frequency of extreme weather events, in the present study.

We estimated the number of excess deaths due to heat and cold in the UK for four different age groups (0-64, 65-74, 75-84 and over 85 years of age). In this case, the results presented in Figures 2.7 and 2.8 were normalised per 100,000 population, as the size of the age groups varies widely. Although the relative risks for individual age groups are not statistically significant in all cases (Appendix A), the results of this analysis provide an indication that the burden of heat and cold is much larger in the age groups of 75-84 and, in particularly, over 85 years of age, compared to younger age groups. Heat-related mortality in the age groups over 65 years of age is expected to increase steeply in the second half of the 21st century, while cold-related mortality will decrease at a lower rate over the same period (Figures 2.7 and 2.8).

Heat- and cold-related mortality estimates varied geographically across UK regions with, (i) the South East, London, East Midlands, West Midlands, the East of England and the South West having more heat-related deaths per year (ranging between 3.5-6.3 deaths per 100,000 population) and, (ii) Wales, London, the North West, the South East, the South West, and the East of England having more cold-related deaths per year (ranging between 68.8-83.9 deaths per 100,000 population) in the 2000s compared to other UK regions (Tables 1 and 2). These patterns of regional vulnerability to heat and cold broadly persist in the following decades included in this assessment (2020s, 2050s and 2080s). It should be noted that regional variability in mortality reflects the pattern of projected daily mean temperatures, as well as the age structure and resilience of regional populations to heat and cold.

The above results do not include the additional heatwave effect, which is estimated to be statistically significant in London. Following the same methodology, we estimated the additional burden of heatwaves on all-cause mortality in London, and compared this with the heat- and cold-related mortality estimates (Table 3). It can be observed that the heatwave effect represents a substantial additional burden of 58%, 64%, 70% and 78% on the heat-related mortality results for London in the 2000s, 2020s, 2050s and 2080s, respectively.

In all cases, we have presented mean estimates of health effects as well as minimum and maximum values, which represent the uncertainty associated with regional climate modelling. However, a full uncertainty analysis, including different emission scenarios, population projections, thresholds for temperature effects and relative risks has not been carried out.

2.3.3 The urban heat island effect

Heat (and additional heatwave) related mortality in London and other large urban areas is likely to be exacerbated by the Urban Heat Island (UHI) effect. UHI describes the effect that cities and urban areas have on surface air temperature, whereby cities can be around 5 to 10°C warmer than surrounding countryside areas (Arnfield, 2003). As a result, urban populations are particularly at risk during hot weather. The UHI effect is most pronounced during the night, when heat which has been stored in concrete and other urban materials is released into the atmosphere (Oke, 1973).

Projections of meteorological parameters provided by UKCP09 do not currently include the effect of the UHI on climate. Therefore, future temperatures are likely to be even higher in cities than they are projected due to the combined effects of climate change and UHI. This emphasises the importance of the monitoring of temperatures within urban areas for health impact assessment for temperature effects. There is also a need to improve urban surface modelling schemes in regional climate models in order to capture the additional effects of urban areas on temperature when investigating climate change impacts.

2.3.4 Cause-specific mortality and chronic illness

Burdens in this assessment were estimated based on all-cause mortality since temperature effects are apparent in many causes. Previous studies have identified that, in high-income settings, people with pre-existing respiratory and cardiovascular problems may be particularly vulnerable to temperature-related mortality and morbidity (Basu and Samet, 2002; Vandentorren *et al.,* 2006; Wilkinson *et al.,* 2004). Additionally, heat risk may be heightened in those with renal disease, diabetes, and neurological disorders (Hajat *et al.,* 2010).

In general, illnesses that compromise thermoregulation, mobility, awareness, and behaviour (including dementia and Parkinson's disease) increase the risk of heat related death (Kovats and Hajat, 2008). People with depression, cardiovascular and cerebrovascular conditions, renal disease and diabetes all need to take extra care in hot weather (Hajat *et al.,* 2010).

Physiological changes in renal function which develop with increasing age could be related to the excess mortality observed in older age population groups during extremely hot weather periods. Older people have a lower threshold for the development of renal failure, and diminished renal conservation of sodium and water during periods of dehydration (Flynn *et al.,* 2005).

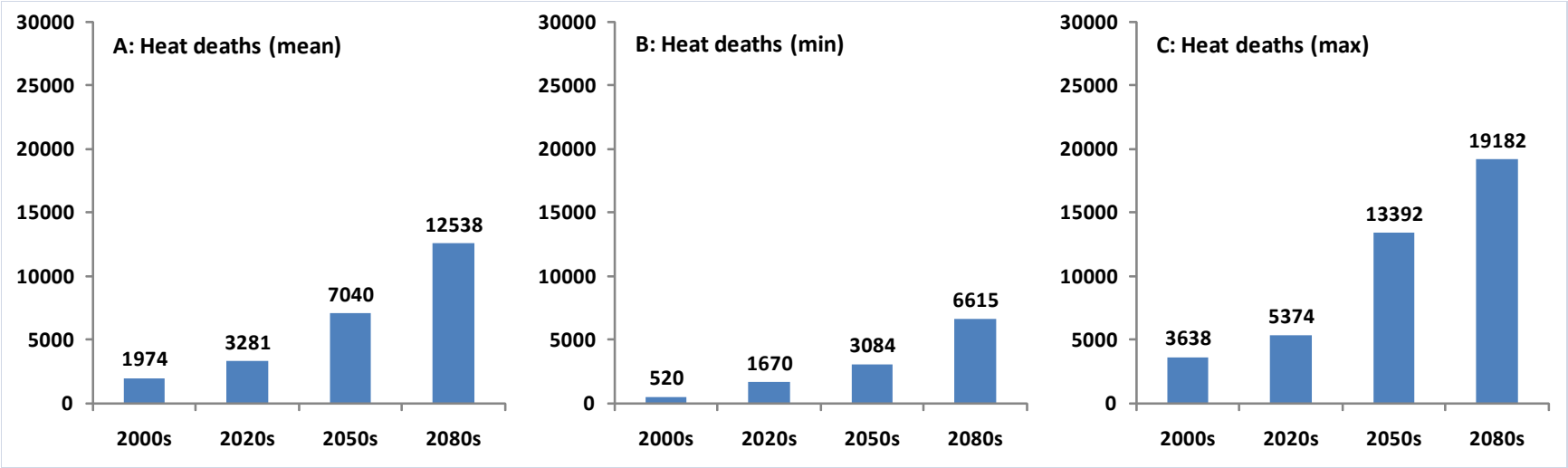

Figure 2.5. Mean (A), min (B) and max (C) estimates of heat-related deaths in the UK per year for all ages based on an ensemble of nine climate model realisations (the additional heatwave effect in London is not included).

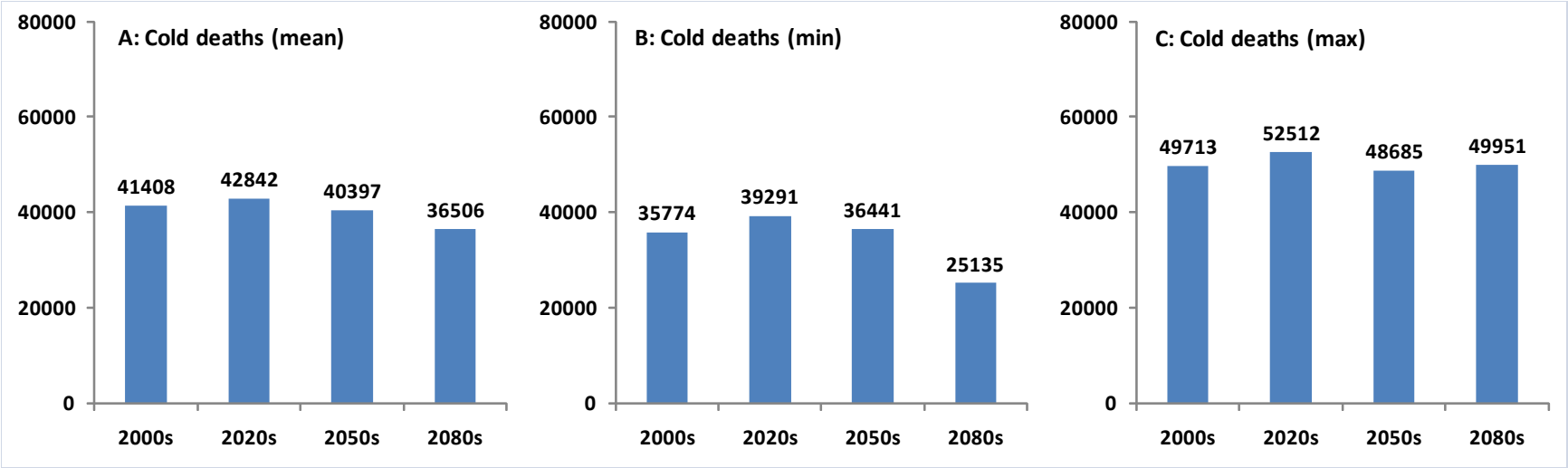

Figure 2.6. Mean (A), min (B) and max (C) estimates of cold-related deaths in the UK per year for all ages based on an ensemble of nine climate model realisations.

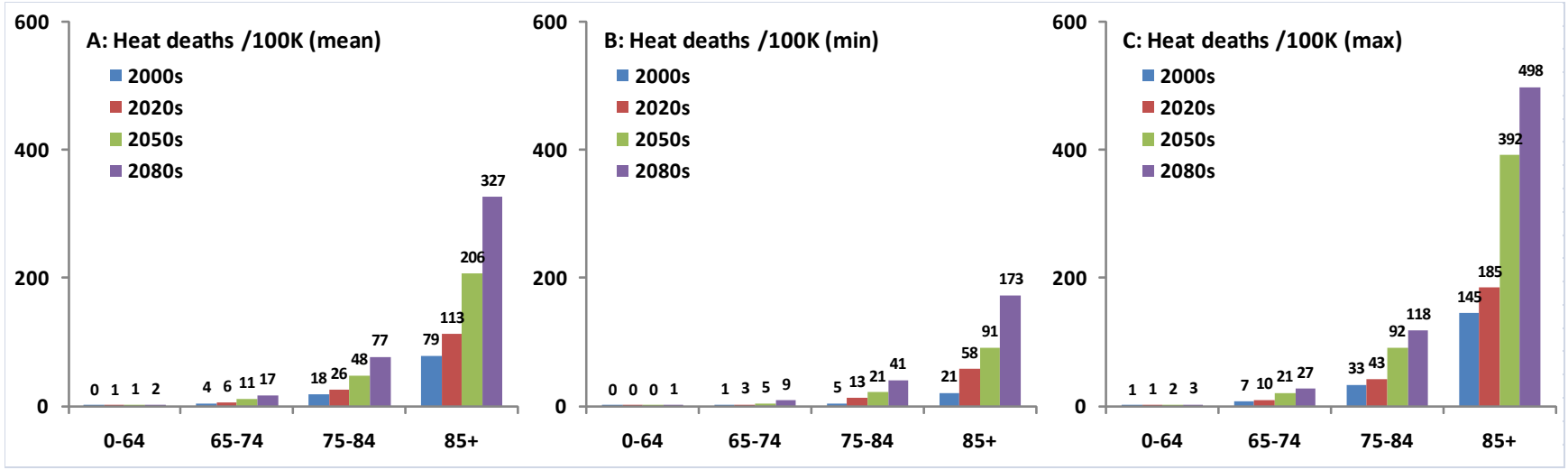

Figure 2.7. Mean (A), min (B) and max (C) estimates of heat-related deaths in the UK per year per 100,000 population in each age group based on an ensemble of nine climate model realisations (the additional heatwave effect in London is not included).

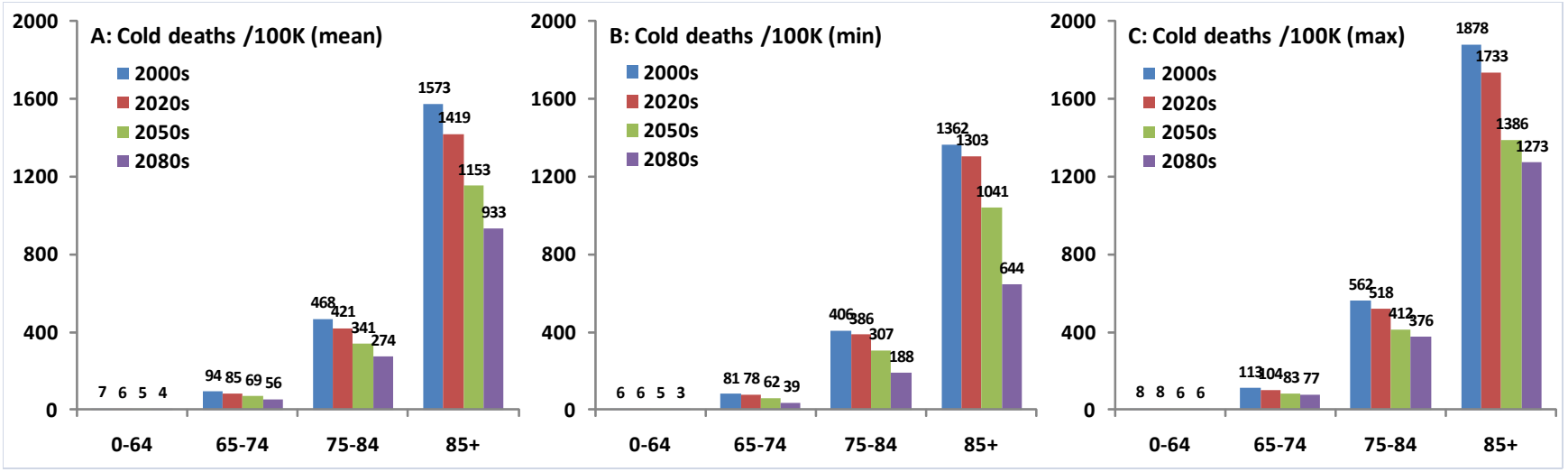

Figure 2.8. Mean (A), min (B) and max (C) estimates of cold-related deaths in the UK per year per 100,000 population in each age group based on an ensemble of nine climate model realisations.

Table 2.1. Mean, min and max estimates of heat-related deaths in UK regions per year per 100,000 population of all ages based on an ensemble of nine climate model realisations (the additional heatwave effect in London is not included).

Heat deaths	2000s			2020s			2050s			2080s		
	mean	min	max	**mean**	min	max	**mean**	min	max	**mean**	min	max
North East	**1.2**	0.5	2.1	**2.1**	1.3	2.9	**3.9**	2.2	7.8	**6.7**	4.0	10.0
North West	**1.3**	0.3	3.1	**2.0**	0.8	3.9	**3.7**	1.8	9.0	**6.2**	3.0	9.8
Yorks & Hum	**1.4**	0.5	2.8	**2.3**	1.1	3.8	**4.4**	2.0	9.8	**7.6**	3.8	12.1
East Midlands	**4.4**	1.4	8.1	**6.5**	3.3	10.2	**11.5**	4.8	21.0	**18.4**	10.2	28.1
West Midlands	**4.2**	1.1	8.3	**6.1**	3.0	10.0	**11.1**	5.0	22.0	**17.2**	8.8	25.9
East England	**3.9**	1.1	7.4	**5.6**	2.9	8.8	**9.9**	3.9	17.6	**15.5**	8.1	23.8
London	**4.4**	0.9	8.8	**6.1**	2.8	10.8	**11.3**	4.3	21.4	**17.5**	8.4	27.9
South East	**6.3**	1.5	11.4	**8.6**	4.6	14.1	**15.3**	6.7	26.1	**22.9**	12.8	34.1
South West	**3.5**	0.7	7.6	**5.1**	2.4	8.7	**9.6**	4.3	18.9	**15.3**	7.8	23.7
Wales	**2.4**	0.7	5.7	**3.5**	1.6	5.8	**6.5**	3.1	14.3	**10.6**	5.3	16.2
Scotland	**0.7**	0.2	1.5	**1.3**	0.3	2.2	**2.4**	1.3	5.2	**4.4**	2.6	7.2
North Ireland	**0.9**	0.3	2.3	**1.6**	0.6	2.6	**2.9**	1.5	6.1	**4.9**	2.9	7.2
Total UK	**3.3**	0.9	6.0	**4.8**	2.4	7.8	**8.8**	3.9	16.8	**14.0**	7.4	21.5

Table 2.2. Mean, min and max estimates of cold-related deaths in UK regions per year per 100,000 population of all ages based on an ensemble of nine climate model realisations.

Cold deaths	2000s			2020s			2050s			2080s		
	mean	min	max	**mean**	min	max	**mean**	min	max	**mean**	min	max
North East	**60.4**	52.9	73.7	**53.9**	47.7	68.1	**44.1**	38.6	54.9	**35.0**	23.8	49.1
North West	**76.5**	67.9	91.6	**69.6**	63.1	85.8	**57.7**	51.7	69.8	**47.4**	33.5	64.2
Yorks & Hum	**62.9**	55.5	75.3	**56.9**	51.5	69.9	**47.0**	41.9	56.7	**38.3**	27.2	51.8
East Midlands	**67.3**	57.0	80.8	**60.7**	55.6	74.2	**48.9**	44.2	59.1	**39.3**	27.1	53.9
West Midlands	**63.5**	53.7	75.9	**57.5**	52.5	70.8	**46.4**	41.9	56.2	**37.4**	25.3	51.5
East England	**68.8**	58.1	81.8	**62.5**	57.6	74.8	**50.2**	45.4	59.5	**40.7**	28.4	54.9
London	**77.3**	65.9	89.6	**71.0**	65.8	83.1	**58.4**	53.2	67.5	**48.8**	35.7	63.0
South East	**71.2**	59.6	84.3	**64.6**	58.8	77.0	**51.6**	45.7	60.9	**41.6**	28.5	56.3
South West	**70.5**	60.0	85.4	**63.5**	56.6	79.2	**49.7**	44.3	60.6	**38.6**	24.4	56.0
Wales	**83.9**	73.7	101.8	**76.1**	69.4	95.5	**61.1**	54.5	75.1	**48.7**	31.9	69.3
Scotland	**55.6**	48.2	71.9	**49.3**	42.4	66.3	**40.8**	34.3	53.5	**31.2**	19.8	46.4
North Ireland	**46.7**	40.3	59.4	**41.5**	35.5	55.0	**34.1**	29.2	43.6	**26.5**	16.6	39.1
Total UK	**68.7**	59.4	82.5	**62.3**	57.1	76.4	**50.6**	45.7	61.0	**40.9**	28.2	56.0

Table 2.3. Mean, min and max estimates of additional heatwave deaths per year (all ages) in London based on an ensemble of nine climate model realisations.

London	2000s			2020s			2050s			2080s		
	mean	min	max	**mean**	min	max	**mean**	min	max	**mean**	min	max
Heat	**325**	63	642	**535**	243	948	**1183**	449	2238	**2087**	1008	3336
Heatwave	**188**	15	459	**343**	92	672	**829**	288	1991	**1630**	644	3061
Cold	**5665**	4829	6570	**6223**	5765	7280	**6108**	5567	7061	**5823**	4266	7514

Medications (including psychotropic medication) that interfere with thermoregulation or suppress thirst may predispose patients to heat related illness and death (Hess *et al.,* 2009; Stoellberger *et al.,* 2009). Furthermore, medication efficacy can be compromised if manufactured drugs (generally licensed for storage at temperatures up to 25°C) are exposed to high temperatures during storage or transit in hot weather (Crichton, 2004).

Our assessment of heat-related mortality included external causes also as there is some evidence that the risk of accidents and violent death, including suicides, increases during hot weather (Page *et al.,* 2007).

2.3.5 Adaptation

The above analyses have not taken into account the effect of physiological and planned adaptation on temperature-related mortality in the future. An observational study by Donaldson and Keatinge (2008) concluded that 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% over the same period. Although the rate at which temperatures are expected to rise in the coming decades and the increased weather variability makes it unclear how extensive future societal adaptation to hot weather will be, it is likely that populations will adapt to some extent to future warming, both in terms of physiology, and also behavioural changes and technological measures such as increased use of air-conditioning.

As future adaptation is likely to be a key driver in determining future vulnerability to weather extremes (Kinney *et al.,* 2008, Christidis *et al.,* 2010), more extensive climate change risk assessments should model the potential contribution of future acclimatisation and adaptation. A previous study of US cities estimated that an assumption of future adaptation reduced projections of temperature-related deaths by 20-25% compared to assumptions of no future adaptation (Kalkstein *et al.,* 1997).

In general, air-conditioning and other cooling systems are likely to become more widely used in the UK in the 21st century, which will generally reduce the vulnerability of the population to heat (Ostro *et al.,* 2010). However the distribution of cooling systems will reflect to a certain extent socioeconomic inequalities, unless they are heavily subsidised, and rising fuel costs may exacerbate this. Prevalence of central air-conditioning among black households in 4 US cities was less than half that in white households, resulting in greater vulnerability to heat-related mortality (O'Neill *et al.,* 2005). It should be noted that increased reliance on active cooling systems in houses, hospitals and care homes could exacerbate energy consumption, climate change and the UHI effect (Vardoulakis, 2010). Furthermore, power blackouts have often occurred during periods of high heat stress (Ostro *et al.,* 2010). Passive cooling options (building orientation, shading, thermal insulation, choice of construction materials, etc.) implemented at the design stage of urban developments may be equally effective as active cooling in reducing the health burden of heat, and would be more environmentally sustainable options.

2.3.6 Modelling choices

Although we considered relative humidity as a potential confounder of the temperature effect, the combined effect of temperature and humidity may also have important effects on health, especially in relation to hot weather. However, previous work found that a temperature-humidity index

(apparent temperature) was not a better predictor of mortality in London compared with temperature alone (Hajat *et al.,* 2006).

As cold thresholds are not as precisely defined as for heat, a cold threshold was assumed at the 60th percentile of the all-year temperature distribution within each region. This broadly corresponds to the maximum daily mean temperature value within the 4 coldest months of the year (December-March) excluding outliers. It is possible that this approach may underestimate cold effects since some cold deaths may occur at other times of the year, but the great majority of the health burdens are likely to be captured. The values of temperature which the 60th percentile thresholds correspond to are broadly consistent with the findings of an earlier epidemiological study on the effects of cold weather on cardiorespiratory mortality in Scotland, which reported a steeper rate of mortality increase at temperatures below 11°C (Carder *et al.,* 2005). There is some scope for uncontrolled heat effects in the all-year models used to assess cold risk, however in sensitivity analyses in which heat effects above the 93rd percentile were also modelled, neither the relative risk or confidence intervals for the national-level cold effect were changed.

Although a log-linear threshold model provides the most consistent basis from which to estimate future burdens, there is evidence that a log-linear assumption may underestimate heat-related risk at very high temperatures (Armstrong, 2006). However, those days are currently very few and so their inclusion would not have a large impact on the estimated heat-related burdens, although there is certain evidence that their frequency may increase in the future. Our analysis indicated little additional heatwave effect except in the case of London, where consecutive hot days may confer additional risk. However, as general heat effects were modelled using lag 0 and 1 days, any additional effect of the longer-duration heatwave term may also reflect general heat effects delayed by more than 1 day, rather than a true additional effect of sustained high temperatures.

Some heat- and cold-related mortality may arise as a result of mortality displacement (*harvesting*), whereby the deaths occur in already frail individuals whose exposure to temperature may simply have hastened their deaths by a matter of a few days or weeks. Previous work has indicated that a proportion of heat-related deaths may be explained by short-term mortality displacement, but that cold-related deaths cannot be explained by this effect (Braga *et al.,* 2002). The methods used in this study do not allow for quantification of the extent to which lives may be shortened due to heat or cold exposure.

2.3.7 Public health protection

Simple health protection measures against heat and cold, which could be implemented by individuals, are likely to be effective. For protection against hot weather, these include the maintenance of adequate fluid intake, reduction of fluid loss by tepid sponging, avoiding drinking alcohol, wearing lightweight, loose fitting clothing, reducing physical activities, avoiding exposure to the sun, avoid going out during the hottest part of the day, taking frequent baths or showers, and moving at-risk individuals such as elderly people to a cooler environment during periods of intense heat (Luber and McGeehin, 2008; Hajat *et al*., 2010). Adjustment of dosages of certain medications such as diuretics may also help maintain adequate fluid balance (Flynn *et al.,* 2005). For protection against cold weather, measures that can be implemented by individuals include dressing warmly (wearing several thin layers rather than one thick layer), staying indoors during periods of severe cold weather, keeping the home warm especially at night (e.g. by improving thermal insulation and

draught proofing doors and windows), and staying generally healthy by eating well, exercising and accepting seasonal flu vaccination if recommended (Conlon *et al.,* 2011).

The Heatwave Plan (operational since 2004) and the Cold Weather Plan (published in 2011) for England are expected to have a positive effect on temperature related health burdens. Both plans aim to protect health and to reduce harm from extreme heat and cold, including advice for relevant bodies and organisations on the protection of vulnerable people (DH, 2011a; 2011b). However, their effectiveness (including public acceptance and adoption of measures) will have to be formally evaluated when a sufficiently long period of time has passed from their full implementation.

2.4 Conclusions

The UK experiences a substantial annual heat- and cold-related health burden associated with exposure to current weather patterns, with the fraction of deaths attributable to cold weather currently much larger than that due to hot weather. The elderly are most at risk from both heat and cold. Future changes in climate are likely to lead to an increase in heat-related deaths in the UK, but also in a proportionally smaller decrease in cold-related impacts. It should be emphasised that health protection measures against hot and cold weather are not complex; therefore the challenge for the public health sector is to promote them effectively. Quantitative assessment is needed of the role that planned adaptation strategies and long-term physiological changes may play in determining future health burdens associated with exposure to hot and cold weather in the UK.

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Appendix A

Relative risks, with lower and upper confidence levels (CI: 95%) for: (i) heat, (ii) additional heatwave, and (iii) cold-related mortality for all ages and specific age groups in the UK regions.

(i) Heat effect	All ages			Ages 0-64			Ages 65-74			Ages 75-84			Ages 85+		
	RR	LCL	UCL	**RR**	LCL	UCL	**RR**	LCL	UCL	**RR**	LCL	UCL	**RR**	LCL	UCL
North East	**1.013**	1.005	1.022	**1.004**	0.986	1.023	**1.017**	1.001	1.034	**1.019**	1.005	1.033	**1.009**	0.993	1.025
North West	**1.014**	1.009	1.020	**1.013**	1.003	1.024	**1.007**	0.996	1.018	**1.007**	0.998	1.015	**1.031**	1.021	1.040
Yorks & Hum	**1.019**	1.013	1.026	**1.003**	0.988	1.017	**1.016**	1.003	1.030	**1.017**	1.007	1.027	**1.035**	1.023	1.047
East Midlands	**1.033**	1.026	1.040	**1.028**	1.013	1.044	**1.015**	1.000	1.030	**1.033**	1.022	1.045	**1.050**	1.037	1.062
West Midlands	**1.027**	1.021	1.033	**1.020**	1.007	1.034	**1.017**	1.004	1.029	**1.028**	1.018	1.038	**1.037**	1.025	1.048
East England	**1.027**	1.021	1.034	**1.022**	1.007	1.038	**1.017**	1.003	1.031	**1.029**	1.018	1.040	**1.036**	1.025	1.047
London	**1.039**	1.033	1.044	**1.025**	1.014	1.036	**1.021**	1.010	1.033	**1.040**	1.031	1.049	**1.058**	1.049	1.068
South East	**1.029**	1.024	1.035	**1.018**	1.005	1.031	**1.024**	1.012	1.036	**1.020**	1.011	1.029	**1.047**	1.038	1.056
South West	**1.020**	1.012	1.027	**1.005**	0.988	1.024	**1.026**	1.009	1.043	**1.022**	1.010	1.035	**1.021**	1.009	1.034
Wales	**1.017**	1.008	1.025	**0.991**	0.972	1.011	**1.009**	0.991	1.028	**1.017**	1.003	1.031	**1.037**	1.021	1.053
Total UK	**1.021**	1.015	1.027	**1.012**	1.006	1.019	**1.014**	1.009	1.018	**1.020**	1.013	1.027	**1.034**	1.025	1.042

(ii) Heatwave	All ages			Ages 0-64			Ages 65-74			Ages 75-84			Ages 85+		
	RR	LCL	UCL	**RR**	LCL	UCL	**RR**	LCL	UCL	**RR**	LCL	UCL	**RR**	LCL	UCL
North East	**0.984**	0.934	1.037	**0.939**	0.832	1.059	**1.054**	0.949	1.171	**1.018**	0.932	1.111	**0.901**	0.809	1.004
North West	**1.018**	0.986	1.052	**1.019**	0.952	1.091	**0.992**	0.924	1.065	**1.044**	0.989	1.103	**1.006**	0.948	1.068
Yorks & Hum	**1.012**	0.977	1.048	**1.027**	0.945	1.117	**1.084**	1.005	1.169	**0.992**	0.936	1.051	**0.974**	0.912	1.041
East Midlands	**0.952**	0.912	0.993	**0.890**	0.807	0.981	**1.002**	0.914	1.098	**0.987**	0.921	1.058	**0.918**	0.852	0.989
West Midlands	**0.985**	0.949	1.023	**0.979**	0.901	1.063	**1.070**	0.991	1.156	**0.954**	0.897	1.016	**0.973**	0.909	1.041
East England	**1.010**	0.971	1.050	**1.011**	0.920	1.111	**0.994**	0.911	1.084	**1.003**	0.939	1.070	**1.021**	0.954	1.092
London	**1.074**	1.034	1.117	**1.046**	0.965	1.133	**1.049**	0.965	1.139	**1.104**	1.034	1.177	**1.073**	1.004	1.147
South East	**1.002**	0.970	1.035	**0.977**	0.903	1.057	**1.013**	0.945	1.085	**1.008**	0.956	1.063	**1.001**	0.950	1.054
South West	**1.030**	0.991	1.070	**1.037**	0.945	1.138	**0.979**	0.897	1.067	**1.025**	0.962	1.092	**1.059**	0.994	1.128
Wales	**1.037**	0.990	1.086	**1.112**	0.995	1.242	**1.052**	0.952	1.163	**1.044**	0.967	1.128	**0.977**	0.894	1.067
Total UK	**1.014**	0.993	1.034	**1.005**	0.973	1.038	**1.031**	1.004	1.059	**1.020**	0.994	1.046	**0.998**	0.966	1.030

(iii) Cold effect	All ages			Ages 0-64			Ages 65-74			Ages 75-84			Ages 85+		
	RR	LCL	UCL	**RR**	LCL	UCL	**RR**	LCL	UCL	**RR**	LCL	UCL	**RR**	LCL	UCL
North East	**1.016**	1.012	1.019	**1.007**	0.999	1.015	**1.015**	1.008	1.022	**1.022**	1.016	1.028	**1.016**	1.009	1.023
North West	**1.018**	1.016	1.021	**1.009**	1.004	1.014	**1.013**	1.009	1.018	**1.022**	1.018	1.026	**1.025**	1.021	1.029
Yorks & Hum	**1.016**	1.013	1.019	**1.003**	0.997	1.009	**1.019**	1.013	1.024	**1.018**	1.013	1.022	**1.021**	1.016	1.026
East Midlands	**1.020**	1.017	1.023	**1.011**	1.005	1.018	**1.012**	1.006	1.017	**1.024**	1.020	1.029	**1.026**	1.021	1.031
West Midlands	**1.018**	1.016	1.021	**1.007**	1.002	1.013	**1.016**	1.011	1.021	**1.018**	1.013	1.022	**1.031**	1.027	1.036
East England	**1.020**	1.018	1.023	**1.010**	1.004	1.016	**1.014**	1.009	1.019	**1.020**	1.016	1.024	**1.031**	1.026	1.035
London	**1.024**	1.022	1.027	**1.012**	1.007	1.017	**1.023**	1.018	1.028	**1.025**	1.021	1.029	**1.035**	1.030	1.039
South East	**1.021**	1.019	1.024	**1.011**	1.007	1.016	**1.016**	1.012	1.020	**1.025**	1.022	1.029	**1.029**	1.026	1.033
South West	**1.021**	1.019	1.024	**1.015**	1.008	1.021	**1.020**	1.014	1.025	**1.026**	1.022	1.031	**1.031**	1.027	1.036
Wales	**1.023**	1.019	1.026	**1.007**	1.000	1.015	**1.009**	1.002	1.016	**1.030**	1.025	1.036	**1.038**	1.032	1.044
Total UK	**1.020**	1.018	1.022	**1.009**	1.007	1.011	**1.014**	1.012	1.017	**1.022**	1.020	1.024	**1.028**	1.024	1.031

3 Health effects due to changes in air pollution under future scenarios

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Summary

- This chapter predominantly considers effects on health from changes in ambient concentrations of ground level ozone (O_3) over the UK. Changes in particulate matter (PM) and nitrogen dioxide (NO_2) concentrations are also briefly discussed.
- Future concentrations of ground level O_3 are difficult to project because of uncertainties in the future emissions in the UK and elsewhere of gases that lead to formation of O_3. Uncertainties are compounded when trying to include effects of climate change as well because climate change can impact on many processes that influence ground level O_3 concentrations.
- Model simulations show that the changes in annual mean ground level O_3 over the UK for a +5 °C air temperature scenario (+1.0 to +1.5 ppbv, depending on geographic region) are generally smaller than the potential changes in ground level O_3 due to emissions changes by 2030 (−3 to +3.5 ppbv, depending on scenario and geographic region) or due to inter-annual meteorological variability (± 1.5 – 2 ppbv).
- UKCP09 projections indicate that temperature increases around +5 °C are not anticipated to occur until towards the end of this century, although this is dependent on future greenhouse gas emission trends. An increase in temperature is also only one way in which future climate change will impact on future ground level O_3 concentrations. Overall, however, current indications are that until at least mid-century the net additional impact of climate change on the health burden associated with ground level O_3 will be smaller than the impact from changes in future anthropogenic emissions.
- The extent of adverse health impact attributable to O_3 (deaths brought forward and hospitalization) depends markedly on the assumption of a threshold concentration for O_3 impacts. Assuming O_3 exposure over the full year is relevant, the attributable health impacts assuming a 35 ppbv threshold or a 50 ppbv threshold are, respectively, approximately a factor of 10 lower or approximately a factor 50 lower than those attributable if no threshold is assumed, with the exact ratios varying with the O_3 scenarios used.
- For the sensitivity experiment with 5 °C temperature increase, and with the assumption of no threshold for O_3 effect, total UK ozone-related deaths brought forward increase by around 500, or by 4%, on the 2003 baseline mortality of around 11,900. The largest mortality increases are in London, South East and East England and the smallest in Scotland and Northern Ireland. When a threshold for O_3 health impact is assumed, there is a proportionally greater increase in total UK ozone-related mortality under the +5 °C scenario, but on much smaller absolute numbers: for a 35 ppbv threshold, a 28% increase of around

300 deaths on a baseline of around 1,200; for a 50 ppbv threshold, a 54% increase of around 100 deaths on a baseline of around 200.

- There are regional differences in health impacts that vary both with the future scenario assumed and with the O_3 threshold used to estimate the impact. This is because of spatial variation in the contribution to O_3 concentrations from long-term average O_3 and from short-term O_3 episodes.

Public health recommendations

- Strengthen warning systems based on air pollution forecasting. Target ozone alerts to high risk groups (individuals with pre-existing illness, elderly, etc.)
- Raise public awareness of the adverse health effects of ground level ozone. Ensure clarity in distinction between surface (or ground level) ozone and the stratospheric ozone layer.

Research needs

- Continued development and validation of detailed chemistry transport models for trace gases and particles that provide coupling between atmospheric chemistry, climate and the land-surface at high spatial resolution.
- Reduction of uncertainties in the emissions inventories of natural sources of O_3 precursors, especially biogenic volatile organic compounds, as well as for components of particulate matter.
- Continued epidemiological and toxicological investigation of the range and extent of health effects of ozone, including those associated with chronic exposure, the potential confounding with temperature, and the extent of geographical and seasonal heterogeneity in O_3 concentration-response coefficient and threshold for health effects for the UK.

3.1 Introduction

This chapter discusses potential future changes to air quality-driven impacts on human health as mediated through changes in exposure to ambient ground level ozone (O_3)[1]. The net change in air quality-related adverse health effects in the future will depend also on changes in exposure to particulate matter (PM) and to nitrogen dioxide (NO_2), which together with O_3 constitute the three ambient air pollutants with greatest population health burden (WHO, 2006). Clearly, O_3 effects should not be considered in isolation from those of other pollutants.

Ground level O_3 has significant impacts on human morbidity and mortality, mostly related to effects on the respiratory system. The effects of O_3 on human health have recently been authoritatively reviewed (e.g. Royal Society, 2008, Chapter 7; TF-HTAP, 2010, Part A, Chapter 5) so will not be repeated here. In summary, there is substantial epidemiological evidence quantifying acute effects from short-term (hours to days) exposure to O_3, but considerable uncertainties remain regarding health effects from chronic exposure (years). This chapter considers only the acute effects, quantified using the standard health-based metric for O_3, the daily maximum running 8-hour mean.

The spatial and temporal variations in concentrations of O_3 in the atmosphere are determined by multiple, complex factors that include its formation within the lower atmosphere via photochemical reactions of precursor gases, its deposition to the surface, and atmospheric transport (Royal Society, 2008; AQEG, 2009). The most important precursor gases for O_3 are methane (CH_4) and carbon monoxide (CO), which are long-lived gases (lifetimes of weeks to years), and nitrogen oxides (NO_x = $NO+NO_2$) and non-methane volatile organic compounds (NMVOC), which are relatively short-lived gases. The concentrations of ground level O_3 over the UK therefore depend on:

(a) the background O_3, which arises from photochemical formation and transport of O_3 throughout the lower atmosphere as well as downward transport of O_3 from the stratosphere;

(b) the local and regional anthropogenic and biogenic emissions of O_3 precursor gases within the UK and the rest of Europe, particularly emissions of NO_x which at low to moderate concentrations contribute to formation of O_3 but at high concentrations reduce O_3 concentrations;

(c) meteorology, via its influences on rates of chemical reactions, loss of O_3 to the surface, long-range transport of O_3, boundary-layer depth and stagnating air pollution episodes.

Climate change can directly or indirectly affect ground level O_3 concentrations through all these processes.

The recent trends for O_3 in the UK are an increase in long-term (annual) mean concentration, due to increasing background O_3 throughout the northern hemisphere, but a decline in the maxima of

[1] Ozone (O_3) is present throughout the atmosphere. It is most abundant in the stratosphere, which is the region of the atmosphere between about 15 km and 50 km above the Earth's surface; the presence of O_3 here has the important consequence of absorbing some of the Sun's harmful ultraviolet (UV) radiation that would otherwise reach the surface. The region of the atmosphere from the surface to about 15 km altitude is the troposphere, and the lowermost 1-2 km of the troposphere is called the mixing layer or planetary boundary layer. This chapter considers the geographical and temporal variations in O_3 which people breathe in the outdoor air in the first few metres above the surface within this mixing layer. This is referred to as 'ground level O_3' in this chapter, but is sometimes also called 'surface O_3.' The O_3 discussed in this chapter always means ground level O_3, unless specifically noted otherwise.

short-term (e.g. hourly and daily) peaks because of Europe-wide reductions in emissions of reactive VOC and NO_x. Historically, concentrations of O_3 in urban areas have been lower than in rural areas because of removal of O_3 through reaction with NO when local emissions of NO are high (as in urban areas). This is often referred to as the urban decrement. However, as NO emissions have decreased, urban O_3 levels are now approaching those of neighbouring rural areas (AQEG, 2009).

Previous estimates of future O_3 over the UK have generally been derived from global models whose horizontal spatial resolutions of a few degrees (hundreds of km) mean that the British Isles is covered by just a few grid cells. In this report high-resolution process-based modelling of ground level O_3 forms the basis for discussion of potential future O_3 concentrations and associated health impacts. This approach is adopted both to fully describe O_3 chemistry and its complex interaction with meteorology, and to simulate the spatial gradients in ground level O_3 concentrations (potentially very important in health burden calculations), that may not be accurately represented by coarse spatial resolution models. The EMEP4UK atmospheric chemistry transport model used here has 5 km horizontal resolution across the UK.

Noting that in the next few decades, changes in anthropogenic emissions are likely to be more influential on ground level O_3 than changes in climate, future EMEP4UK O_3 projections based on emissions scenarios for 2030 relative to 2003 are presented. Although EMEP4UK projections for 2050 are not available, the possible implications for O_3 of emissions scenarios for 2050 and beyond are outlined. Since fully-coupled EMEP4UK simulations of future climate are also unavailable, the impacts of climate change on ground level O_3 are investigated through a temperature sensitivity simulation with EMEP4UK, with the temperature change set in the context of the climate changes projected for the UK by UKCP09, as used in other chapters of this report. The simulated O_3 changes are also set in the context of variability of ground level O_3 arising from inter-annual differences in meteorology. The impacts of these simulated changes in O_3 on UK mortality and morbidity are calculated both with and without inclusion of a threshold concentration for health effects. The impacts on future concentrations of particulate matter and nitrogen dioxide are also briefly discussed

3.2 Methods

3.2.1 Chemistry-transport modelling

EMEP4UK is a nested, grid-based chemistry-transport model (CTM) driven by high-resolution meteorology and national emissions, including biogenic, that produces a detailed representation of the physical and chemical state of the atmosphere over Europe (Vieno *et al.*, 2010). The underlying CTM is the EMEP Unified Model (Simpson *et al.*, 2012), which has been modified to enable application at 5 km spatial resolution over a British Isles inner domain. The EMEP4UK model is driven by the Weather Research Forecast (WRF) model at the same horizontal resolution. The WRF model in turn is constrained by boundary conditions from the US National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Global Forecast System (GFS) at 1° resolution, every 6 hours. Simulations are achieved using a one-way nested domain approach in which large scale modelling over an outer domain at 50 km resolution for Europe provides the boundary conditions for finer-scale modelling over the 5 km inner domain. The EMEP UM and

EMEP4UK models have been extensively validated and used for numerous policy applications (Fagerli *et al.*, 2011; Carslaw, 2011).

Emissions scenarios to 2030

EMEP4UK simulations were performed using three commonly-used O_3 precursor emissions projections, notionally for year 2030, derived by IIASA (the International Institute of Applied Systems Analysis), which span a wide range of possible futures (see Dentener *et al*. (2005) for more details):

- **A2**: Based on the IPCC SRES (Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios) A2 socioeconomic scenario (Nakicenovic *et al.*, 2000), (generally regarded as pessimistic for O_3 precursor emissions), and assuming no additional implementation of air quality legislation;
- **B2+CLE** ('current legislation'): Based on the IPCC SRES B2 socioeconomic scenario, but also including implementation of air quality legislation prevailing in year 2000;
- **B2+MFR** ('maximum feasible reduction'): Also based on the IPCC SRES B2 scenario, but including maximum feasible reductions in emissions through implementation of all abatement measures existing in 2000, regardless of cost.

Together the three scenarios represent a useful range of potential futures. These are the same scenarios discussed in section 7.2.3 of the 2008 edition of this report (HPA, 2008), but the output here is derived from a much higher spatial resolution model.

The extent of emissions changes between 2003 and 2030 averaged over the British Isles for the key precursor species under each scenario are given in Table 3.1. No changes in the spatial distribution of emissions were applied. Output from global model simulations set the corresponding global CH_4 concentrations (Dentener *et al.*, 2005), and the EMEP4UK outer domain O_3 boundary conditions (Stevenson *et al.*, 2006), appropriate for each scenario.

Table 3.1. Percentage changes in annual anthropogenic emissions between 2003 and 2030 (summed over all grid squares in the inner EMEP4UK domain; i.e. the British Isles), and the concentration changes in CH_4 and in the O_3 at the inner domain boundary.

	A2 scenario	B2+CLE scenario	B2+MFR scenario
ΔNO_x emissions	+43%	−20%	−43%
ΔCO emissions	+13%	−49%	−57%
ΔVOC emissions	+49%	−14%	−26%
ΔCH_4 concentrations (2003: 1760 ppbv)	+403 ppbv	+328 ppbv	0 ppbv
ΔO_3 concentrations at model boundary (annual mean) (2003: 39.5 ppbv)	+5.8 ppbv	+2.7 ppbv	−1.8 ppbv

Temperature sensitivity experiment

Although simulations of EMEP4UK under possible future climates are not available, sensitivity studies with EMEP4UK that isolate the temperature-related drivers on O_3 (Vieno *et al.*, 2010) are

discussed in the results section. In these EMEP4UK simulations, temperatures are uniformly increased in the inner domain by 5 °C from their values in 2003 with this temperature increase set in the context of UKCP09 temperature projections up to the 2080s.

3.2.2 Health impact assessment methodology

Population health burdens for O_3 were calculated for the 12 UK administrative regions listed in Table 3.2 via the following approach which links O_3 exposure in a region with population and underlying adverse health rate in that region:

Daily mortality = daily O_3 × concentration-response coefficient × baseline death rate × population

Throughout this chapter, 'daily O_3' refers to the daily maximum running 8-hour mean, as is widely used in O_3 health effect studies. Daily maximum 8-hour O_3 concentrations were derived for the whole year for each UK region by calculating the mean of the daily O_3 values for all EMEP4UK grid cells in that region.

Table 3.2. UK administrative regions and their populations in 2003 and 2030. The regional annual mean O_3 concentrations from EMEP4UK simulations for 2003 (baseline year), for +5 °C temperature sensitivity on the baseline year, and for projections for 2030 for three emissions scenarios, A2, B2+CLE and B2+MFR, were calculated as the mean of all daily maximum 8-hour O_3 across each region for the year.

	2003		2030 emissions scenarios				+5 °C c.f. 2003
Region	**Population (1000s)**	**Baseline O_3 (ppbv)**	**Population (1000s)**	**A2 O_3 (ppbv)**	**B2+CLE O_3 (ppbv)**	**B2+MFR O_3 (ppbv)**	**+5 °C O_3 (ppbv)**
South West – SW	5,003	36.9	6,197	37.4	38.9	36.3	38.3
South East –SE	8,080	35.0	9,859	33.6	37.3	35.5	36.8
London – LN	7,380	31.4	9,029	28.5	34.4	33.7	33.2
East England – EE	5,468	33.8	6,963	32.4	36.5	34.7	35.6
Wales – WA	2,929	35.8	3,313	37.2	38.0	35.4	37.0
West Midlands – WM	5,310	33.3	6,037	33.2	35.6	33.5	34.7
East Midlands – EM	4,254	32.6	5,237	31.8	35.3	33.5	34.2
North West – NW	6,799	33.6	7,411	34.2	35.9	33.7	34.8
Yorkshire & Humberside – YH	5,029	32.8	6,180	32.8	35.3	33.4	34.2
North East – NE	2,540	33.8	2,804	35.0	36.0	33.6	35.0
Scotland – SC	5,057	35.4	5,522	38.1	37.3	34.4	36.1
Northern Ireland – NI	1,703	35.1	1,998	37.6	36.9	34.1	35.8
Total population	59,552		70,550				

To quantify mortality, an all-cause mortality concentration-response coefficient of 0.3% per 10 $\mu g\ m^{-3}$ increase in daily maximum running 8-hour mean O_3 was used (equivalent to 0.6% increase per 10 ppbv O_3), as recommended by the World Health Organization (WHO, 2004) and used in similar studies (Section 3.3.2). This coefficient estimates deaths brought forward by at least one day, but provides no other insight as to how much further forward the death occurs.

To quantify morbidity, a concentration-response coefficient of 1.4% increase in respiratory hospital admissions per 10 ppbv increase in O_3 was used (COMEAP, 1998). The hospital admissions quantified by this coefficient can be both brought forward and additional admissions. Both coefficients were applied equally to all ages in the population and followed that used in previous UK studies (HPA, 2008; Stedman and Kent, 2008).

Baseline daily mortality rates for all causes, excluding external, for a representative year were calculated based on a mean of values for each day of the year between 1993 and 2006 from data obtained from the Office for National Statistics (http://www.ons.gov.uk). The use of a daily baseline mortality rate rather than a single annual rate takes account of variations in mortality throughout the year. Furthermore, the daily mortality rates were calculated for each of the 12 administrative regions separately. Baseline daily morbidity data were not available, so an annual baseline morbidity rate was used, derived from emergency respiratory hospital admissions obtained from the NHS Hospital Episode Statistics site (http://www.hesonline.nhs.uk). The annual mean morbidity rate for each region was based on data for the years 2005 – 2008 and ranged from 991 emergency respiratory hospital admissions per 100,000 for the South East to 1,403 per 100,000 in Northern Ireland. The UK average morbidity rate across all regions was 1,151 per 100,000.

The population figures for the 12 UK regions for 2003 given in Table 3.2 were obtained from ONS data (www.statistics.gov.uk), whilst the 2030 population estimates were derived by linear interpolation between projections by ONS for 2026 and 2031 (English regions) and 2028 and 2033 (Wales, Scotland and Northern Ireland).

The premature mortality and hospitalizations for each administration region were calculated daily then summed over the year to obtain the annual premature mortality and morbidity estimates attributable to exposure to O_3. Calculations were undertaken assuming no threshold, and for thresholds of 35 ppbv (70 $\mu g\ m^{-3}$) and 50 ppbv (100 $\mu g\ m^{-3}$) for O_3 health effects, and for the whole year of exposure. The threshold values follow previous recommendations from a UNECE/WHO task force on health aspects of air pollution (UNECE/WHO, 2004). No attempt is made to isolate the effects of O_3 episodes, both because of the difficulty in defining an 'episode' in this context and because there is little firm evidence regarding an appropriate concentration-response coefficient to use during episode conditions. However, the extent of population health burden arising from exposures on days of higher concentrations is revealed from comparison of burdens derived with and without O_3 concentration thresholds.

A previous health impact assessment for O_3 for the years 1995, 2003 and 2005 used a slightly different technique (Stedman and Kent, 2008). Ozone maps at 1 km $\times$ 1 km resolution were produced for the UK using interpolation of measurements from the national network rural sites (for the 'well-mixed' afternoon period of 12.00-18.00), with corrections for altitude and the urban decrement (mapping methodology described in Coyle *et al.* (2002)). The health impact assessment applied 1 km^2 population data from the 2001 census to the 1 km^2 interpolated modelled O_3 and summed for the whole UK. Differences between the analyses here and the method used by Stedman and Kent (2008) are that here a time-resolved 5 km $\times$ 5 km gridded chemical transport model is used rather than a semi-empirical pollution mapping model for the O_3 data and that health impacts are derived for 12 UK regions separately rather than the UK as a whole. However, in the results presented here regional mean values of O_3 are used, rather than data on a regularly spaced grid.

3.3 Results for ozone

3.3.1 Simulations of ozone concentrations

Ozone projections based on anthropogenic emissions scenarios to 2030

Figure 3.1 illustrates the change in annual mean ground level O_3 for the three different emissions scenarios between 2003 and 2030 using meteorology for the year 2003. The same underlying data expressed as the annual mean of daily maximum 8-hour O_3 across all EMEP4UK grid cells in each of the 12 UK administrative regions is given in Table 3.2, for the baseline year 2003 and for the three future emission scenarios. Table 3.2 shows that in 2003 the highest annual mean O_3 concentrations were in South West England, Wales, Scotland and Northern Ireland and the lowest values were in London, the East Midlands and Yorkshire and Humberside, the latter being the eastern regions associated with cities and high-NO_x levels (see below).

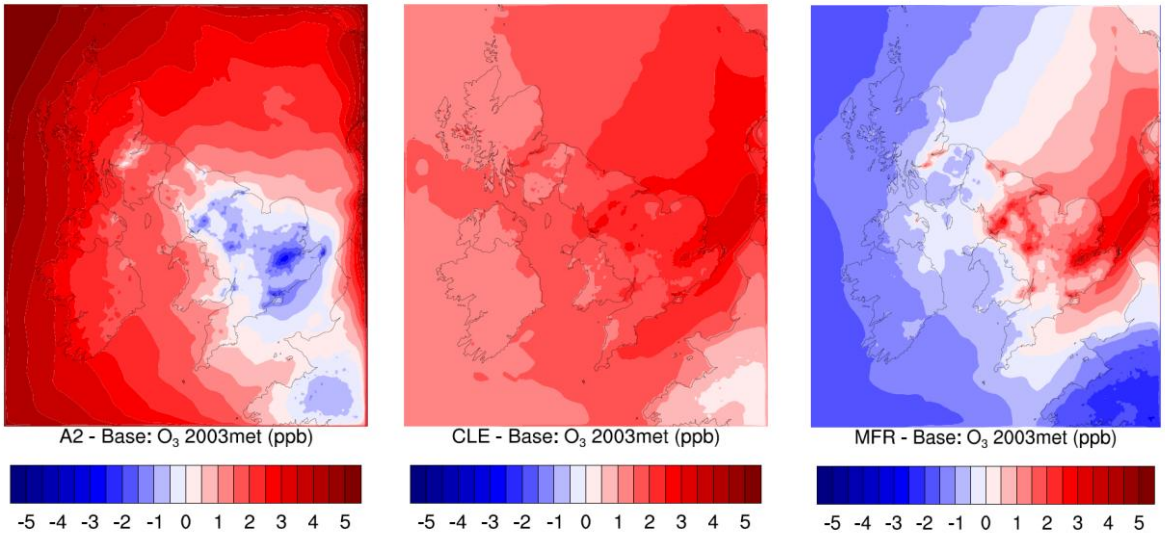

Figure 3.1. Changes in annual mean ground level O_3 (ppbv) (2030 – 2003) for emissions scenarios A2 (left), B2+CLE (centre) and B2+MFR (right), simulated by EMEP4UK (all using 2003 meteorology).

The key features in Figure 3.1 and Table 3.2 are: for the B2+CLE scenario, increases in O_3 of 0.5-3 ppbv everywhere over the UK; for the A2 scenario, decreases over most of England (except the far north), reaching −2 ppbv in urban areas but −3 ppbv in the London area, and increases of 0-3 ppbv everywhere else; and, for the B2+MFR scenario, the reverse of the pattern under A2 (increases of 0-3.5 ppbv over most of England, plus south Wales, Edinburgh-Glasgow and Belfast, and decreases up to −1.5 ppbv elsewhere).

These changes in UK ground level O_3 reflect differences in the amount of background O_3 imported to the domain (approximately set by the boundary conditions in Table 3.1), in conjunction with differences due to changes in UK NO_x emissions that influence the extent of O_3 removal through reaction with NO in high NO_x (i.e. urban) regions (section 3.1). Thus in the A2 scenario, background O_3 increases because of hemispheric increases in O_3 precursors, including CH_4 and CO, but the increased localised NO_x emissions (primarily related to traffic density and power generation) over

most of England leads to increased loss of O_3 by reaction with NO. This effect is prominent over most major UK cities (Figure 3.1). The greater annual mean ground level O_3 concentration over most of England for the B2+MFR scenario is due to the substantial reductions in NO_x emissions causing a decrease in the loss of O_3 by this chemical reaction (again a prominent feature over UK cities). These localised O_3 increases are superimposed on the general decrease in background ground level O_3 in this scenario. The O_3 changes are greatest under the B2+CLE scenario (Scotland excepted) (Table 3.2), since O_3 concentrations increase as a result of both increases in background O_3 concentration (as in the A2 scenario) and decreases in UK NO_x emissions (as in the B2+MFR scenario) (Table 3.1).

These results for the B2+MFR scenario differ markedly from those reported using the STOCHEM global CTM in Section 7.2.3 of the previous HPA (2008) report. The sensitivity of model-simulated changes of ground level O_3 to model horizontal resolution is illustrated in Figure 3.2. This shows the 2030-2003 change in summer ground level O_3 (mean for June-July-August (JJA)) under the B2+MFR emissions scenario produced by 3 models of different spatial resolution. The right-hand panel shows the ensemble-mean result for a number of global CTMs (which include the STOCHEM model) (Stevenson *et al.*, 2006). The coarse-scale (~200 km horizontal resolution) global CTMs simulate decreases in O_3 everywhere over the British Isles under the B2+MFR emissions scenario whereas the higher spatial resolution models simulate increases in O_3 over much of England. The higher resolution model clearly captures the increased O_3 concentrations attributable to the NO_x reductions in the most densely populated areas of the UK. These differences in model capability clearly have a major impact on health burdens calculated from model-derived exposure to O_3.

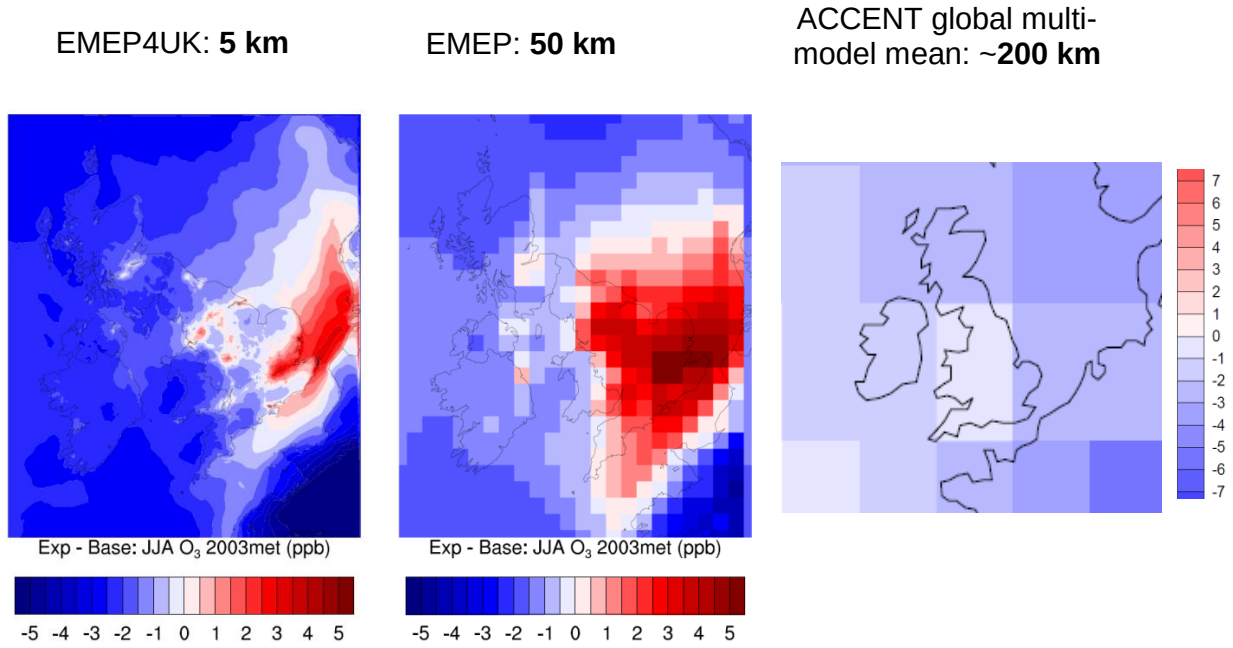

Figure 3.2. Changes in June-July-August (JJA) mean ground level O_3 (ppbv) (2030-2003) for the Maximum Feasible Reductions (MFR) emissions scenario, for models with spatial resolution of 5 km (EMEP4UK), 50 km (EMEP UM), and ~200 km (multi-model mean of 26 global models with mean resolution about 3°, as used in Stevenson *et al*. (2006)).

Ozone projections based on anthropogenic emissions scenarios for 2050 and 2100

High-resolution simulations with EMEP4UK for emissions scenarios beyond 2030 have not been undertaken. However, an updated B2+CLE emissions scenario, extended to 2050, has been used by a number of CTMs in coarser (~200 km) spatial resolution global simulations (Royal Society, 2008, Chapter 5). For these simulations, spatially averaged ground level O_3 across Europe decreases overall in 2050 relative to 2000, and the simulated 2050 European annual mean O_3 is about mid-way between the B2+CLE and B2+MFR values simulated by global models for 2030 (Royal Society, 2008, Figure 5.9a). However, changes in O_3 are not uniform throughout the year; whilst spring and summertime O_3 is lower in 2050 than in 2000, O_3 concentrations in winter are higher. Note also that this simulation is for Europe-wide mean ground level O_3, and from coarse spatial scale global models whose ground level O_3 simulation can differ from higher resolution models, as illustrated in Figure 3.2.

The Royal Society (2008) report also presents O_3 projections for 1990-2100 from the Pollution Climate Model (PCM), which simulates partitioning of oxidants (O_3 and NO_2) for different NO_x emissions (see Sections 3.3.2 and 5.4 of Royal Society (2008)). These results also indicate that future UK ground level O_3 will be determined by the interplay between imported levels of background O_3, and, especially in urban locations, the magnitude of local NO_x emissions (e.g. Figure 5.13, Royal Society (2008)). The emissions scenarios used by the PCM in Royal Society (2008), like most air quality emissions scenarios, project reductions in UK NO_x emissions, and these will lead to localised increases in O_3, due to reduced reactive removal with NO. However there are expected benefits of reduced O_3 in more rural downwind locations where background NO_x levels are lower.

Background O_3 is influenced by hemispheric emissions and global levels of CH_4. Different projections of O_3 for the latest IPCC Representative Concentration Pathways (RCP) scenarios for 2000-2100 mainly reflect the much higher levels of CH_4 in one scenario (RCP8.5), which leads to higher levels of background O_3 (Cionni *et al.*, 2011; Wild *et al.*, 2012). Future changes in natural emissions of O_3 precursors that are sensitive to climate, as well as climate change impacts on ground level O_3 are discussed below.

In summary, depending on the anthropogenic emissions trajectory worldwide, and the extent of current NO_x concentrations in a particular geographic area, ground level O_3 in different parts of the UK may increase or decrease. If some countries worldwide do not follow the 'current legislation' emissions course on which they have agreed then the decreases in UK background O_3 projected beyond 2030 (upon which localised episodes are superimposed) are likely to be reversed.

Year-to-year variability in simulated ground level ozone

The impact of inter-annual variability in meteorology is illustrated in Figure 3.3 which shows the change in annual mean ground level O_3 between 2003 and 2004. Both simulations use the same emissions and outer domain boundary conditions in order to isolate the effect of the different meteorology. Although 2003 included the extreme August heat-wave episode, annual mean ground level O_3 was greater in most of the UK in 2004 (by >1 ppbv across the northern half of the UK), the exception being the southern-most counties and the near continent which had greater annual mean O_3 in 2003. This illustrates that inter-annual variability of ground level O_3 can vary both geographically and with season.

Comparison of Figures 3.1 and 3.3 illustrates the general magnitude of impact on ground level O_3 from potential changes in emissions to 2030 (−3 to +3.5 ppbv, depending on scenario) relative to impact from changes due to regional meteorology alone (−1.5 to +2 ppbv). Whilst the O_3 changes due to meteorology are smaller they are nonetheless considerable, being up to ~50% (depending on scenario) of the changes projected to 2030 from anthropogenic emissions changes. Andersson and Langner (2007) analysed inter-annual variability of O_3 over Europe over a longer time period (1958-2003), using a regional CTM. Over the UK, these authors found typical year-to-year variability of ~10%, broadly consistent with the variation in ground level O_3 simulated by EMEP4UK between 2003 and 2004 (Figure 3.3).

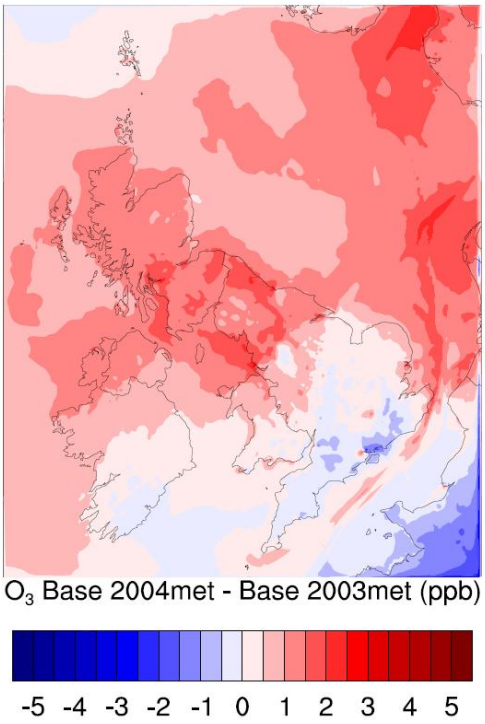

Figure 3.3. Example impact of meteorological variability on annual mean ground level O_3 (ppbv) simulated by EMEP4UK (year 2004 meteorology – year 2003 meteorology; fixed emissions and boundary conditions).

Potential sensitivity of ground level ozone to climate change

Climate can influence ground level O_3 in many ways, as described in detail elsewhere (AQEG, 2007; Royal Society, 2008; AQEG, 2009; Jacob and Winner, 2009), some of which have been simulated in models. Natural emissions of O_3 precursors generally increase as the climate warms, in particular isoprene from vegetation, NO from soil, and CH_4 from wetlands. Countering increases from higher temperatures, there is evidence that increases in CO_2 reduces plant VOC emissions (Arneth *et al.*, 2010). In addition, changes in soil moisture associated with climate change will influence O_3 dry deposition, leading to increased ground level O_3 when soils become drier. On average, this effect is suggested to be small for the UK (Andersson and Engardt, 2010) although Vieno *et al*. (2010) found large influences of dry deposition on O_3 in south-east UK on certain days during the 2003 heatwave. Coarse-resolution global CTM studies suggest that, overall, the net impact of climate change on

ground level O_3 is generally a decrease in remote areas, where NO_x concentrations are low, but an increase in some densely populated areas, where NO_x concentrations are high (TF-HTAP, 2010).

Climate change may also affect ground level O_3 through changes in atmospheric transport and mixing processes, from small scales (e.g. boundary layer ventilation and convection), through synoptic scales (e.g. location of storm tracks and prevalence of anticyclonic 'blocking highs'), up to planetary scales (e.g. increases in the Brewer-Dobson circulation), together with shifts in modes of climate variability such as the North Atlantic Oscillation (which in turn may affect the frequency of storms). Changes in these processes may affect inter-annual variability of ground level O_3 (see above) as well as O_3 episodes. Import of polluted air from continental Europe to the UK can be a significant component of ground level O_3 in the UK (Vieno *et al.*, 2010), so changes in this aspect of synoptic (long range) transport, as well as climate-mediated changes in continental European O_3, will be important for UK O_3. At present the consensus is that global climate models cannot reliably predict future trends in 'blocking highs' which can influence import of O_3 into the UK and stagnation events (Scaife *et al.*, 2010).

Figure 3.4 illustrates the influence of increased temperature on ground level O_3 at high resolution over the entire UK as simulated by EMEP4UK for a +5 °C uniform increase in temperature (compared with the 2003 baseline) for the whole year. This temperature increase was applied only to the inner (UK) domain so that changes to O_3 outside the UK domain are not represented. The same underlying data expressed as the regional annual mean of the daily maximum 8-hour O_3 across all EMEP4UK grid cells in each of the 12 UK administrative regions is given in Table 3.2.

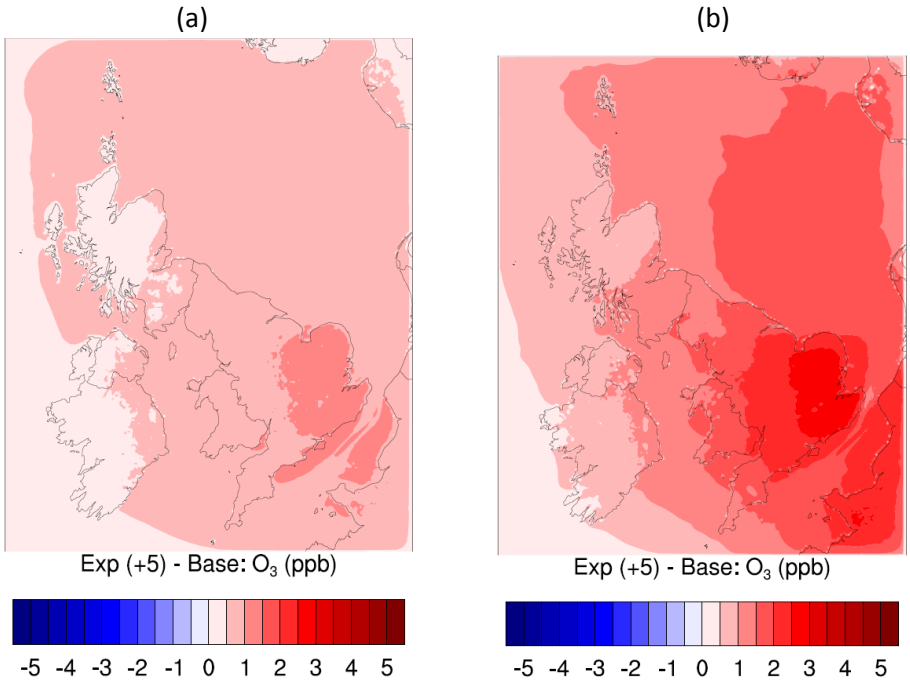

Figure 3.4. Change in ground level O_3 (ppbv) simulated by EMEP4UK for a +5°C increase in temperature applied uniformly for the whole year within the UK model domain shown, relative to the base simulation for meteorological year 2003; (a) annual mean, (b) summer mean (June-July-August).

Figure 3.4a shows that annual mean ground level O_3 increases everywhere, with the largest increases (1.0-1.5 ppbv) in south-east England and the English Channel. Summer mean increases in ground level O_3 are larger than annual increases everywhere, reaching 2.5-3 ppbv in parts of south-east England (Fig. 3.4b). Ground level O_3 increases of up to 10 ppbv were simulated on individual days during the August 2003 heat-wave at a site in south-east England (Vieno *et al.*, 2010). In these simulations the relevant processes acting on O_3 in relation to increased temperature are enhanced isoprene emissions, reduced O_3 dry deposition to the surface, and enhanced decomposition of peroxyacetylnitrate (a temporary atmospheric reservoir species for NO_x) which leads to local O_3 increases. These annual mean changes in ground level O_3 due to higher mean temperatures are generally lower than potential changes in ground level O_3 due to 2030 emissions changes (−3 to +3.5 ppbv, depending on scenario) or due to year-to-year variability in regional meteorology alone (−1.5 to +2 ppbv).

To contextualise the results of this +5 °C sensitivity experiment for O_3, Table 3.3 summarises the summer (JJA) mean surface air temperature increases projected for three future decades by UKCP09 (http://ukclimateprojections.defra.gov.uk), for three climate scenarios (low (B1), medium (A1B), or high (A1F1) emissions of greenhouse gases). See Chapters 1 and 2 for discussion on UKCP09 temperature projections.

Table 3.3. Summer (JJA) mean surface air temperature increases (compared with a 1961-90 baseline) from the UKCP09 projections (http://ukclimateprojections.defra.gov.uk), for three future decades, and for three climate scenarios (low (B1), medium (A1B), or high (A1F1) emissions of greenhouse gases). Quantitatively, 'central estimate' corresponds to 50% probability that temperature increases will not exceed the stated values, and 'unlikely to be greater than' corresponds to 67% probability that temperature increases will not exceed the stated values.

UKCP09 climate scenario	2020s		2050s		2080s	
	Probability level		Probability level		Probability level	
	Central estimate	Unlikely to be greater than	Central estimate	Unlikely to be greater than	Central estimate	Unlikely to be greater than
Low (B1)	1-2 °C everywhere	1-2 °C everywhere	2-3 °C almost everywhere	3-4 °C southern England, 2-3 °C everywhere else	3-4 °C southern England, 2-3 °C everywhere else	3-4 °C almost everywhere, 2-3 °C NI & far north of Scotland
Medium (A1B)	1-2 °C everywhere	1-2 °C everywhere	2-3 °C everywhere	3-4 °C most of England & Wales, 2-3 °C NI & Scotland	4-5 °C small part southern England, 3-4 °C everywhere else	4-5 °C almost everywhere, 3-4 °C NI & far north of Scotland
High (A1F1)	1-2 °C everywhere	1-2 °C everywhere	3-4 °C southern England, 2-3 °C everywhere else	3-4 °C almost everywhere, 2-3 °C far north of Scotland	5-6 °C small part southern England, 4-5 °C everywhere else	6-7 °C small part southern England, 5-6 °C nearly everywhere else

According to the UKCP09 projections (Table 3.3), summer mean temperature increases of 5 °C are unlikely to occur in the UK until the 2080s and then only if climate change follows the medium or high climate change scenarios (or worse). There is 50% probability that summer mean temperature increases will reach or exceed 3 °C by the 2050s in southern England under the high climate change scenario, and 33% probability that increases will reach or exceed 3 °C over much of the UK by the 2050s, even under the low climate change scenario.

In summary, and within the range of current model uncertainty, indications from the EMEP4UK temperature sensitivity simulation (and others elsewhere) are that on a timescale up to at least the mid-21st century the net impact of climate change alone on UK mean ground level O_3 is likely be considerably smaller than the impact of changes in anthropogenic precursor emissions, and within the range of model uncertainty and inter-annual variability. If climate perturbations become more pronounced on a multi-decade time horizon then impacts on ground level O_3 may become stronger. The EMEP4UK perturbed temperature simulation suggests that the temperature aspect of climate change will increase annual and summer mean ground level O_3 in the UK and this will likely counteract reductions in background O_3 arising from increased destruction of O_3 through increased HO_x radicals derived from the increased water vapour in the air at higher temperatures. However, the net impact of climate change is sensitive to NO_x concentrations so the direction and magnitude of the effect of climate change on ground level O_3 in the UK will also depend on future NO_x emissions. Climate change may have relatively greater influence on future peak episodic O_3 than on annual mean O_3 (Jacob and Winner, 2009) but changes in O_3 episodes due to climate change are highly uncertain.

Changes in population exposure to O_3 due to climate change adaptation factors

As well as the influence that climate change may have directly, such as changes to future anthropogenic emissions of O_3 precursors (e.g. evaporative VOC emissions), the indirect influence of mitigation and adaptation responses to climate change should be considered. It is likely that individual and population behaviour will be modified in the future due to the effects of climate change. On an individual level, increased temperature in future is likely to affect lifestyle in terms of time spent outdoors in hot weather where the risk of exposure to O_3 is greatest. At a population level, climate change adaptation and mitigation concerns may lead to changes in vehicle and industrial emissions which will influence O_3 chemistry. Modification of building design in future is likely to have an impact on O_3 exposure, through changes in air conditioning and ventilation measures. Vulnerable populations are likely to have less access to air conditioning and rely on open windows for ventilation, increasing the risk of exposure indoors from outside sources. Development techniques for mitigation for and adaptation to climate change in urban areas could be used to reduce the extent of the urban heat island and associated air pollution by introducing green areas, increasing water availability, and changing urban geometry. As well as changes to the environment and behaviour to consider, it is possible that climate change will act as a modifier to the health effects of O_3. For example, evidence suggests that the health impact of O_3 is more significant at higher temperatures in London (Pattenden *et al.*, 2010).

3.3.2 Health impact assessment results

Changes in average vs. episodic O_3 concentration

Population exposure to O_3 is influenced both by long-term-average and episodic concentrations of O_3. When no threshold for a health impact is assumed, it does not matter (in terms of an annual total health burden) how the O_3 concentration varies from day to day; but if a threshold is assumed then it is the days of highest O_3 concentration that contribute most to the estimated annual impact on health. The numbers of days with O_3 above a certain threshold vary geographically and according to emission scenario or temperature sensitivity applied, as illustrated in Figure 3.5. This figure shows the percentage of days on which daily maximum 8-hour O_3 exceeded 35 ppbv and 50 ppbv for the model simulations under the three future emissions scenarios and the +5 °C temperature scenario, for the three regions South East England, London and Scotland.

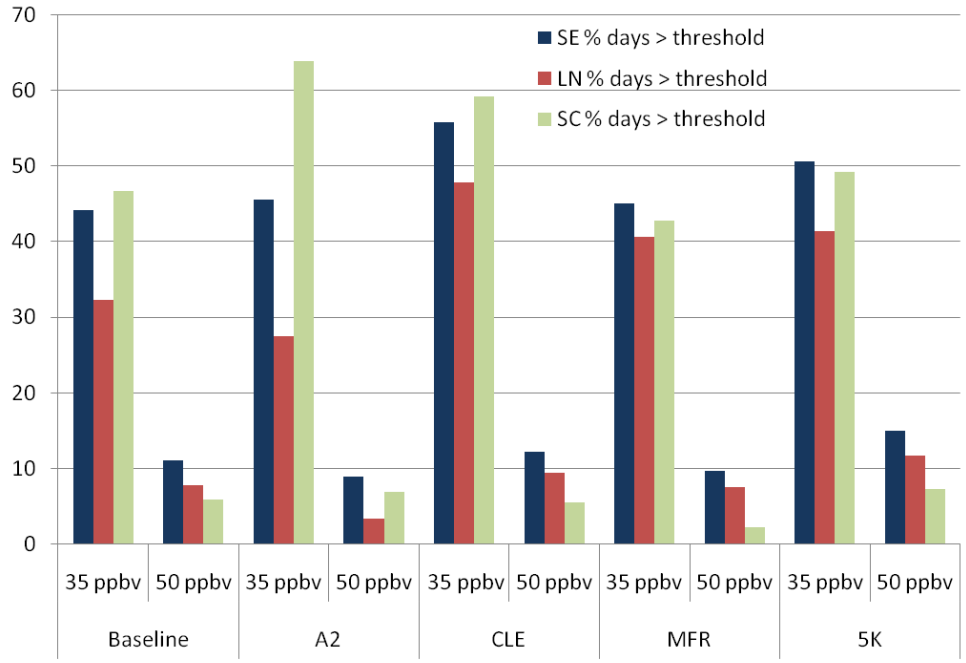

Figure 3.5. Percentage of days where daily maximum 8-hour O_3 exceeded 35 ppbv and 50 ppbv for baseline (2003), A2, B2+CLE, B2+MFR (2030) scenarios and the +5 K temperature sensitivity experiment, for example administrative regions South East (SE), London (LN) and Scotland (SC).

Under the A2 scenario there are fewer days with O_3 above 35 ppbv in London in 2030 compared with the baseline but more days with O_3 above 35 ppbv in Scotland (the number of days >35 ppbv in the South East region is about the same in the two years). Similarly, there are fewer days with O_3 >50 ppbv in London and SE England under the A2 scenario but more days in Scotland with O_3 exceeding 50 ppbv. In contrast to the A2 scenario, under the B2+MFR scenario, there are more days when O_3 exceeds 35 and 50 ppbv in London but fewer days in Scotland as compared to the baseline. For the B2+CLE scenario there are more days with O_3 >35 ppbv in 2030 than in 2003 in all three regions illustrated, whereas the number of days with O_3 >50 ppbv increases slightly in London but is about the same as in 2003 for the South East England and Scotland regions. For the +5 °C temperature

sensitivity experiment the number of days with daily O_3 greater than 35 and 50 ppbv increased in all three regions (and in all regions in the UK). These trends reflect the patterns of changes in ground level O_3 already discussed in Section 3.3.1).

Health impacts – 2003 baseline

Results for the calculations of premature mortality and morbidity health impacts attributable to O_3 are shown in Tables 3.4 and 3.5, respectively. The figures for 2003 are broadly similar to those reported by Stedman and Kent (2008). When no threshold is assumed, the present work yields a UK total of 11,859 deaths brought forward and 31,542 hospitalizations attributable to O_3 in 2003, compared with 10,943 and 25,276, respectively, in Stedman and Kent (2008). The difference in numbers reflects variation in the methods used to perform the health impact assessment e.g. the use of daily versus annual baseline mortality rates, and regional-average ozone estimates.

The total O_3-related mortality and morbidity estimates for 2003 in Tables 3.4 and 3.5 are also broadly consistent with the values 10,107 and 35,727, respectively, from the Climate Change Risk Assessment (CCRA) for the UK Health Sector (Hames and Vardoulakis, 2012). Again, variations between estimates reflect differences in methodology; in particular, the lower morbidity estimate of 31,542 in Table 3.5 is because the present work only considered emergency respiratory hospitalizations rather than all respiratory hospital admissions as was used in the CCRA.

Table 3.4. Regional and total UK annual deaths brought forward attributable to O_3 assuming no threshold, a 35 ppbv threshold and a 50 ppbv threshold for the 2003 baseline, and 2030 projections under the A2, B2+CLE and B2+MFR emissions scenarios. The 2030 mortality data include the estimated population changes.

	Annual deaths brought forward, no threshold				**Annual deaths brought forward, with 35 ppbv threshold**				**Annual deaths brought forward, with 50 ppbv threshold**			
	2003		**2030**		**2003**		**2030**		**2003**		**2030**	
Region	**Base-line**	A2	B2+ CLE	B2+ MFR	**Base-line**	A2	B2+ CLE	B2+ MFR	**Base-line**	A2	B2+ CLE	B2+ MFR
SW	**1159**	1457	1513	1416	**146**	200	219	153	**31**	25	37	22
SE	**1601**	1879	2086	1985	**208**	211	305	234	**57**	38	67	46
LN	**1063**	1182	1429	1401	**119**	94	178	150	**36**	19	43	35
EE	**1019**	1249	1401	1336	**124**	125	202	154	**28**	16	36	24
WA	**687**	807	825	769	**73**	105	107	71	**12**	10	14	7
WM	**1034**	1176	1258	1187	**102**	119	149	107	**18**	11	21	12
EM	**796**	956	1060	1009	**83**	88	131	97	**16**	9	20	11
NW	**1453**	1617	1694	1591	**127**	153	181	121	**16**	7	17	9
YH	**994**	1222	1314	1243	**85**	103	139	97	**12**	5	15	7
NE	**562**	642	661	618	**46**	64	68	43	**5**	3	5	2
SC	**1193**	1402	1373	1270	**100**	172	145	84	**9**	8	9	4
NI	**298**	375	368	340	**25**	47	39	22	**3**	3	3	1
TOTAL	**11859**	**13966**	**14982**	**14165**	**1236**	**1480**	**1864**	**1333**	**242**	**156**	**285**	**180**

Table 3.5. Regional and total UK annual respiratory hospitalizations attributable to O_3, for the situations described in Table 3.4

	Annual hospitalizations no threshold				**Annual hospitalizations with 35 ppbv threshold**				**Annual hospitalizations with 50 ppbv threshold**			
	2003		**2030**		**2003**		**2030**		**2003**		**2030**	
Region	**Base-line**	A2	B2+ CLE	B2+ MFR	**Base-line**	A2	B2+ CLE	B2+ MFR	**Base-line**	A2	B2+ CLE	B2+ MFR
SW	**2986**	3752	3895	3641	**388**	529	582	408	**83**	67	99	58
SE	**3871**	4536	5038	4790	**524**	529	769	591	**147**	97	171	119
LN	**3228**	3582	4330	4240	**376**	296	563	474	**115**	61	136	113
EE	**2602**	3182	3575	3406	**329**	331	538	408	**74**	43	98	65
WA	**1643**	1930	1971	1838	**179**	256	263	175	**31**	26	34	18
WM	**2824**	3208	3432	3234	**290**	335	424	305	**53**	31	62	35
EM	**2384**	2857	3170	3014	**257**	272	408	303	**49**	29	62	36
NW	**4152**	4614	4834	4538	**375**	448	535	360	**47**	22	51	28
YH	**2706**	3322	3577	3381	**241**	289	392	276	**34**	16	42	21
NE	**1285**	1469	1511	1412	**110**	149	161	102	**11**	8	12	4
SC	**2705**	3180	3113	2876	**232**	395	335	194	**22**	20	22	8
NI	**1157**	1456	1430	1318	**98**	185	153	88	**10**	13	12	4
TOTAL	**31542**	**37087**	**39876**	**37687**	**3398**	**4014**	**5124**	**3684**	**677**	**433**	**800**	**509**

If a threshold for O_3 effects is assumed then total annual premature mortality attributable to O_3 in 2003 drops dramatically, from 11,859 (no threshold) to 1,236 for a threshold of 35 ppbv, and to 242 for a threshold of 50 ppbv (Table 3.4). (The corresponding mortality estimates from Stedman and Kent (2008) for the same thresholds are 1,565 and 402, respectively.) Decreases in O_3-attributable morbidity in 2003 are similarly large, decreasing from 31,542 hospitalisations when no threshold is assumed to 3,398 and 677 hospitalizations under assumptions of a 35 ppbv and 50 ppbv threshold, respectively. (Comparator values from Stedman and Kent (2008) are 3,614 and 929, respectively.)

The premature mortality data given in Table 3.4 is expressed per 100,000 population in Table 3.6. The health burden attributable to O_3 in 2003 (assuming no threshold) is generally greatest in the South East and North West of England, where population levels are high, and in Scotland, where annual mean O_3 is high (Tables 3.4 and 3.5). Despite London having the lowest annual mean O_3 (Table 3.2) and lowest mortality rate (Table 3.6), the large population puts it in 5th place regionally for the mortality-related health burden attributable to O_3 in 2003 (Table 3.4). The attributable mortality rate is greatest in the South West, Wales and Scotland (Table 3.6) where annual mean O_3 is greatest (Table 3.2). The picture is slightly different if thresholds are assumed.

Table 3.6. Regional and total UK annual deaths brought forward per 100,000 population attributable to O_3 assuming no threshold, a 35 ppbv threshold and a 50 ppbv threshold for the 2003 baseline, and 2030 projections under the A2, B2+CLE and B2+MFR emissions scenarios.

	Annual deaths brought forward per 100,000, no threshold				Annual deaths brought forward per 100,000, with 35 ppbv threshold				Annual deaths brought forward per 100,000, with 50 ppbv threshold			
	2003	2030			2003	2030			2003	2030		
Region	**Base-line**	A2	B2+ CLE	B2+ MFR	**Base-line**	A2	B2+ CLE	B2+ MFR	**Base-line**	A2	B2+ CLE	B2+ MFR
SW	23.2	23.5	24.4	22.8	2.91	3.22	3.53	2.47	0.62	0.40	0.59	0.35
SE	19.8	19.1	21.2	20.1	2.57	2.14	3.09	2.37	0.71	0.39	0.68	0.47
LN	14.4	13.1	15.8	15.5	1.61	1.04	1.97	1.66	0.49	0.21	0.47	0.39
EE	18.6	17.9	20.1	19.2	2.26	1.80	2.91	2.21	0.50	0.23	0.52	0.34
WA	23.5	24.4	24.9	23.2	2.48	3.16	3.23	2.14	0.41	0.31	0.41	0.22
WM	19.5	19.5	20.8	19.7	1.92	1.98	2.47	1.77	0.35	0.18	0.35	0.20
EM	18.7	18.3	20.2	19.3	1.95	1.68	2.51	1.86	0.37	0.18	0.37	0.22
NW	21.4	21.8	22.9	21.5	1.86	2.06	2.44	1.64	0.23	0.10	0.23	0.12
YH	19.8	19.8	21.3	20.1	1.69	1.67	2.24	1.58	0.24	0.09	0.24	0.12
NE	22.1	22.9	23.6	22.0	1.83	2.27	2.43	1.54	0.18	0.12	0.17	0.06
SC	23.6	25.4	24.9	23.0	1.97	3.11	2.62	1.51	0.18	0.15	0.17	0.06
NI	17.5	18.7	18.4	17.0	1.44	2.35	1.94	1.11	0.15	0.16	0.15	0.05

Health impacts – 2030 projections

Tables 3.4 and 3.5 respectively provide the regional health impacts on premature mortality and morbidity attributable to O_3 under the three different emissions scenarios. It must be noted that these data also reflect the estimated population increase in each region in 2030 (Table 3.2). Therefore Table 3.6 expresses the premature mortality data per 100,000 population. Figure 3.6 illustrates the changes in estimated annual mortality rate per 100,000 between 2003 and 2030 for the different scenarios; the patterns in changes in hospitalization are similar.

When no threshold for O_3 impact is assumed, all three 2030 emissions scenarios project increased mortality and hospitalization in all regions compared with 2003 (Tables 3.4 and 3.5). The highest UK total health impacts are associated with the B2+CLE (current legislation) scenario. This scenario gives increases in mortality and hospitalization of 3,123 and 8,334 respectively, which represents a 26% increase for both on their 2003 values of 11,859 and 31,542 respectively. These health impact increases are not just driven by the increase in UK population, which is 18% greater in 2030 than in 2003, but reflect the increase in ground level O_3 over most of the UK under this scenario (Figure 3.1). Figure 3.6a confirms that mortality rate per 100,000 increases in all regions under the B2+CLE scenario. Although the B2+CLE scenario gives the largest health burden for the UK as a whole, for the low population regions of Scotland and Northern Ireland, it is the A2 scenario (with O_3 increases in these regions) that gives the largest absolute health burden for both the no-threshold and 35 ppbv threshold assumptions (Table 3.4), and the largest increase in mortality rate (Figure 3.6a). The A2

and B2+MFR scenarios show roughly similar increases in total UK mortality and hospitalization in 2030, 18% and 19% for the two scenarios respectively, but with regional differences between the two scenarios (Figure 3.6a). For example, the increase in mortality and hospitalization is larger for the B2+MFR scenario than for the A2 scenario in London, the South East and East England, whereas the increase in these two health impacts is smaller under the B2+MFR scenario than the A2 scenario for Scotland, Northern Ireland and Wales (Tables 3.4 and 3.5). In fact, for these latter regions it is the increase in population that drives the increase in absolute numbers of health impacts under the B2+MFR scenario since mean ground level O_3 (and hence also O_3 health impact rates) decrease in these regions under this scenario (Figures 3.1 and 3.6a).

When a 35 ppbv threshold is assumed, the B2+CLE scenario shows a markedly larger proportional increase in health impact in 2030 than in 2003: a 51% increase in mortality and morbidity on 2003 values compared with the 26% increase when no threshold is assumed (Tables 3.4 and 3.5), but of course the numbers of deaths and hospitalizations are very considerably fewer when a threshold is assumed. There are also regional differences. When a threshold for O_3 effect of 35 ppbv is assumed, everywhere except London shows a decrease in ozone health burden rate under the B2+MFR scenario for 2030 (Figure 3.6b); but after taking into account health burden changes due to projected population changes only the more rural regions in the north and west of the UK such as Scotland, Northern Ireland, Wales and northern England have a slight decrease in mortality under this scenario, whilst the other regions show an increase. For the A2 scenario and a 35 ppbv threshold, most regions have increased health burdens in 2030 but London shows a decrease because of the strong O_3 loss by reaction with NO under this scenario in this wholly urbanised region.

With a 50 ppbv threshold assumption, mortality and hospitalizations increase very slightly in 2030 for the B2+CLE scenario compared with 2003, and decrease for the A2 and B2+MFR scenarios (Tables 3.4 and 3.5). However the absolute numbers and changes in mortality and hospitalization are considerably smaller than those derived for the 35 ppbv threshold or no threshold assumptions. For nearly all regions and all emissions scenarios the health burden rate per 100,000 decreases under a 50 ppbv threshold assumption (Figure 3.6c); so where Tables 3.4 and 3.5 show increased health burdens this is mainly due to increased population.

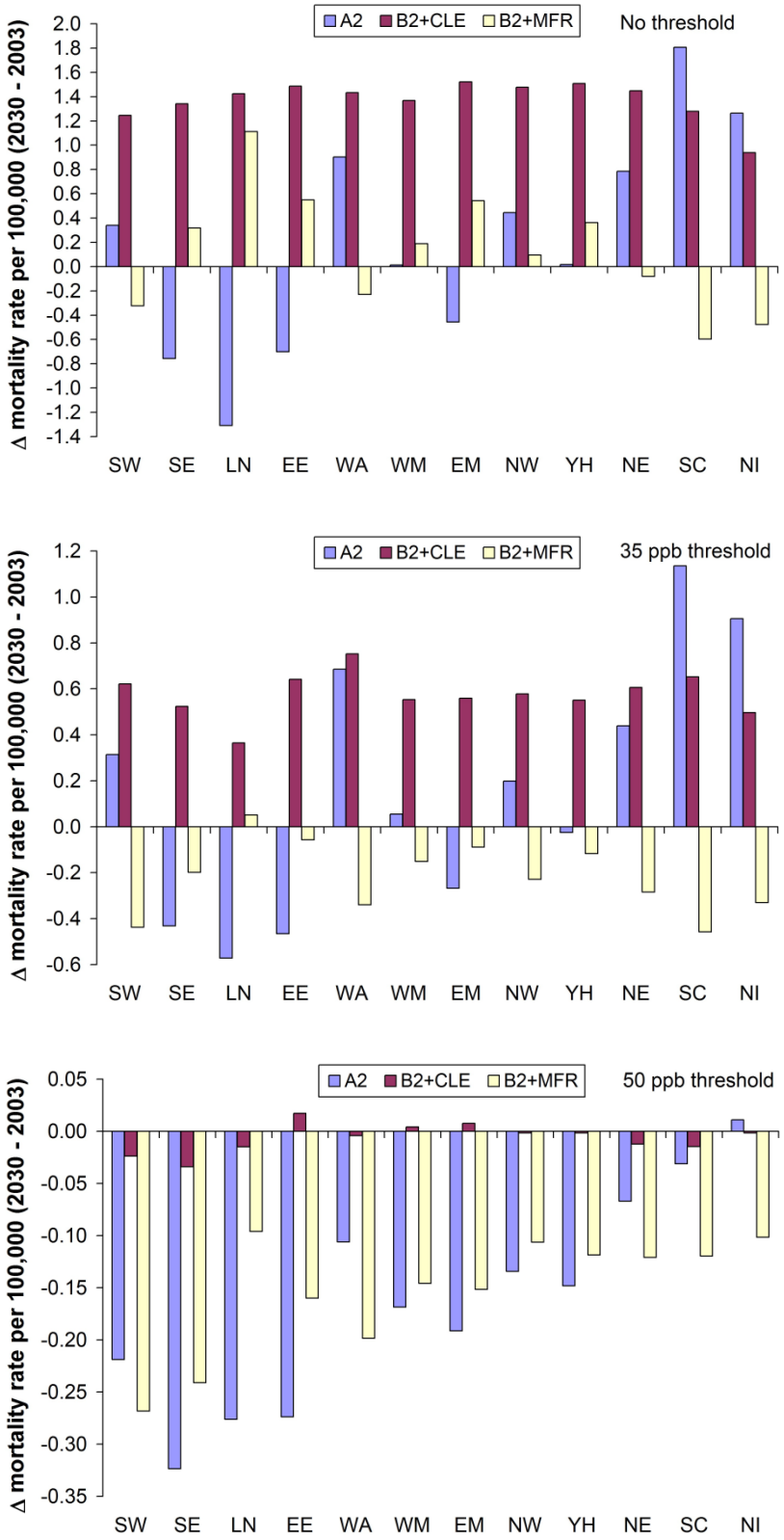

Figure 3.6. Changes in regional annual mortality rate per 100,000 population between 2003 and 2030 for the three emissions projection scenarios and assumptions of no threshold (top), and 35 ppbv (middle) and 50 ppbv thresholds (bottom) for O_3 effects. The regional acronyms are defined in Table 3.2. Note the different y-axis scales.

Health impacts – temperature sensitivity (+5 °C) experiment

The deaths brought forward in each region for the +5 °C simulation (c.f. 2003 baseline) are presented in Table 3.7. Morbidity results follow similar trends. Since there are no changes in population in these calculations, the changes in absolute numbers of health impact shown in Table 3.7 directly reflect the changes in exposure to O_3. The deaths brought forward per 100,000 population are also included to enable direct comparison with data in Table 3.6 for the three 2030 emissions scenarios.

Regardless of O_3 threshold assumption, the health impact increases in the +5 °C temperature simulation for all regions of the UK, since ground level O_3 increased in all regions of the UK, although the magnitude of increase varies with region (Figure 3.4 and Table 3.2). Under the assumption of no threshold for O_3 effect, total UK mortality increases by 461, or by 3.9% on the baseline mortality of 11,859 (Table 3.7). The largest increases in mortality are in London, South East and East England and the smallest in Scotland, Northern Ireland and Wales, directly reflecting the larger and smaller increases in ground level O_3 in these respective groupings of regions under the +5 °C scenario. When a threshold for O_3 health impact is assumed, there is a proportionally greater increase in total UK mortality under the +5 °C scenario compared with their respective baselines, but the absolute mortality numbers are again considerably lower than for the no threshold assumption: a 28% increase for the 35 ppbv threshold assumption (346 extra deaths brought forward above the corresponding baseline of 1,236), and a 54% increase for the 50 ppbv threshold assumption (131 extra deaths brought forward above the corresponding baseline of 242) (Table 3.7).

3.4 Potential changes in exposure to other air pollutants

As is the case for O_3, discussed in detail here, the biggest influence on future UK concentrations of the other main ambient air pollutants, particulate matter (PM) and NO_2, will be the trends in the anthropogenic primary and precursor emissions in the UK and regionally. Qualitatively, it is possible to anticipate that concentrations of NO_2 and PM will increase if anthropogenic emissions follow the A2 type of scenario described above, but will decrease if emissions follow a B2+MFR type of scenario.

As for O_3, the potential influences of climate change on PM and NO_2 concentrations are complex and two-way. Jacob and Winner (2009) provide a recent review on some of the possible effects of climate change on air quality, including PM. The Air Quality Expert Group reviewed the topic in the UK context (AQEG, 2007). Exposure to NO_2 is usually greater in winter (when NO_x emissions from combustion are generally higher and NO_2 photochemical lifetime is longer), particularly during low-wind-speed stagnation events. The latter have been suggested to decrease in future under climate change (AQEG, 2007; HPA, 2008), but surface wind-speed projections from global models are highly uncertain. On the other hand, winter mid-latitude storm frequency is predicted to decrease under a future climate leading to increased air pollution stagnation (Jacob and Winner, 2009).

Exposure to PM is enhanced both by poor dispersion conditions (in winter and summer) but also, as for O_3, during photochemically active periods that enhance the generation of secondary inorganic and organic components of PM. Of note here is that secondary organic PM is also enhanced by increased emissions of isoprene from vegetation. Both short-term (days) and long-term (years) exposure to PM is associated with adverse health outcomes and the present epidemiological

evidence is that adverse outcomes remain at the lowest exposures, i.e. there is no observable threshold for effects (COMEAP, 2006; COMEAP, 2009). Therefore, even if the net effect of climate change was a decrease in wintertime exposure to PM in the future, such exposure will still contribute a significant fraction of long-term exposure.

Table 3.7. Regional and total UK annual deaths brought forward attributable to O_3 assuming no threshold, and thresholds of 35 and 50 ppbv for a +5 °C temperature perturbation compared with the 2003 baseline. Deaths brought forward per 100,000 population are given in parentheses. (Note that % values are derived from underlying non-integer values of numbers of deaths.)

	Annual deaths brought forward, no threshold			Annual deaths brought forward, with 35 ppbv threshold			Annual deaths brought forward, with 50 ppbv threshold		
Region	**2003 baseline**	**+5 °C temp**	**% change**	**2003 baseline**	**+5 °C temp**	**% change**	**2003 baseline**	**+5 °C temp**	**% change**
SW	1159 (23.2)	1201 (24.0)	**3.6**	146 (2.9)	179 (3.6)	**23.1**	31 (0.6)	45 (0.9)	**44.8**
SE	1601 (19.8)	1680 (20.8)	**4.9**	208 (2.6)	272 (3.4)	**30.7**	57 (0.7)	82 (1.0)	**42.1**
LN	1063 (14.4)	1121 (15.2)	**5.5**	119 (1.6)	159 (2.2)	**34.0**	36 (0.5)	51 (0.7)	**42.2**
EE	1019 (18.6)	1070 (19.6)	**5.0**	124 (2.3)	164 (3.0)	**32.3**	28 (0.5)	42 (0.8)	**54.3**
WA	687 (23.5)	708 (24.2)	**3.1**	73 (2.5)	89 (3.0)	**23.0**	12 (0.4)	18 (0.6)	**52.3**
WM	1034 (19.5)	1075 (20.2)	**4.0**	102 (1.9)	133 (2.5)	**30.1**	18 (0.3)	30 (0.6)	**62.5**
EM	796 (18.7)	832 (19.5)	**4.4**	83 (1.9)	109 (2.6)	**31.1**	16 (0.4)	26 (0.6)	**65.8**
NW	1453 (21.4)	1503 (22.1)	**3.4**	127 (1.9)	163 (2.4)	**28.3**	16 (0.2)	28 (0.4)	**81.3**
YH	994 (19.8)	1031 (20.5)	**3.8**	85 (1.7)	111 (2.2)	**30.2**	12 (0.2)	22 (0.4)	**81.8**
NE	562 (22.1)	580 (22.8)	**3.2**	46 (1.8)	59 (2.3)	**27.2**	5 (0.2)	9 (0.4)	**94.2**
SC	1193 (23.6)	1216 (24.0)	**1.9**	100 (2.0)	117 (2.3)	**17.4**	9 (0.2)	16 (0.3)	**71.6**
NI	298 (17.5)	303 (17.8)	**1.9**	25 (1.4)	28 (1.7)	**16.0**	3 (0.2)	4 (0.2)	**59.1**
TOTAL	**11859**	**12320**	**3.9**	**1236**	**1582**	**28.0**	**242**	**373**	**54.3**

Some global modelling studies suggest that the potential for natural forest fires in the boreal region (Canada and northern Russia) will increase in a warmer, drier future (Scholze *et al.*, 2006) which will increase the potential for PM exposure from long-range transport of smoke particles. Aeroallergens and climate change are discussed in Chapter 4 of this report.

3.5 Conclusions

Ground level O_3 concentrations are sensitive to many factors including the extent of local, regional and hemispheric precursor gas emissions (from both anthropogenic and natural sources), local and regional meteorology, and changes in climate. This makes it difficult to predict future O_3 concentrations over the UK, and hence the associated health impacts.

The model simulations described here show that increases in annual mean ground level O_3 under a +5 °C air temperature scenario (1.0 to 1.5 ppbv, depending on geographic area) are generally lower than the potential changes in ground level O_3 due to emissions changes by 2030 (−3 to +3.5 ppbv, depending on scenario assumed) or due to inter-annual variability from meteorological influences alone (−1.5 to +2 ppbv). It is emphasised that an increase in temperature is only one way in which future climate change can influence future ground level O_3 concentrations. Other influences may enhance or offset changes due to temperature alone.

Ground level O_3 concentrations are particularly sensitive to the amount of NO_x in the air and, because of the nature of NO_x sources (transport and other combustion sources), concentrations of NO_x can have strong spatial gradients. An important observation from this work was the different results obtained for ground level O_3 obtained with the higher spatial resolution model used here compared with the coarser (~200 km) grids used in the global chemical transport models in Stevenson *et al*. (2006).

The relative extent and geographical distribution of adverse health impact of exposure to ground level O_3 follows the simulated O_3 concentrations, but absolute health burdens also critically depend on whether a threshold concentration of O_3 below which there is no impact is assumed. Assuming O_3 exposure over the full year is relevant, the health impacts assuming a 35 ppbv threshold or a 50 ppbv threshold are approximately only one-tenth or one-fiftieth, respectively, of that attributable if no threshold is assumed. Geographical contrasts are particularly notable between the densely populated areas in the south east of the UK (London, South East and East England) and the more rural regions in the north and west (Scotland, Northern Ireland and Wales). Future absolute health burdens also depend on future populations.

It is important to recognise limitations in this work. Foremost, the results presented here are those from a single model. Uncertainties in the model simulations of regional O_3 include *inter alia*, uncertainties in simulating high resolution meteorology, uncertainties in precursor emissions especially biogenic sources, uncertainties in photochemical schemes, uncertainties in parameterisations of O_3 dry deposition, and uncertainties in scenarios of future emissions and climate.

Different health impact attribution methodologies may also yield different results. For example, there are uncertainties in the magnitude of concentration-response coefficient, and the portion of the year for which O_3 exposure is relevant for health impact. Coefficients used here are derived from consideration of (mainly) full-year time series studies that focus on short-term population exposure to O_3, and in this work O_3 exposure over the full year was considered. In addition, the issues of the existence or not of a threshold and the potential confounding due to temperature is complex, as highlighted in recent work for the UK (Pattenden *et al.*, 2010; Atkinson *et al.*, 2012). Complications also arise due to seasonally-varying correlations between O_3 and other air pollutants with health

effects, particularly PM. However, most studies find the effects of O_3 are relatively independent of those of PM (WHO, 2006).

This study applied concentration-response coefficients developed to describe health impacts from short-term exposure. There may be additional health impacts from longer-term exposure. The morbidity coefficient was applied to emergency respiratory hospital admissions, so this estimate may miss morbidity for other potentially O_3 related illness, for example, the effects of long-term exposure on the development of cardiovascular disease. It has also been assumed that baseline mortality and morbidity rates remain constant in the future, although regional estimates have been calculated, and daily baseline mortality rates have been used.

Moreover, the application of concentration-response coefficients and thresholds to current and projected O_3 exposures includes two further uncertainties: whether coefficients and threshold values apply to all UK population equally, i.e. there is no difference in concentration-response coefficients between urban and rural populations, or other demographic or geographic heterogeneity; whether current coefficients and threshold values are valid for conditions in the future. Regarding the second of these, it is not possible to predict changes in concentration-response coefficients and threshold effects of any autonomous adaptation to future O_3 levels. However, a number of potential adaptations can be highlighted. There is some evidence for physiological adaptation to O_3 from a study that reported diminished mortality effects later in the summer, reaching the null effect by September (Zanobetti and Schwartz, 2008). Also, behaviour and hence exposure may change. For example, in a warmer future climate, windows may be open for longer periods in naturally ventilated buildings, or individuals may spend more time outdoors. On the other hand, there may be increased use of air-conditioning leading to decreased exposure to ambient O_3. Further discussion of responses to increased temperatures and as mediated via the built environment is contained in Chapters 2 and 5 of this report.

Finally, the adverse health impacts of exposure to ambient air do not just arise from exposure to O_3. Exposure to ambient particles is also highly relevant.

3.5.1 Public Health protection from the effects of air pollution on health

In the UK, Defra compiles daily information (the Daily Air Quality Index) from automated monitoring stations to inform the public of the current levels of UK air pollution by sorting monitoring data into bands from Low to Very High (http://uk-air.defra.gov.uk/). Defra also provides a 24 hour forecast and publishes news and health advice when target thresholds are exceeded.

In order for health protection measures to effectively reduce harm from exposure to air pollution, it is important to target vulnerable populations – those working outdoors, those with pre-existing illness, the elderly and very young. Personal air pollution alerts for concerned individuals are currently used; for example, the airTEXT service in London (http://www.airtext.info/) which is based on the Daily Air Quality Index. An improvement on systems for which the public subscribes individually might be a system where vulnerable people are targeted based on previous identification by medical practitioners, and institutions such as care homes are informed of any increased risk of air pollution episodes. The Department of Health publishes an annual Heatwave plan for England and in conjunction with the Met Office has produced a heat-health alerts system (http://www.metoffice.gov.uk/weather/uk/heathealth). There is potential for linking this to air

pollution alerts during summer months, when both temperatures and ozone levels are more likely to be elevated.

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4 Effects of aeroallergens on human health under climate change

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Summary

- Climate change may result in earlier seasonal appearance of respiratory symptoms and longer duration of exposure to aeroallergens.
- The effects of climate change on plant distribution through range shifts and invasions can expose the population to pollen from more plants with different flowering seasons.
- Variations in the potency of allergen carriers (e.g. the amount of allergen per pollen grain) might make it difficult to correlate symptoms and effectiveness of treatment with pollen or fungal spore counts. The problem of variations in potency might be overcome by monitoring atmospheric concentrations of allergens instead of pollen grains or fungal spore counts.

Public health recommendations

- Expand and improve the monitoring network of aeroallergens, with emphasis on greater coverage and a move toward rapid automated or semi-automated techniques.
- Put in place measures to monitor and contain the spread of invasive plants such as ragweed.
- Improve the quality of information about the type and seasonal occurrence of aeroallergens provided to health care professionals, so that they can effectively plan treatment and clinical trials for remedies.
- Disseminate high quality information about the presence of aeroallergens to the public via the media and patient organisations, so that sufferers can understand their symptoms, avoid exposure and manage their medication.

Research needs

- Develop low-cost automated (e.g portable flow cytometry) or non automated (e.g lateral flow devices) allergen monitoring devices for pollen and fungal spores, and combine measurements with numerical forecast models to produce an integrated system for modelling atmospheric concentrations of aeroallergens;
- Obtain exposure-response relationships for quantifying health impacts associated with aeroallergens;
- Gain a better understanding of the possible effects of climate change on future trends of prevalence of allergic disorders and asthma, for example by using already existing cohorts in the UK and existing and historical datasets of pollen counts. This would lead to a detailed assessment of the demand for health care provision related to these disorders with changes in climate.

4.1 Introduction

Allergic rhinitis (AR) is closely associated with asthma suggesting the theory of "one airway, one disease" where there may be a relationship between both disorders. Amongst people with AR, 20-30% either suffer from asthma or will develop asthma later on (Bousquet *et al.,* 2001; Demoly and Bousquet, 2006). There is also a possibility that increased pollen exposure and sensitisation are responsible for some proportion of an increase in asthma incidence and exacerbation (Héguy *et al.,* 2008; Schmier and Ebi, 2009), although the exposure-response curve for an effect of aeroallergens on asthma exacerbations is not known (Atkinson and Strachan, 2004). AR and asthma significantly reduce quality of life and have a significant economic impact on society (Bousquet *et al.,* 2001).

The prevalence of asthma and allergic rhinitis increased dramatically in Europe during the second half of the 20th century. However, the effects of climate change on respiratory allergy are still unclear (D'Amato and Cecchi, 2008). For atopic asthma or allergic disease to develop, it is considered that both genetic predisposition and exposure to aeroallergens (pollen and fungal spores) are required (Gilmour *et al.,* 2006). One reason for the observed increase in prevalence may be exposure to aeroallergens (Huynen *et al.,* 2003; Beggs and Bambrick, 2005; Ziska *et al.,* 2011), but a great deal of uncertainty exists in predicting the effects of climate change on pollen or fungal spore related allergies (D'Amato and Cecchi, 2008). For instance, there are uncertainties involved in climate change scenarios, uncertainties related to the effect of changing climate on the production of allergenic pollen by plants or allergenic spores by fungi, and uncertainties involved in assessing the effects of airborne allergens on allergic respiratory diseases. The latter can be summarised as follows:

1. Effects on the already allergic population, defined as people experiencing symptoms when one or more types of pollen and/or fungal spores are in the air. Climate change can affect allergenic plants by changing their flowering times (most of them flower earlier; section 4.3.1) and also their distribution (section 4.3.3). As a consequence, allergic people could experience a longer allergy season (early symptoms + exposure to pollen from more plants with different flowering seasons = more months of symptoms).

2. Effects on the prevalence of allergic diseases (the total number of cases in the population, divided by the number of individuals in the population). In other words, will climate change have an effect on the number of people who suffer from allergic diseases? Epidemiological studies seem to indicate that in high prevalence countries like the UK the increase of prevalence of asthma and respiratory allergic diseases is coming to a plateau, while prevalence is still increasing in developing countries and in countries with a lower prevalence (Asher *et al.,* 2006 , Bousqet *et al.,* 2007; de Benedictis *et al.,* 2009). The introduction of new pollen types, such as ragweed, could be responsible for new sensitisations in atopic individuals (Cecchi *et al.,* 2010a), but this has still to be confirmed (Cecchi *et al.,* 2010b). In the UK, the overall prevalence of all types of sensitisation is 42.6% with the most important outdoor aeroallergens being: grass pollen (21.8%), *Alternaria spores*(7.3%), birch pollen(5.9%) and *Cladosporium* spores (3.5%) (Bousqet *et al.,* 2007).

4.2 Methods

The information provided in this report relates to spring, summer and autumn mean temperature (^{o}C) projections for low, medium and high emissions data from UKCP09 for the 2020s, 2050s and 2080s (at 50% probability levels), (Figure 4.1).

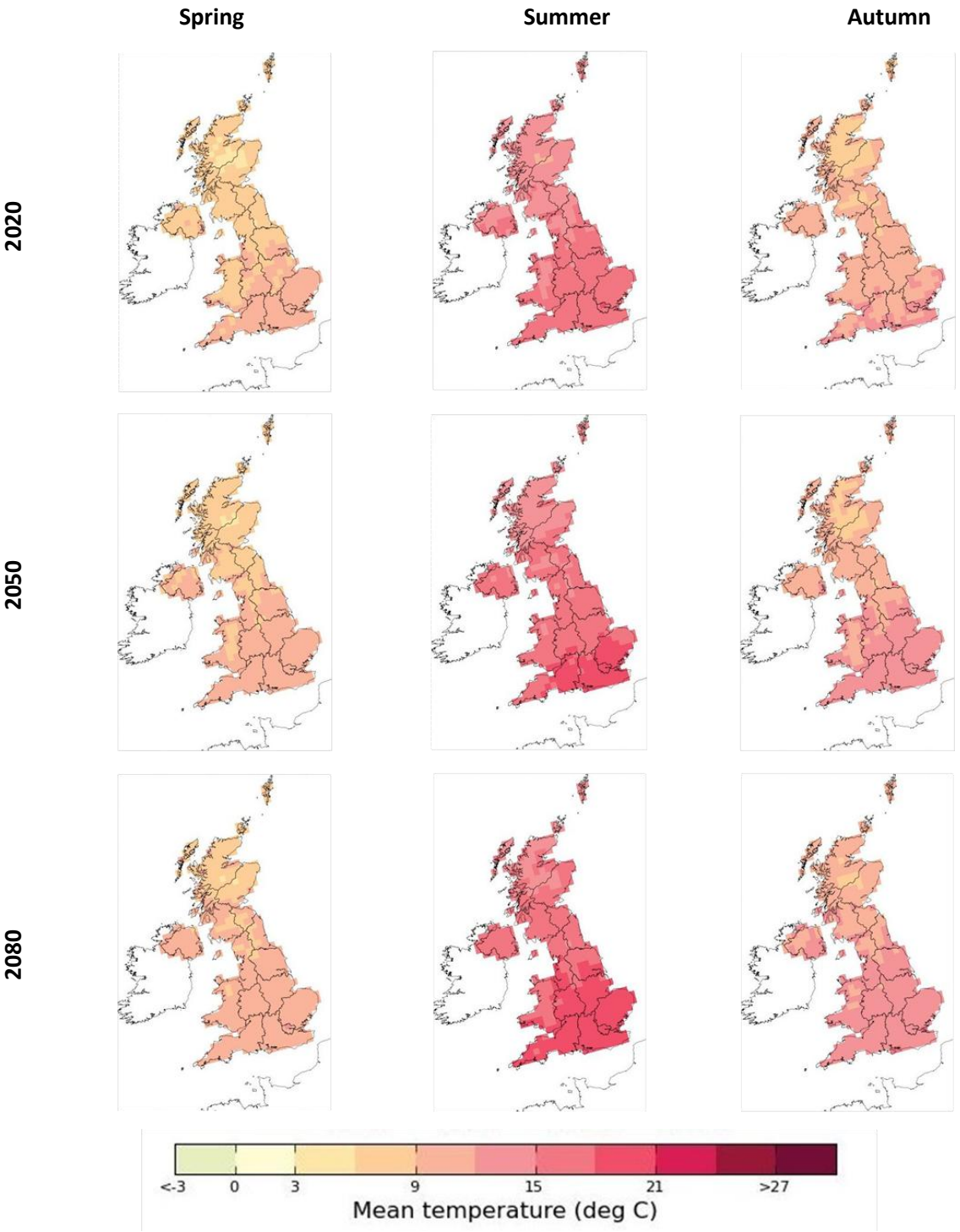

Figure 4.1. UKCP09 Spring, Summer and Autumn mean temperature (^{o}C) projections for the UK at medium emission scenario (50% probability level of change). (Source: Jenkins *et al.,* 2009)

4.3 Effects of climate change on allergenic plants

4.3.1 Effects on plant phenology[1]

Pollen from wind pollinated (anemophilous) plants is the most important cause of the symptoms of pollen related allergy in humans (Emberlin, 1997). However, not all wind-dispersed pollen is allergenic. Some of the most important pollen types in terms of allergy in the UK include those from the Betulaceae, Fagaceae, Poaceae, Urticaceae, and Asteraceae families. Pollen grains from anemophilous plants tend to have characteristics that facilitate dispersal by the wind, being small (typically 20- 40 µm in diameter) and low or not ornamented (Emberlin, 1997). As a result, episodes of long distance or regional scale transport of pollen have been reported (Smith *et al.,* 2005; Cecchi *et al.,* 2006; Cecchi *et al.,* 2007; Stach *et al.,* 2007; Smith *et al.,* 2008; Šikoparija *et al.,* 2009; Kasprzyk *et al.,* 2011).

Global average surface temperatures have increased by about 0.7°C over the past hundred years (1906-2005) (Solomon *et al.,* 2007). There is high confidence that this temperature increase has led in many regions towards earlier greening of vegetation in the spring (based on Normalised Difference Vegetation Index derived from satellite images) linked to longer thermal growing seasons due to recent warming (IPCC, 2007). A number of studies have shown that events such as breeding or blooming, now occur earlier in the year (Ahas *et al.,* 2002; Fitter and Fitter, 2002; Parmesan and Yohe, 2003; Root *et al.,* 2003). Warming has been slightly greater in winter, and changes in spring phenophases are more pronounced than those that occur in summer and autumn (Ahas *et al.,* 2002; Fitter and Fitter, 2002; Walther *et al.,* 2002; Aasa *et al.,* 2004; Solomon *et al.,* 2007; Bertin, 2008). Indeed, it was shown that birch pollen seasons started earlier toward the end of the last century (Emberlin *et al.,* 1997), which is probably the result of the warm temperatures experienced in the 1990s.

The relationship between flowering phenology and temperature is not straightforward. Trees belonging to the Betulaceae family (i.e. hazel, alder and birch) are important sources of allergenic pollen during early spring in the UK. They are greatly dependent on temperature and require chilling (vernalisation) before winter dormancy is terminated, followed by a period of heat before growth is resumed and flowering occurs (Emberlin *et al.,* 2007). There is an inverse relationship between the amount of chilling in the autumn and the amount of heat required for flowering in spring (Frenguelli and Bricchi, 1998; Emberlin *et al.,* 2007). This means that following a warm winter more heat is required during spring for the plant to flower and *vice versa*. For example, the effect of increases in winter temperatures on hazel flowering phenology was demonstrated by Emberlin *et al.* (2007). The authors entered start dates of hazel pollen seasons into regression models with medium-high emissions scenario data from UKCIP02 for the 2020s, 2050s and 2080s (Hulme *et al*., 2002) and found that warmer October temperatures made the season start later, warmer December temperatures made the season start earlier and the combination of warmer October and December temperatures meant that there was little change to the start of flowering. The analysis has been repeated using low, medium and high emissions data from UKCP09 for the 2020s, 2050s and 2080s (10%, 50% and 90% probability levels). The new results show a similar pattern to the earlier analysis

[1] the study of organisms affected by climate, especially dates of seasonal phenomena

conducted by Emberlin *et al*. (2007). However, at the 90% probability levels there is a tendency for the hazel pollen season to start earlier if both October and December temperatures are increased.

4.3.2 Effects on pollen production

A recent study presented by Ziello *et al*. (2011) examined trends in the amount of airborne allergenic pollen, from both grasses and trees, recorded at a number of pollen-monitoring sites from across Europe. The analysis showed increases in the amount of some of the most important allergenic pollen types. Such increases could be related to changes in plant phenology. For instance, Rogers *et al*. (2006) demonstrated that ragweed (*Ambrosia*) plants released from dormancy earlier in spring accumulated more resources through the season, which increased biomass reproductive effort and resulted in 54.8% more pollen production compared to those released from dormancy 30 days later.

In addition, increased concentrations of atmospheric CO_2 affect plant function (Ziska and Caulfield, 2000), and so plants grown in higher concentrations of CO_2 generally grow faster, are larger at maturity and produce more pollen (Ziska and Caulfield, 2000; Wayne *et al.,* 2002). Rogers *et al*. (2006) also showed that ragweed plants released from dormancy later, but grown in elevated levels of 700 ppm CO_2, had increased biomass and pollen production thereby removing the disadvantage of a later start to the growing season.

Increases in the amount of allergenic pollen are not just related to climatic change. It has been hypothesised that the ornamental planting of birch trees in urban areas can influence spatial variations of *Betula* pollen levels in the UK (Corden *et al.,* 2002; Stach *et al.,* 2008). It may also be associated with agricultural cropping and forestry in the area. This is an example of the number of different variables that should be considered when examining atmospheric pollen concentrations.

4.3.3 Effects of plant distribution

The effects of climate change on plant distribution can be summarised as: (1) range shifts; and (2) invasions by species such as *Ambrosia artemisiifolia* (Walther *et al.,* 2002). Plant species are expected to undertake spatial (poleward and upward) shifts in ranges (IPCC, 2007) that will influence the abundance and distribution of allergenic plants (Walther *et al.,* 2002). It is possible as a result of this shift that species such as *Ambrosia artemisiifolia* may become more prevalent in all parts of the UK. This can affect the exposure of the population to different aeroallergens and change the overall incidence of sensitisation as a direct result of the introduction of a new allergen affecting people who before may have been unaffected (Asero, 2002; Confalonieri *et al.,* 2007). In addition, the introduction of new invasive plant species with highly allergenic pollen presents important health risks (Confalonieri *et al.,* 2007). In Europe, the pollen grains from the genus *Ambrosia* (Family Asteraceae) are considered to be very troublesome and potent aeroallergens (Rich, 1994). *Ambrosia maritima* is the only native species of *Ambrosia* in Europe. Four other species have been introduced from North America. The most widespread and important in terms of allergy is *Ambrosia artemisiifolia* (common or short ragweed), although *Ambrosia trifida* (giant ragweed) is important locally (Stach *et al.,* 2007). Each *A. artemisiifolia* plant can produce millions of pollen grains in one season but the threshold value for clinical symptoms for the majority of sensitised patients is below 20 ragweed pollen grains/m^3 daily average (Jäger, 1998; Stach *et al.,* 2007). Furthermore, *Ambrosia* pollen appears to induce asthma about twice as often as other pollen, and there is significant cross-reactivity between ragweed species within the *Ambrosia* genus as well as between the major

allergens of *Ambrosia* and *Artemisia* (Jäger, 2000; White and Bernstein, 2003; Taramaracaz *et al.,* 2005). The potential for invasive species to trigger allergies was demonstrated by the development of ragweed pollen allergy in migrants from Korea to the USA (Kim *et al*., 2006).

A warm continental climate and dry soils favours the growth of *A. artemisiifolia*. In northern Europe the growing season is too short for seed maturation, so populations of *A. artemisiifolia* rely on the regular introduction of seeds from outside sources. These seeds can remain dormant for at least 39 years if conditions are unsuitable for germination (Stach *et al.,* 2007). *A. artemisiifolia* is a pioneer plant that tends to grow in any habitat if two conditions are fulfilled: (1) available seeds; (2) soil disturbance. As a result, the presence of *A. artemisiifolia* is often related to human activities (Skjøth *et al.,* 2010). *A. artemisiifolia* plants have been recorded in Britain (Figure 4.2). They are generally recorded as a casual (rarely persistent) plant on rubbish tips, dockyards, arable fields and waste ground, as well as in places where bird seed is scattered (Preston *et al.,* 2002; NBN, 2011). As a result A*. artemisiifolia* is often found around ports or large urban areas such as London (Figure 4.2).

Figure 4.2. Grid map of *Ambrosia artemisiifolia* plants recorded in the UK (1991-2010), (NBN, 2011).

The three main regions in Europe now recognized as being polluted by *A. artemisiifolia* are: the Rhône Valley (France), northern Italy and the Pannonian Plain (Skjøth *et al.,* 2010). Seasonal temperatures (1961-1990 mean) taken from two cities situated on the Pannonian Plain, Budapest and Debrecen (WMO, 2011a; WMO, 2011b), have been compared to seasonal temperatures from UKCP09 at medium emission scenario (Figure 4.1). Mean summer (June, July and August) temperatures recorded in Budapest and Debrecen (20.2 °C and 19.7 °C, respectively) are expected to be reached in a large area of southeast England in 2050 and extend across much of southern and central England and South Wales in 2080. Similarly, autumn (September, October and November) temperatures from Budapest and Debrecen (11.1 °C and 10.7 °C, respectively) are projected to be recorded across a large part of England, Wales and Northern Ireland by 2080 (Figure 4.1). Increased temperatures during summer and early autumn could result in faster and more intensive

germination of introduced seeds as well as increased vegetative growth and the development of staminate flowers, thereby increased pollen production. However, ragweeds are termed short-day plants because flowering is initiated by a shortening length of day (Allard, 1932). The influence of photoperiod may mean that seeds will not ripen before the arrival of cold weather (Allard, 1932; Deen *et al.,* 2001), which would impact on the plants ability to produce stable populations. This is further complicated by the fact that ragweed seeds need a period of cold weather (stratification) before they can germinate (Deen *et al.,* 2001), which might not occur if winter temperatures are too warm.

4.4 Effects of climate change on fungi

Fungal spores account for a significant proportion of aeroallergenic exposure in humans. Many species of fungal spores are significantly smaller than pollen grains. Fungal spores range in size from 2 µm to 10 µm, and atmospheric concentrations are up to 100 fold greater than pollen (Bush and Prochnau, 2004). A major difference in human exposure to fungal spores in comparison to pollen is that they are not localised to specific regions. However, lower fungal spore counts are found in cold areas with higher concentrations in those areas with higher humidity (Phipatanakul, 2005). Fungal spores occur mainly in outdoor environments but concentrations indoors are driven by outdoor concentrations (Burge, 2002). Climate change will potentially affect the distribution and the fungal spore levels commonly observed in the environment and medical conditions, e.g. provoking or exacerbating asthma attacks in children (Atkinson *et al.,* 2006), which result from exposure to fungal spores. There are two main types of allergenic fungal spores. Those which develop on specific plants and crop hosts outdoors and are saprophytic or pathogenic, and fungi whose distribution is more general and related to the occurrence of specific niche (often indoor) environments e.g xerophyllic fungi (fungi which can tolerate very dry conditions). Fungi that are commonly considered allergenic include those from the Deuteromycota or fungi imperfecti (e.g. *Alternaria* and *Cladosporium*), Ascomycota (e.g. *Didymella* and *Leptosphaeria*) and Basidiomycota (e.g. *Coprinus* and *Ganoderma*) (Horner *et al.,* 1995; Lacey, 1997; Kurup *et al.,* 2000; Simon-Nobbe *et al.,* 2008). Airborne fungi associated with severe asthma and other respiratory diseases include *Alternaria*, *Aspergillus*, *Cladosporium* and *Penicillium*.

4.4.1 Effect of climate change on outdoor allergenic fungal spores

Alternaria and *Cladiosporium* are dominant outdoor allergenic fungi which contain many species that are pathogenic on plants. *Cladosporium*, which comprises approximately 500 species, are saprophytic fungi (fungi which feed on dead material) and epiphytes that can invade senescing (dying) tissues of many plants such as leaves, induce disease in ripe fruits of some plant species, and occupy other diverse environments. Fungal spore exposure is more closely associated with asthma than exposure to pollen (Newson *et al.,* 2000). All climate change scenarios (high – low emissions) predict an increase in average temperatures across the UK (Hulme *et al*., 2002). This is likely to increase the symptoms of asthma suffers in the population through direct and indirect mechanisms associated with the availability and efficacy of aeroallergens (Freed, 1995). Higher humidity and temperatures are likely to give rise to many more “spore storms” such as that documented in North America on 6–7 October 1937, when large air masses travelled from the central prairies to the Atlantic conveying several tons of mould spores across several hundred miles (Durham, 1938). High levels of fungal spores have also been associated storms occurring in different areas of the world (Griffin, 2007). Other outcomes related to climate change may produce longer term effects on

aeroallergenic fungi. Studies have demonstrated that an increasing carbon to nitrogen ratio associated with rising atmospheric CO_2 concentrations is consistent with increased sporulation by allergenic fungi (Wolf *et al.,* 2010). These types of mechanism could act to increase allergenic fungal exposure. We conclude that the increased carbon-to-nitrogen ratio associated with rising atmospheric CO_2 concentration and climate change is consistent with increased sporulation of allergenic fungi, which may contribute to the increasing prevalence of allergies and asthma.

4.4.2 Effect of climate change on mycotoxigenic allergenic fungal spores

Mycotoxins are naturally occurring substances produced by toxigenic fungi that commonly grow on a number of crops and that cause adverse health outcomes when consumed by humans and animals. The allergenic potential of mycotoxins is as yet poorly understood. Climate change will not influence all species of mycotoxigenic fungi in the same way. There are environmental conditions under which a particular mycotoxigenic fungus will occur. Increasing average temperatures could lead to changes in the distribution of mycotoxins on susceptible crops due to changes in cropping in the UK. Of the host of toxic compounds collectively produced by *Aspergillus* and *Penicillium* species, the three most important are the aflatoxins (AF), ochratoxin A (OTA) and patulin. Aflatoxin produced by *Aspergillus flavus*, *A. parasiticus*, *A. nomius* and *A. wentii*, is a genotoxic liver carcinogen and toxin widely distributed but associated especially with maize, groundnuts, tree nuts, figs, dates and certain oil seeds such as cottonseed. Mycotoxins are prevalent in fungal spores of toxigenic species and given the well documented potency of mycotoxins to human health (Lui, 2010) any impact of climate change in the prevalence of mycotoxin fungi as aeroallergens could have major health implications. An example of this can be found in toxins produced by the airborne *Fusarium sp*. Strains of toxigenic aeroallergenic *Fusarium graminearum* produce the toxins deoxynivalenol (DON) or nivalenol (NIV) and zearalenone (ZER), while *F. culmorum* produces only DON and ZER (Miller, 2008). There are reports that a series of warm European summers has seen the occurrence of the formerly predominant species, *F. culmorum*, to be replaced by *F. graminearum* (Miller, 2008). European strains of *F. graminearum* commonly produce NIV so further warming due to climate change would be expected to favour *F. graminearum*, the species that is the most virulent plant pathogen and perhaps a shift to a NIV/ZER contamination pattern from DON/ZER pattern in the UK (Usha *et al.,* 1993).

4.5 Effects on the potency of aeroallergens

In addition to changes in aeroallergen exposure, climate change could have an effect on the potency of pollen and fungal spores. Potency is linked to allergen concentrations, which for birch has been shown to vary spatially and temporally (Buters *et al.,* 2008). High levels of pollen aeroallergens are sometimes associated with thunderstorms. There are also several well documented examples of asthma epidemics associated with thunderstorms during the grass pollen season (Venables *et al.,* 1994). However, it is unclear how the frequency of thunderstorms may be affected by climate change. Projected future increases in CO_2 can lead to increased allergenicity of ragweed pollen (Singer *et al.,* 2005) although this is not unequivocal as it was found that a significantly higher amount of allergen was extracted from pollen in plants grown in rural compared to urban sites (Ziska *et al.,* 2003). For fungi, Wolf *et al.* (2010) also found that the quantity of *Alternaria alternata* antigen per spore decreased as the leaf carbon to nitrogen ratio increased due to higher concentrations in atmospheric CO_2, although total antigen production increased due to the increase in the number of spores. Such variations in potency might make it difficult to correlate symptoms and effectiveness of

treatment such as prophylactic medication with pollen or fungal spore counts, and so one answer might be to monitor atmospheric concentrations of allergens (Buters *et al.,* 2010), which would be a more direct estimate of the potential health risk to allergen sufferers and as such would be a more accurate measure to use in assessing any treatment.

4.5.1 Indoor aeroallergens

House Dust Mite (HDM) is the most important indoor aeroallergen in the UK, but the prevalence of sensitisation may actually decrease because prevalence tends to be low in warmer parts of Europe (Bousqet *et al.,* 2007). However there are other documented examples of population centres with different environmental patterns (and similar underlying risk factors) showing the same asthma prevalences. On the other hand, it is very likely that some weather events and extremes, such as warm spells/heat waves and heavy precipitation events, will become more frequent (IPCC, 2007). As a result, it has been hypothesised that people might spend more time indoors during extreme summer weather events and thereby increase their exposure to HDM allergens, although it could also be argued that people may spend more time outdoors in general due to milder winters, autumn and spring seasons (see Chapter 5 on the Indoor Environment). Furthermore, heavy precipitation may lead to increased fungal growth in flood damaged properties (Cecchi *et al.,* 2010a).

4.6 Conclusions

The impact of climate change on aeroallergenic reactions in humans may result in a direct effect on the potency of aeroallergens associated with pollen and fungal spores. This will result in existing allergy sufferers coping with longer pollen seasons and with more rapid symptom development. However there will also be a longer term indirect effect on UK populations through changes in plant and fungal distributions. The UK populations in the southern-most counties under the medium emission scenario could be exposed to an increased allergenic load due both to an increased range of existing allergenic plant species and occurrence of potentially novel aeroallergens from invasive plant species.

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5 Health effects of climate change in the indoor environment

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Summary

- Climate change may exacerbate health risks and inequalities associated with building overheating, indoor air pollution, flooding damage, and water and biological contamination in the indoor environment, if adequate adaptation measures are not taken.
- Indoor environments can allow growth and propagation of pathogenic ecosystems. Overcrowding and poor ventilation are the recognised environmental risk factors for airborne infectious disease transmission.
- Climate change mitigation and adaptation policies in the built environment can reduce greenhouse gas emissions and also bring ancillary public health benefits by reducing heat and cold-related mortality, indoor air pollution and mould growth.
- Increased airtightness of dwellings may have some negative effects on human health related to thermal stress and chemical and biological contamination, if adequate ventilation is not maintained.
- High risk groups include the elderly (especially those living on their own), individuals with pre-existing illnesses, people living in overcrowded accommodation, and the socioeconomically deprived. Living in a top floor flat generally increases exposure to high temperatures. Living in a ground, lower-ground or basement flat may increase health risks related to flooding. Radon levels are also higher in basements.
- Hospitals, general practices and care homes may be adversely affected by high temperatures during heatwaves. This includes patient wards as well as pharmaceutical storage places. Heavy precipitation and flooding may also adversely affect health care infrastructure.

Public health recommendations

- Better understanding of the current and emerging building infrastructure, and its potential associations with climate-sensitive health impacts in the indoor environment.
- Promote long-term, energy efficient building design interventions to ensure adequate ventilation in increasingly airtight buildings.
- Vulnerability, health equity and cost-benefit analyses need to be carried out prior to climate change adaption and mitigation interventions in the built and indoor environment. Susceptible population groups need to be identified and supported.
- Predict, monitor and prepare for emerging biological risks to health. Identify risk reduction strategies in the indoor environment that will help cope with disease outbreaks.

Research needs

- Characterise potential health risks and benefits associated with current and future building infrastructure (including construction materials, indoor products, furnishings, mechanical ventilation systems, domestic energy microgeneration, building vegetation and rainwater harvesting systems) under different climate change scenarios.

- Develop practical health impact assessment methodologies accounting for the combined direct and indirect effects (including health equity) of climate change in the indoor environment.
- Optimise indoor modelling of temperature, humidity and air quality in relation to outdoor environmental conditions.
- Adjust epidemiological exposure-response relationships derived from outdoor data to reflect indoor environmental conditions and occupancy patterns.

5.1 Introduction

People living in developed countries typically spend 90% of their time indoors, with vulnerable individuals (elderly, young children, people with compromised health) spending an even larger proportion of their time indoors (Harrison *et al*., 2002; Vardoulakis, 2009). Furthermore, it has been estimated that approximately 60% of this time is spent in the home (Thatcher and Layton, 1995). The quality and range of frequented indoor environments (e.g. homes, offices, schools, hospitals and care homes) play an important role in the physical as well as mental health and wellbeing of their occupants.

Although building structures are primarily intended to protect occupants from inclement weather, provide shelter and enhance their wellbeing, they can also cause or exacerbate certain health risks. Risks related to housing conditions may be broadly defined as physiological and psychological risks, and risks of infection and injury. These may be attributed to indoor air pollution, extreme temperatures, pests and infestations, noise, airborne infectious diseases, water contamination, mould contamination, domestic injuries and poisoning, and mental health effects (WHO, 2011). The form of the built environment (e.g. its density) can also play a role in the exacerbation or prevention of non-communicable "life-style" diseases such as cardiovascular illnesses. The same applies to health inequalities which can also be aggravated or mitigated through changes in housing conditions and in the built environment more generally.

There is growing evidence that climate change, if unmitigated, is likely to have a significant impact on population health, notably by amplifying existing risks related to heat exposure, and chemical and biological contamination in buildings (Haines *et al*., 2007; McMichael, 2011). For example, increasing summer temperatures will increase the risk of building overheating especially in UK cities, increasing the health risk associated with heat stress. Furthermore, in a changing climate, the behaviour of building occupants is also likely to change either spontaneously or as a result of planned climate change adaptation and mitigation policies. For example, time spent indoors as well as ventilation patterns (e.g. opening of windows) and housing conditions (e.g. air conditioning and thermal insulation) may change in the future due to changes in the climate and socioeconomic factors.

The building sector accounts for a large proportion of energy consumption and associated greenhouse gas emissions in high income countries. The UK Government is committed to an 80% reduction in carbon emissions by 2050. Currently around 27% of total carbon emissions come from homes and 17% from non-domestic buildings (DCLG, 2009). Therefore, policies to mitigate and adapt to climate change in the residential and wider building sector can play a key role in attaining this goal by reducing total carbon emissions (Bone at al., 2010).

Policies to mitigate and adapt to climate change in the residential building sector can bring a range of public health benefits (see Chapter 10), but could also cause some negative health effects. For example, enhanced thermal efficiency in dwellings may be achieved by reducing the permeability of the building envelope, which could in certain circumstances result in higher concentrations of indoor air pollutants. On the other hand, improved indoor temperature and humidity control can help the adaptation to warmer summers and wetter winters predicted for the UK under climate change scenarios (UKCP09), reducing the risk of heat exposure and mould growth in buildings.

Climate change mitigation and adaptation policies will modify the physical environment and introduce new urban infrastructure, e.g. green roofs[1] and decentralised water systems in the built environment, which can have an impact on indoor ecosystems and disease transmission. Buildings can provide a unique ecosystem for microorganisms to grow, propagate, disperse and ultimately, cause various adverse health outcomes to their occupants. They can also contribute to the spread of infections by linking the infected host with susceptible victims sharing the same microenvironment. Overcrowding and poor ventilation are recognised environmental risk factors for airborne disease transmission. However, buildings can also serve as a barrier that protects occupants from outdoor bio-contaminants and pathogens, which have different health impacts, dose-response and attack rates on different susceptible groups. In the context of climate change, and related mitigation and adaptation policies in the built environment, it is crucial to understand and predict possible public health outcomes in this changing bio-landscape.

Identifying the health effects of climate change on the indoor environment, and opportunities and risks related to climate change adaptation and mitigation, can help optimise the public health effort to protect the UK population. In this chapter, we explore a range of health risks in the domestic indoor environment related to climate change, as well as the potential health benefits and unintended harmful effects of climate change mitigation and adaptation policies in the UK building sector. These have been grouped in the following categories: (i) building overheating and thermal comfort, (ii) indoor air quality, (iii) flooding damage and water contamination, and (iv) indoor allergens and infections. The health effects of climate change associated with the indoor environment are illustrated in Figure 1, which indicates dominant indoor and outdoor pollution sources, building characteristics and occupancy patterns that may affect human exposure levels. Aspects related to vector, water and food-borne diseases that can be transmitted in the indoor environment have been covered in Chapters 8 and 9.

5.2 Overheating of buildings and thermal comfort

Climate projections for the UK (UKCP09; Jenkins *et al*., 2009) indicate increases of 2-5^{o}C in mean outdoor temperatures (under a medium emissions scenario) by 2080, with the largest increases expected in the south, where population density is higher, and the smallest increases in the north. Heatwaves, i.e. periods of exceptionally hot weather, are also likely to become more frequent and intense in the UK in future decades. This will increase the risk of building overheating, with daily mean temperatures being significantly higher indoors than outdoors in some naturally ventilated buildings. In cities, the urban heat island effect (whereby cities can be around 5-10^{o}C warmer than surrounding countryside areas) will exacerbate further building overheating (Davies *et al*., 2008).

Susceptibility to building overheating mainly depends on: (a) building location and orientation, and surface of its transparent elements (e.g. windows) which all affect solar gains; (b) heat gains from internal sources, such as cooking, lighting and household appliances; and (c) the thermal mass of the building, i.e. the heat absorption capacity of the building envelope. For example, large and poorly shaded south-facing windows can contribute to the building overheating problem. Heavy construction materials generally increase the thermal mass of a building. If these materials have the opportunity to cool at night, they can provide relief from daytime overheating.

[1] Building roof partially or completely covered with vegetation and a growing medium, often planted over a waterproofing membrane.

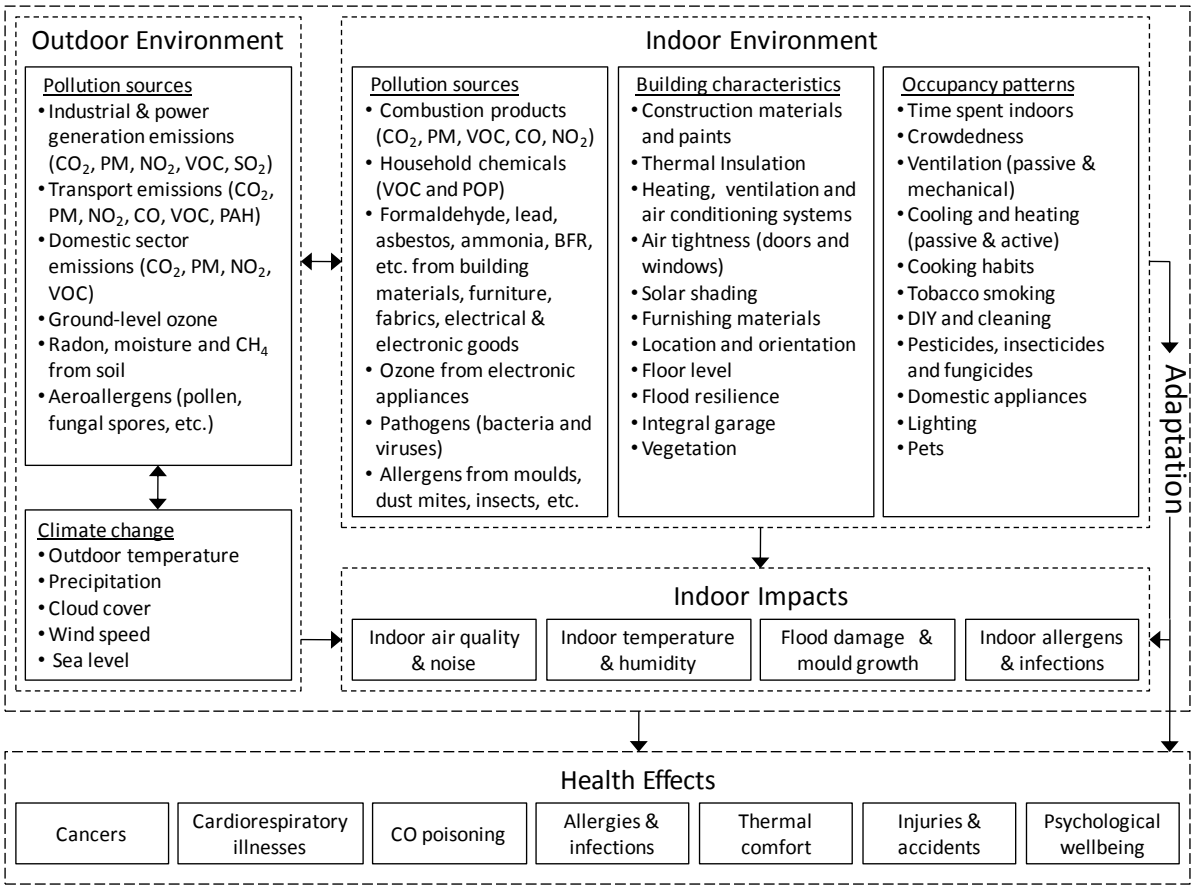

Figure 5.1. Links between climate change, indoor and outdoor environment, and health effects (PM: particulate matter; VOC: volatile organic compounds; PAH: polycyclic aromatic hydrocarbons; POP: persistent organic pollutants; BFR: brominated flame retardants; CH_4: methane; NO_2: nitrogen dioxide; SO_2: sulphur dioxide; CO: carbon monoxide, CO_2: carbon dioxide).

Traditionally, UK housing has had low thermal performance and high levels of air permeability, with ventilation in dwellings predominantly achieved by air infiltration via the building structure and window opening. Most buildings are cooled in summer by natural ventilation (i.e. window opening). This approach has prevented thermal discomfort in residences, but as outdoor temperatures are likely to increase under climate change scenarios, natural ventilation may not provide a significant cooling benefit (Hacker *et al*., 2005). Furthermore, environmental noise, and safety and security issues may discourage window opening in certain residential properties. Therefore, existing buildings in the UK are likely to become increasingly uncomfortable in summer, especially in urban areas, unless other methods of cooling are used.

Adequate ventilation is essential for the correct functioning of the building, especially when it is occupied. If ventilation is inadequate, there is the potential for poor indoor air quality and thermal comfort which may affect the health of the occupants. Adaptation to increasing outdoor temperatures is expected to involve greater use of mechanical cooling devices. Mechanical ventilation and air conditioning can reduce indoor temperatures and relieve heat stress if appliances are operated and maintained in accordance with the manufacturers' instructions, but they increase energy consumption (Ostro *et al*., 2010). Heavy use of air conditioning can also overload the electricity supply infrastructure during periods of hot weather increasing the risk of power failure

(Kovats and Hajat, 2008). Pressure to reduce greenhouse gas emissions from the building sector will place emphasis on heat recovery, passive cooling, solar shading, use of reflective (i.e. high albedo) materials and paints, use of vegetation (e.g. green roofs), and control of internal heat sources (e.g. cooking and lighting) in existing and new houses.

As a climate change mitigation policy, improved thermal insulation in buildings prevents the loss of heat in winter, which can reduce energy consumption for space heating as well as reducing cold-related impacts on occupants' health. However, it may increase the risk of overheating during periods of hot weather as it can reduce heat loss from buildings (Sharples and Lee, 2009). Modelling indoor summer temperatures in London dwellings, Mavrogianni *et al*. (2012) showed that thermal insulation has considerable impact on indoor temperatures. They demonstrated that combined retrofitting of roof insulation and window upgrades reduced daytime living-room temperatures during the warmest periods, while internal retrofitting of wall and floor insulation increased daytime living-room temperatures.

Elderly people, particularly those in hospital or long-term care institutions, are physiologically more vulnerable to heat stress, (Donaldson *et al*., 2002). Hospitals, General Practices and care homes may be adversely affected by high temperatures during heatwaves. This includes patient wards as well as pharmacies where medicines are stored. People with pre-existing medical conditions (e.g. mental disorders, neurological or cardiovascular disease), and those who are overweight or have reduced mobility, are likely to be more vulnerable during prolonged hot periods and heatwaves.

Socioeconomically deprived and isolated individuals may also be at higher risk as they are more likely to live in residences with inadequate heating and cooling, thermal insulation, shading or ventilation. Living in a top floor flat or right under the roof (e.g. loft conversions) would generally increase exposure to high temperatures and related health risks (Vandentorren *et al*., 2006; Mavrogianni *et al*., 2012). Urban living could also exacerbate heat exposure, particularly during night time (which could affect sleep quality), due to the urban heat island effect (Watkins *et al*., 2007). The Heatwave Plan and the Cold Weather Plan for England are discussed in Chapter 2.

5.3 Indoor air quality

Exposure to high concentrations of air pollutants indoors could cause acute health effects, such as intoxication and death due to short-term exposure to high concentrations of carbon monoxide (CO) (de Juniac *et al*., 2011), as well as chronic health effects, such as lung cancer (Darby *et al*., 2005), leukaemia (Duarte-Davidson *et al*., 2001) and mesothelioma (Rudd, 2010) due to long-term exposure to radon, benzene and asbestos, respectively. Non-fatal levels of indoor pollutants may also cause or aggravate chronic obstructive pulmonary disease (COPD), respiratory infections, cardiac and cardiovascular disease, as well as a range of allergic symptoms, such as atopic dermatitis, rhinitis, conjunctivitis and hay fever (Chauhan and Johnston, 2003; Blanc *et al*., 2005). Certain pollutants, such as tobacco smoke and other combustion products, house dust mites and pollen, may aggravate asthma symptoms (Jones, 1999; Rushton, 2004). One in 11 children and 1 in 12 adults in the UK suffer from asthma (COMEAP, 2010a).

Indoor air pollution can result from the ingress of outdoor pollutants and from internally generated contaminants (Milner *et al*., 2011; WHO, 2011). Pollutants can also infiltrate into the house from the soil, such as radon from under the building, methane and other landfill gases from contaminated soil

(Crump *et al*., 2004). In inadequately ventilated houses, pollutants remain indoors for longer and have the potential to accumulate. As outdoor air pollutant concentrations (CO, PM_{10}, $PM_{2.5}$, NO_2, SO_2, and volatile organic compounds)[2] are generally predicted to decrease in the future in the UK (with the exception of ground level ozone, as discussed in Chapter 3), the impact of internal sources, such as cooking, smoking and chemical emissions from indoor materials, on indoor air quality is likely to become proportionally more important.

It should be noted that indoor air quality levels are highly variable, depending on building location and orientation, building materials, indoor combustion sources, tobacco smoking, use of household chemical products and ventilation rates (Milner *et al*., 2011). However, there is experimental evidence that certain pollutant concentrations in houses, for example those of formaldehyde, may exceed (e.g. due to indoor use of particle boards and adhesives) outdoor air pollution levels (Lai *et al*., 2004; Delgado *et al*., 2009; WHO, 2010). Milner *et al*., (2011) reported indoor/outdoor (I/O) ratios for combustion-related air pollutants in residential buildings estimated experimentally in different parts of the world, including two UK cities (Birmingham and Oxford).

5.3.1 Combustion Products

Nitrogen oxides (NO_X) and carbon monoxide (CO) are products of combustion (i.e. open fires, tobacco smoking, cooking and heating appliances) with well documented effects on health (WHO, 2000). NO_2 has been mainly associated with respiratory illness in children, although the evidence is not conclusive (COMEAP, 2004). There is also recent evidence suggesting that children with asthma or infants who are at risk of developing asthma and female adults are more sensitive to the respiratory effects of indoor NO_2 exposure (Breysse *et al*., 2010). For CO, health risks mainly come from malfunctioning or unflued domestic appliances which burn fuels (e.g. gas heaters).

CO concentrations in UK houses are generally low, although comparatively high peaks can occur when unflued appliances such as gas cookers are in use (COMEAP, 2004). Indoor concentrations of NO_2, CO and other combustion products (including environmental tobacco smoke) may rise in increasingly airtight houses, if adequate ventilation is not provided.

5.3.2 Particulate Matter

Particulate matter (PM) concentrations in houses are affected by indoor sources (e.g. cooking and smoking), the infiltration of particles from outdoors and their removal from indoors by deposition and filtration (Gehin *et al*., 2008). Long- and short-term exposure to ambient PM levels has been associated with increased mortality and morbidity (COMEAP, 2010b). Indoor PM in particular has been associated with increased respiratory illness including asthma (Simoni *et al*., 2002; Weisel, 2002). There is also some limited evidence that the effect of simultaneous exposure to dust (i.e. total suspended particles) and ozone at relatively high concentrations is larger than the effect of these two pollutants individually in indoor environments (Mølhave *et al*., 2005).

The use of wood burning stoves may increase in permitted zones in the UK as a result of higher fossil fuel prices and the trend towards renewable energy sources. Whilst particulate pollution from modern stoves is much lower than was previously common with open fires, higher emissions can still

[2] PM_{10} and $PM_{2.5}$ are particles with aerodynamic diameters generally less than 10 and 2.5 µm respectively, which can travel deeply into the human respiratory system.

occur during start-up, stoking and reloading. Polycyclic aromatic hydrocarbons (PAHs) in wood smoke are of particular concern because of their carcinogenic potential (Jones, 1999).

5.3.3 Volatile Organic Compounds

Volatile organic compounds (VOCs) such as formaldehyde, benzene and other aromatic hydrocarbons are common indoor air pollutants emitted from building materials, furniture, paints, household products, tobacco smoke and other combustion sources (Bernstein *et al*., 2008). Outdoor concentrations of VOCs in urban areas are mainly related to road traffic emissions and are usually higher at ground level near busy streets (Vardoulakis *et al*., 2011). The health effects of VOCs include irritation to the eyes or nose, headaches, dizziness, nausea and allergic reactions (Jones, 1999). Some VOCs are carcinogenic, e.g. formaldehyde and benzene.

There is evidence suggesting a link between the use of household products that raise indoor levels of VOCs and an increased risk of certain symptoms, such as wheezing, vomiting, diarrhea and headache among infants and their mothers (Farrow *et al*., 2003). Frequent use of domestic chemical products in the prenatal period has been associated with persistent wheezing in young children (Sherriff *et al*., 2005). In an experimental study in Nottingham, Venn *et al*. (2003) found that domestic VOCs are not a major determinant of risk or severity of childhood wheezing illness, though formaldehyde may increase symptom severity, and indoor damp increases both the risk and severity of childhood wheezing illness. However, it is unlikely that current levels of VOCs in UK domestic indoor environments are posing a significant health risk, except for susceptible groups such as people with chronic illness, allergies and multiple chemicals sensitivity who are highly sensitive to these compounds (Institute for Environment and Health, 1999).

Stricter regulations and higher industrial standards are now in place to reduce the VOC content of building materials and household products. In the context of climate change and its mitigation and adaptation policies, it is unlikely that any change in the built environment will increase indoor VOC emissions. However, if building ventilation rates decrease, this will reduce the removal of VOCs from indoors.

5.3.4 Persistent Organic Pollutants

Persistent organic pollutants (POPs) ubiquitous in the indoor environment, such as polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs), have been associated with a wide range of negative health effects including cancer, immunosuppression, metabolic, neurobehavioural, endocrine and reproductive disorders (UNEP, 2011). Although overall levels of POPs will continue to decline globally as a result of global emission reduction initiatives such as the Stockholm Convention, there is a risk that human exposure to POPs, via inhalation of air and ingestion of surface dust in the indoor environment, may be altered directly and indirectly by climate change. For example, climate change may affect emissions of persistent organic pollutants (POPs) by changing their rate of mobilisation from materials or by altering use patterns (Lamon *et al*., 2009; UNEP, 2011).

It is plausible that higher indoor temperatures will lead to greater volatile emissions of POPs, as well as VOCs, from household products and materials leading to higher airborne concentrations, although enhanced natural ventilation (e.g. opening of windows) may balance higher indoor volatile emissions during summer (Haghighat and De Bellis, 1998; Hazrati and Harrad, 2006). POPs concentrations are typically 1-2 orders of magnitude higher in indoor air compared to outdoor air (Bohlin *et al*., 2008;

Harrad *et al*., 2010). Furthermore, indoor sources of certain POPs used as brominated flame retardants, such as PBDEs, and fabric treatment products for stain resistance, such as perfluorooctane sulfonate (PFOS), may become more significant in future climate-controlled buildings (UNEP, 2011). Increased use of thermal wall insulation in houses in particular may increase indoor contamination with flame retardants, such as hexabromocyclodecane (HBCD) used in insulation materials. Climate change may also have an impact on exposure levels to these typical indoor pollutants by altering the amount of time individuals spend indoors. In the UK, it is likely that people will be inclined to spend more time outdoors due to generally milder ambient air temperatures associated with climate change, although the opposite will probably occur during more frequent and prolonged extreme weather events (heatwaves and heavy precipitation).

5.3.5 Radon

Radon is a naturally occurring radioactive gas, emitted from rocks and soils, and can reach high concentrations in enclosed buildings on certain geological outcrops (Hunter *et al*., 2009). Although radon is present in low concentrations in all indoor air, geological conditions in certain areas can lead to higher than average levels. Radon levels are usually higher in basements or other structural areas in contact with soil (Field *et al*., 2000; WHO, 2009a). Some of the highest radon levels have been found in the southwest of England, but levels well above average have been found in some other parts of the UK. Radon is the largest source of human exposure to ionising radiation in the UK and is estimated to be responsible for more than 1,100 lung cancer deaths per year (HPA, 2012). It produces a radioactive dust in the air which becomes trapped in the airways and emits radiation that damages the lung and increases the risk of lung cancer. Although it has been argued that meteorological parameters may be capable of directly influencing indoor radon concentrations over extended periods (Groves-Kirkby *et al*., 2006), it is likely that climate change adaptation and mitigation measures affecting building ventilation will have a more significant influence on radon exposure. Low ventilation rates can encourage concentrations of radon gas to build-up in properties. Indoor exposure to tobacco smoke, which is another leading cause for lung cancer, is similarly going to be affected by building ventilation rates as well as by smoking habits[3].

5.3.6 Ozone

In the case of secondary pollutants (i.e. not directly emitted from pollution sources) such as ground level ozone (O_3), infiltration from outdoors is by far the dominant factor affecting indoor concentrations. In built-up areas, outdoor concentrations of ozone are usually higher near the top of urban canyons compared with street-level concentrations (Vardoulakis *et al*., 2011). Ozone is associated with reduced lung function, exacerbation of chronic respiratory illness, increases in respiratory hospital admissions and all cause mortality (WHO, 2000). Exposure to ozone may also increase the risk of sensitisation to airborne allergens in predisposed individuals (D'Amato, 2002).

Under certain emission scenarios predicting an increase in ground level ozone (see Chapter 3), indoor ozone levels may also increase, unless natural ventilation of buildings (e.g. opening of windows) is reduced (Weschler, 2006). Increased ozone infiltration may be enhanced by the generally larger increases in ground level ozone concentrations predicted in urban areas compared to rural areas in the UK. Ozone can also be generated indoors from printers, photocopiers and other

[3] In England in 2008/09 around 69% of adults reported that they do not allow smoking at all in their home, an increase from 61% in 2006 (NHS, 2010).

electronic appliances (Destaillats *et al*., 2008). Increased indoor concentrations of ozone could result in higher levels of formaldehyde and ultrafine particles through chemical reactions (Uhde and Salthammer, 2007). It should be noted, however, that ozone is removed rapidly by chemical reactions in the indoor environment (Jakobi and Fabian, 1997).

5.3.7 Climate change mitigation and adaptation measures

In a drive to reduce carbon dioxide (CO_2) emissions and conserve energy, buildings are being built to increasingly "tighter" specifications. Climate change mitigation policies in the building sector, such as "zero carbon buildings", will involve a combination of measures to improve energy efficiency, use of onsite renewable energy sources (heat pumps, photovoltaics, biomass boilers and other "microgeneration" options) and/or offsite low-carbon or renewable energy supply to meet the remaining energy demand.

Measures to improve the energy efficiency in dwellings focus on reducing thermal losses from the building envelope through compact building form and increased airtightness. This can be achieved with improved wall and roof insulation, and energy-efficient doors and windows (Roberts, 2008). Although this will enhance thermal comfort in winter, in certain circumstances it may result in higher concentrations of indoor contaminants, such as $PM_{2.5}$, CO, VOCs and radon, which could have an negative effect on human health (Wilkinson *et al*., 2009; Bone, *et al*., 2010).

A range of refurbishment measures can be implemented to control ventilation and reduce thermal loses through the building fabric, while maintaining acceptable levels of indoor air quality. Mechanical ventilation with heat recovery (MVHR) systems can substantially increase air exchange rates, reducing exposure to pollutants from indoor sources, if properly installed, operated and maintained (Wilkinson *et al*., 2009). Air filtering could also remove a fraction of allergens, particles and ozone in buildings with mechanical ventilation systems (Weschler, 2006). However, optimum location of ventilation inlets away from outdoor pollution sources is important in minimising ingression of contaminants into dwellings (Zero Carbon Hub, 2012).

It should be noted that refurbishment and retrofit activities, such as wall insulation and window replacement, may pose a health hazard to construction workers and occupants if materials containing asbestos or lead are present (Schenck *et al*., 2010). Increased CO poisoning risk has been associated with sealing of windows and other areas of air leakage. Furthermore, acute CO exposure from cleanup equipment and alternative energy sources used indoors after flooding events has been reported (Richardson and Eick, 2006).

5.4 Flood damage and water contamination

A higher frequency of heavy precipitation and flooding events in winter, as projected for the 21st century in the UK under climate change scenarios (UKCP09), will put pressure on existing buildings and pose a health risk to their occupants. The Climate Change Risk Assessment for the Floods and Coastal Erosion Sector estimates that one in six of all UK properties are vulnerable to some degree of flood risk (Ramsbottom *et al*., 2012). The annual clean up and damage costs amount to more than £1.3 billion and the frequency of river flooding may double or even quadruple by the 2080s. Continued building development on flood plains is adding to the risks together with rising sea levels.

Whilst deep flood water can cause serious damage in buildings potentially undermining their structural integrity, the management of surface water run-off around buildings and the quality of the building structure determine moisture transport into the indoor environment (IOM, 2011). If unmitigated, high moisture levels may result in mould growth on indoor building materials.

Chapter 7 of this report looks in detail at the impact of flooding on health including deaths and injuries, which are mostly sustained outdoors. Major health problems indoors relate to contaminated drinking water (including chemical and microbial contamination), mould growth, accidents (including electrocution), CO poisoning (from cleanup equipment use), and mental health effects (psychological distress, anxiety, depression and post-traumatic stress disorder), which can affect flooded residents in both the short and long term.

5.4.1 Climate change adaptation and mitigation measures

Although the location of buildings currently vulnerable to flooding is well known, consideration should be given to the effect that climate change may have on the extent and potential severity of flooding in the future. Flood defence schemes are expensive and adaptation is therefore likely to be a slow process. Living in a basement, ground or lower-ground floor flat may increase the health risks related to flooding.

Ideally, new building developments should be placed away from flood-risk areas. However, when this is not possible, e.g. if the building already exists or replaces an existing building, then adaptation measures to reduce the effects of flooding must be considered. New buildings can be designed to be flood resistant, but it is very difficult and expensive for existing households to adapt their indoor environment to prevent flood waters from entering their property. Simple adaptation measures such as tiling at risk areas of a house and raising electrical power points and electrical equipment above flood levels can be more easily achieved (RIBA, 2011). Nevertheless, more vulnerable groups, like the elderly or the poor, are unlikely to be able to afford even such simple adaptation measures.

More extensive use of “green” construction materials in buildings may be seen as a climate change mitigation policy reducing greenhouse gas emissions. Environmentally friendly “green” construction materials, e.g. cellulose and wood products, require less energy for manufacturing compared to traditional construction materials such as steel, aluminium and concrete (UNEP, 2009). However, some of these materials are also prone to water damage and mould growth (especially if untreated or if the treatment has faded[4]), which can be exacerbated by heavier winter precipitation and more frequent flooding events. This could have a significant impact on public health since indoor dampness and mould have been associated with a 30-50% increase in several respiratory and asthma-related health outcomes (Fisk *et al*., 2007).

Therefore, the use of “green” construction materials in the building sector needs to be carefully considered in relation to future climatic conditions. New building materials need to be tested to ensure that they are not more prone to mould and other hazardous biological or chemical contamination compared to existing materials, taking into account their entire life span in the building from installation to demolition.

[4] Use of biocides in these materials is subject to the EU Biocides Directive, 98/8/EC.

5.5 Indoor allergens and infections

In indoor environments, dust mites, moulds, pets and insects are the major sources of allergens. Mould is a ubiquitous microbial contaminant in the built environment and in most cases can establish its ecosystem once the appropriate humidity level (RH >70%) is reached (WHO, 2009b). Occupants of damp and mouldy buildings are at increased risk of infections, allergic reactions, asthma, irritation, and hypersensitivity pneumonitis due to the pathogenicity of some mould species (e.g. *Aspergillosis*) and the vast diversity of bio-products produced by mould, such as allergens, VOCs, glucans and mycotoxins (Rea *et al*., 2003; Fisk *et al*., 2007). Damp, condensation, water leakage and flooding are some of the common mechanisms, which can supply water to mould growth. Depending on the hygrothermal properties and composition of the building materials and the climatic conditions, different kinds of mould and bio-products can be produced (WHO, 2009b). In modern, well-insulated homes, the warm and humid indoor climate is ideal for dust mites to grow (see also Chapter 4).

Other microbes that can successfully develop an ecosystem in the built environment and cause diseases are *Legionella* species, *nontuberculous mycobacteria*, *Pseudomonas aeruginosa*, *Acinetobacter spp.* and *Enterobacter spp.* from different types of water reservoirs as well as pathogens found on building surfaces after flooding (CDC, 2003; Taylor *et al*., 2012). *Legionella* in particular can more readily amplify in evaporative cooling systems, cooling towers and mains water entering buildings in a warmer environment (Morey, 2010).

The addition of features such as green walls and roofs, rainwater harvesting and greywater recycling systems in buildings can also provide a new habitat for microbial growth and dispersal (Schenck *et al*., 2010; EA, 2011). If a pathogenic ecosystem is established, it can provide a continuous microbial source and pathway to adversely affect public health outcomes unless adequate mitigation actions are implemented. These urban water infrastructures can also provide a breeding ground for disease vectors such as mosquitoes. However, a suitable climate is required to support such ecosystem (see Chapter 8). If established, the proximity of such an ecosystem to the indoor environment can pose a higher vector-borne disease transmission risk to the occupants.

The built environment can play a key role in the airborne transmission of infections such as tuberculosis (TB) through poor ventilation and overcrowding. According to a systematic review by Li *et al*. (2007), there is strong evidence of the association between ventilation, airflow and the transmission of airborne infectious diseases in buildings, but insufficient data to quantify the minimum ventilation requirements in various indoor environments for preventing transmission. London was named the capital of TB in Europe in 2010 (Zumla, 2011). It is possible that with a growing population, space available per person may decrease in residential buildings, especially in densely populated urban areas (Williams, 2009). To compensate for this risk factor, ventilation rates in residential buildings should be increased to maintain the same amount of fresh air supply per person. Climate change mitigation policies focusing on energy efficiency in the built environment may have an opposite effect on ventilation rates in future buildings. Reducing ventilation rates can also increase the humidity level indoors and promote mould growth. It should be noted that temperature and relative humidity affect the survival time of bioaerosols, while sunlight is a natural disinfectant.

Finally, it has been reported that climate change is likely to increase dust levels in the atmosphere, particularly in the summer, and these dust particles can carry different kinds of pathogens (Morey, 2010). The use of natural ventilation techniques instead of, or with, mechanical ventilation systems ("mixed mode" ventilation) is one of the available measures to reduce energy consumption in the built environment sector. Therefore, ingress of airborne dust and pollen into naturally ventilated dwellings needs to be taken into consideration as part of climate change mitigation and adaptation policies.

5.6 Public health response

5.6.1 Hospitals, care homes and surgeries

Extreme weather events such as heatwaves and heavy precipitation can compromise the quality of the indoor environment by causing building overheating, flooding, and disrupting power generation and distribution. There is a possibility that current health care building infrastructure, including hospitals, care homes and surgeries in the UK, may not be resilient to climate change and related extreme weather events (Hames and Vardoulakis, 2012). Floods in particular could cause substantial disruption to the NHS building infrastructure as 7% of hospitals and 9% of surgeries and health centres in England are built in flood risk areas (EA, 2009). Heatwaves may also cause disruption to health care services if indoor temperatures in hospitals, care homes and surgeries are not adequately controlled. Overall, there is a risk that more frequent and intense extreme weather events associated with climate change could compromise health care delivery if adequate adaptation measures, involving flood defence, thermal insulation, passive and active cooling and ventilation, are not adopted.

A recent study by Oven *et al*. (2012) has identified parts of England where population and climate change projections (UKCP09) suggest that risks due to extreme weather (increasing frequency and severity of floods and heatwaves) and vulnerabilities associated with ageing of the population are most likely to change rapidly in the next 20 years. These regions include part of the country experiencing rapid growth in older population groups (aged 65 years and above) such as the South East, East of England, Yorkshire and Humber and the North West. In these areas, climate change adaptation strategies in the health care sector may be most severely tested.

5.6.2 Risk assessment systems and guidelines

There are several risk based assessments, systems and guidelines aiming to protect human health in the indoor environment that are relevant to climate change adaptation. Some examples, including the Climate Change Risks Assessment, the Housing Health and Safety Rating System, radon action levels, building regulations, and indoor air quality guidelines, are briefly presented here.

- The Climate Change Risk Assessment for the Built Environment Sector (Capon and Oakley, 2012) identified a number of opportunities and threats posed by climate change. It noted that the UK's built environment includes 27 million homes and nearly 2 million commercial and industrial properties, hospitals, schools and other buildings. Opportunities include milder winters providing a reduced requirement for indoor heating and a reduction in cold weather related deaths. Threats include increased summer temperatures causing uncomfortable indoor temperatures further enhanced by the urban heat island effect

(particularly at night), increased probability of flooding of buildings, and increased probability of building subsidence and water shortages. All of these risks can have an impact on the physical and mental health of building occupants. Although enhanced building regulations can help new dwellings to become more resilient to climate change, it is more difficult and expensive to adapt existing building stock to cope with greater temperature and precipitation extremes. Most of the identified risks are likely to have a disproportionate effect on socially vulnerable groups such as the elderly, the poor and those with underlying health problems.

- The Housing Health and Safety Rating System (HHSRS) uses a risk assessment model to identify household hazards, mainly in the rented sector, including excess heat and cold, damp and mould growth, CO and other fuel combustion products, asbestos, lead and radon gas, and assesses any potential risk to the occupants (DCLG, 2006a). By assessing both the probability of occurrence and the potential harm to the occupant, it uses a formula to generate a numeric score which allows comparison across a wide range of household hazards. This allows a judgement to be made as to whether that risk is acceptable or not. It provides a scoring format (categories A to J) so as to give legal form to the risk involved. If any hazard scored falls into category A, B or C, then the Local Authority has a responsibility to take formal legal action against the property owner.
- It is essential that new buildings are designed to be flood resistant, especially those constructed in potential flood-risk areas, such as coastal areas and flood plains. Furthermore, they should provide protection from heat and cold through adequate shading, thermal insulation and ventilation. The building code for sustainable homes (DCLG, 2006b) sets standards for energy efficiency which ensure reductions in greenhouse gas emissions, limit the effects of solar gains of buildings in summer, and improve water efficiency including better management of surface run-off water.
- Protection from exposure to radon gas in houses needs to give consideration to climate change mitigation and adaptation measures. The HPA has defined its Radon Action Level at 200 becquerels per cubic metre (Bq m^{-3}), but has also introduced a new Target Level of 100 Bq m^{-3}. The HPA recommends that people in homes where radon levels have been recorded above the Action Level should aim to reduce radon to as low as reasonably practicable, if possible below the Target Level. Householders with measured radon levels between these two figures should think carefully about preventative action to protect their health, especially if there are smokers in the house. The HPA recommends that Target and Action Levels should be applied to other premises where occupancy by members of the public exceeds 2,000 hours per year and to all schools. An active radon sump, fitted with a fan, is the most effective way to reduce indoor radon levels.
- In the workplace, indoor air pollutants are regulated in the UK by the Health and Safety Executive. In the home environment there is no such regulation. However, the UK Committee on the Medical Effects of Air Pollutants (COMEAP, 2004) has recommended guideline values for five pollutants (NO_2, CO, formaldehyde, benzene and benzo[a]pyrene) in indoor air. The World Health Organization has also developed indoor air quality guidelines on specific pollutants (WHO, 2010), as well as separate guidelines on dampness and mould (WHO, 2009b). Guidelines for environmental tobacco smoke (ETS), a major indoor pollutant, were included in the second edition of the WHO Air Quality Guidelines for Europe (WHO, 2000).

5.7 Conclusions

Climate change may have several direct and indirect adverse health effects in the indoor environment related to building overheating, indoor air pollution, flooding and water damage, and biological contamination. On the other hand, climate change mitigation and adaptation policies in the residential building sector involving improved building design and ventilation, passive cooling, and energy efficiency measures can result in benefits to health. However, building retrofitting assessments should be carried out prior to installation of cooling and ventilation systems, insulation materials, and replacement doors and windows, to ensure that any potential health hazards (e.g. associated with exposure to lead or asbestos) are identified. Health effects associated with the installation and use of renewable energy microgeneration systems (e.g. photovoltaics, wind turbines, solar water heating and biomass boilers) in the domestic environment also need to be assessed.

Ventilation is a key aspect that affects indoor air quality (chemical and microbial), moisture-related allergens (mould and dust mites) and thermal comfort in dwellings (Davis *et al*., 2004; Wargocki *et al*., 2002). A recent report of the Institute of Environment and Health, Cranfield University, has focused on health impacts due to changes in the indoor environment in the context of climate change, highlighting a number of research needs in this area (Crump, 2011). The need for research into the performance of highly energy efficient homes, the quality of the ventilation systems and the impact on health and wellbeing of occupants was also identified by Crump *et al*. (2009).

Behavioural aspects of building occupancy, including opening of doors and windows, cooking methods, tobacco smoking, use of cleaning and DIY products, and responding to improved thermal efficiency by increasing indoor temperatures may compromise indoor air quality and energy savings. Overall, climate change is likely to act as a risk modifier in the indoor environment, potentially amplifying existing health risks, associated with exposure to indoor air pollutants, contaminated water, allergens and mould, and exacerbating health inequalities. Well-targeted and cost-effective adaptation and mitigation measures could minimise these risks and provide ancillary health benefits.

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6 Climate change, ultraviolet radiation and health

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Summary

- Climate change may affect ambient levels of ultraviolet radiation (UVR) in the UK. However, the critical factors affecting human exposure are lifestyle and behaviour. If people are exposed to higher levels of UVR throughout their lives, this is likely to increase the risk of non-melanoma skin cancers.
- Data from the Health Protection Agency solar monitoring sites suggest that a small upward trend in total solar UVR reaching the Earth in the UK is slowing. However, occasional events, such as thinning of stratospheric ozone[1] over the Arctic region, may contribute to increased incidence of erythema.
- The amount of UVR received at ground level also depends on variations in cloud cover and sun elevation. The effects of different types of clouds on UVR flux are complex, wavelength dependent and are still being investigated, as are changes to cloud cover due to climate change.
- Extreme events affecting the atmosphere, such as volcanic ash clouds may reduce the level of UVR exposure.
- Since behaviour is such an important factor for personal UVR exposure, it is only possible to speculate on the impact of any potential increase of temperature on exposure levels. It is possible that people will spend more time outdoors in the UK, especially for recreation. However, if this results in fewer holidays overseas to sunny climates, then it could result in fewer malignant melanomas.
- The benefit of being outdoors should be taken into account. Reasonable sun exposure is likely to be beneficial for the production of vitamin D, and is likely to be linked with exercise, fresh air and circadian rhythm entrainment. For example, in the UK it is unlikely to be necessary to apply protection measures for up to 15 minutes exposure to the summer sun at midday.

Public health recommendations

- The messages relating to the risk and benefit of exposure to optical radiation from the sun need to be appropriate for specific target groups such as young people and the elderly, and take account of the difference between exposure in the UK and recreational exposure in some locations overseas.
- Guidelines should be given for target audiences on how they can optimise their sun exposure protection strategy based on the sensitivity of their own skin and that of others for whom they may be responsible, to avoid excessive sun exposure. Simple, positive messages, such as "enjoy the sun without burning" should be used.
- Information should be freely and widely available to warn of any increases of ultraviolet radiation exposure related to the thinning of the stratospheric ozone layer.

[1] Throughout this chapter, the ozone under consideration is located in the stratosphere, above around 10 km from the surface of the earth.

Research needs

- The relation between solar UVR spectral irradiance, as determined on a horizontal plane, needs to be correlated with actual population exposure. This will require further personal monitoring studies or theoretical modelling and will need to consider different population groups.
- The current solar UV measurement network for terrestrial solar radiation should be extended to include further measurement sites – perhaps to include the Channel Islands and locations where the UK population tend to spend recreational periods at home and overseas. Such installations may be permanent (to add to the current database) or temporary to cover specific events. The data from the additional sites will add to the database that can be used to identify regional trends in UVR exposure.
- UV spectroradiometers are used at a small number of sites across the UK. Such equipment is expensive. However, a range of small, lower cost, single-shot spectroradiometers are now available and the use of these for routine solar UV monitoring should be investigated. This would provide the capability to assess UV and visible optical radiation exposures in terms of a range of different action spectra[2] – for example erythema, non-melanoma skin cancer, vitamin D production and circadian rhythm entrainment. Such equipment may also be able to provide an indication of stratospheric ozone events.
- Epidemiological studies are required to better understand the relationship between changes in ambient temperature and sun-related behaviour (including both sun exposure and sun protection).

[2] Action spectra are used to relate the effectiveness of different wavelengths of optical radiation at producing a given effect.

6.1 Introduction

Previous reviews outlined the ways in which stratospheric ozone depletion was increasing the amounts of solar ultraviolet radiation (UVR) reaching the earth's surface (DH, 2002), the detrimental health impacts and potential benefits of exposure (HPA, 2008). The summary and recommendations from the 2008 report (Bentham, 2008) are reproduced below. These are developed further in this report.

The 2008 report recognised that there was a need to balance the risk from exposure to solar UVR with the important health benefits from vitamin D. There is convincing evidence that vitamin D has a role in skeletal health. However, it was stated that further research was required to support claims that there were associations with other chronic diseases, such as cancer.

At the time of the last report, there was evidence that the ozone layer was expected to recover by 2050. However, it was stated that solar UV-B increases due to stratospheric cooling association with climate change may delay the recovery by between 15 and 20 years. It was also postulated that decreases in cloud cover, particularly during potentially extended summer months, may lead to changes in behaviour and therefore increases in personal UVR exposure.

The recommendations from the report emphasised the need to maintain health promotion campaigns to limit personal exposures to damaging UVR. However, clearer advice was needed on how the public could maintain adequate vitamin D levels.

The beneficial and detrimental effects of optical radiation (including UVR) on humans depend on wavelength. Action spectra for erythema, non-melanoma skin cancer and vitamin D production have been published by the International Commission on Illumination (CIE, 1998, 2000, 2006). For example, when the UVR irradiance is weighted with the erythemal action spectrum, it is termed erythemal irradiance, E_{er} (CIE, 2011). Background information on UVR and biologically effective irradiance is provided in Box 6.1.

As the human race has spread across the world, it has adapted to the ambient UVR level (Jablonski and Chaplin, 2000): as populations have moved away from equatorial regions, skin colour has become lighter. This is likely to be a combination of less need to protect from the harmful effects of UVR with the need to increase the ability to generate vitamin D (WHO, 2006).

The human eye is recessed to protect it from the sun when the sun is high in the sky. Natural aversion responses will limit direct eye exposure when the sun is lower in the sky. However, thin or broken cloud cover may increase ocular exposure due to light scattering, as may many of the surfaces and materials described below.

Skin exposure to UVR occurs when the skin is directed towards the sun on a clear day. However, reflecting surfaces, such as thin clouds, snow, water, sand, some building wall materials and concrete paving can also lead to increased exposure.

Box 6.1. Ultraviolet radiation (UVR)

The optical radiation received from the sun covers a wide spectral region, from the infrared (which we perceive as warmth), visible radiation (which allows us to see) and ultraviolet radiation (UVR). Optical radiation is usually characterised by its wavelength, but the boundaries between the different spectral regions are not exact. Therefore, by international agreement, the wavelength ranges are defined for convenience. Our eyes are sensitive to visible radiation (light) from approximately 380 nm (blue/violet end of the spectrum) to 780 nm (red end of spectrum), although higher exposure levels are needed to trigger a visual sensation towards the outer boundaries. Our eyes are considered to be most sensitive to light at 555 nm (green) under bright light conditions.

The UVR region of the optical spectrum overlaps with the visible region and is assumed to be at wavelengths below 400 nm. The lower boundary for UVR is not precise, but for standardisation is usually considered to be at 100 nm. However, wavelengths between 100 nm and 180 nm are only transmitted in a vacuum and therefore have no direct consequences for health.

The UVR region is sub-divided to take account of transmission in the skin and potential interaction mechanisms, which may result in adverse health effects. UV-A (315 nm to 400 nm) penetrates furthest into the layers of the skin due to its longer wavelength. It plays a role in skin photoaging and can affect the immune system. UV-B (280 nm to 315 nm) is considered the most damaging, causing tanning and sunburn (erythema) and it can also affect the immune system. Although UV-C (<280 nm) can directly damage DNA (epithelium, cornea and bacteria), all UV-C is attenuated by stratospheric ozone and therefore is not usually encountered naturally at ground level on Earth. All UV-C and approximately 90% of the solar UV-B is absorbed by stratospheric ozone whilst most of the UV-A passes through the atmosphere. However, the ratio of UV-B to UV-A varies with solar zenith angle (i.e. how high the sun is in the sky) and season (Hooke *et al*., 2011).

In the electromagnetic spectrum, UVR extends between the blue end of the visible spectrum and low-energy X-rays, straddling the boundary between ionising and non-ionising radiation (which is conventionally set at a wavelength of 100 nm) (Figure 6.1).

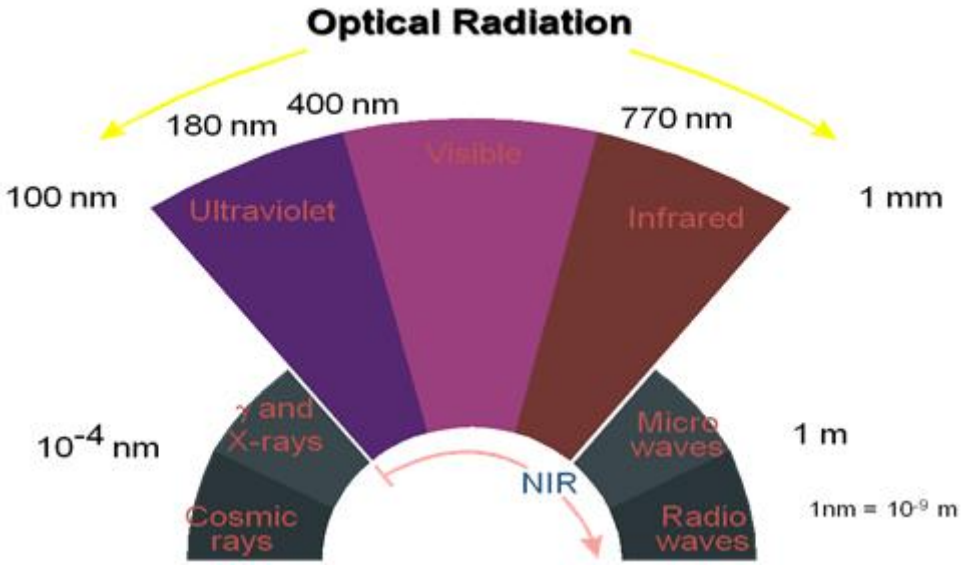

Figure 6.1. Optical radiation as part of the Electromagnetic spectrum

Biologically effective irradiance

The amount of UVR at each wavelength, when displayed graphically, is the UVR spectrum in W m^{-2} nm^{-1}. Figure 6.2 shows the solar UVR spectrum measured at solar noon on 26 June 2011 (cloud-free sky) at Chilton, Oxfordshire.

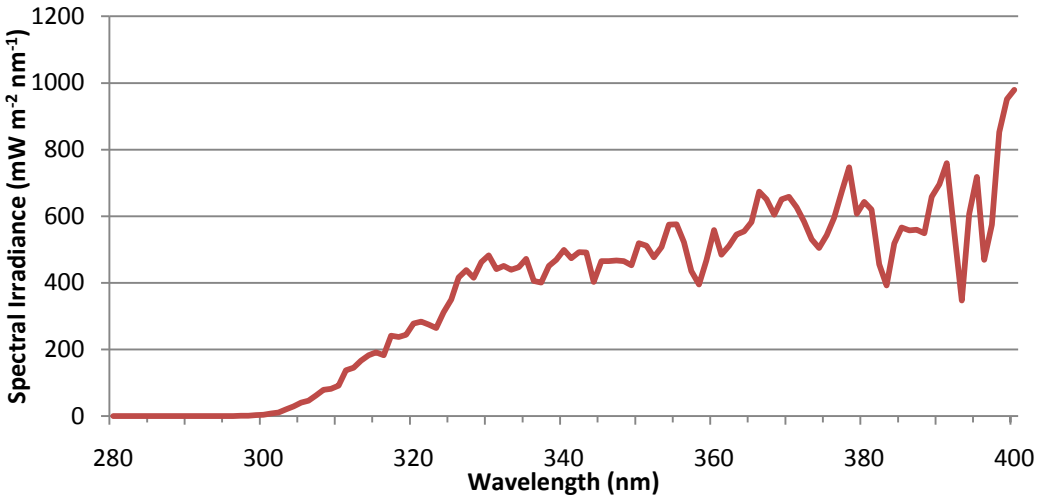

Figure 6.2. Solar UV Wavelength Spectrum - Chilton, Oxfordshire, Clear Day, June 2011

Since some wavelengths are more effective than others in causing biological damage, UVR exposure and dose are computed with the weighted functions called action spectra, which expresses the relative effectiveness of UV radiation at various wavelengths for a particular biological process. The action spectra for erythema, non-melanoma skin cancer (NMSC) and vitamin D is presented in Figure 6.3 (note that the y-axis is on a logarithmic scale). The greatest influence of UVR on biological effects is for wavelengths at around 300 nm or below.

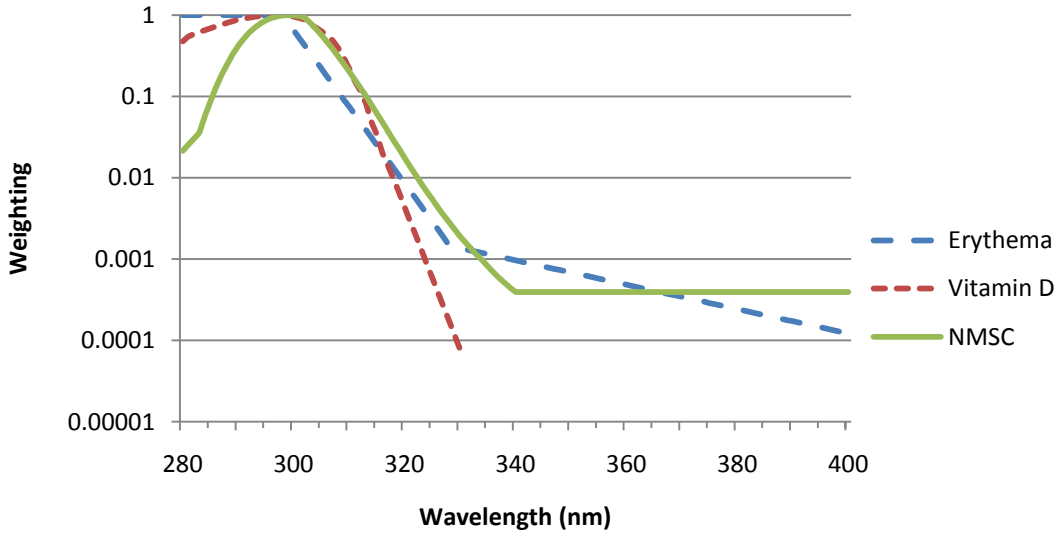

Figure 6.3. Action spectra for erythema, non-melanoma skin cancer (NMSC) and vitamin D formation

When the solar UV spectrum measured at solar noon on 26 June 2011 (cloud-free sky) at Chilton (Fig.6.2) is multiplied by the respective weighting factor at each wavelength (figure 6.3), the result is a weighted solar UVR spectrum (figure 6.4) for the three different action spectra.

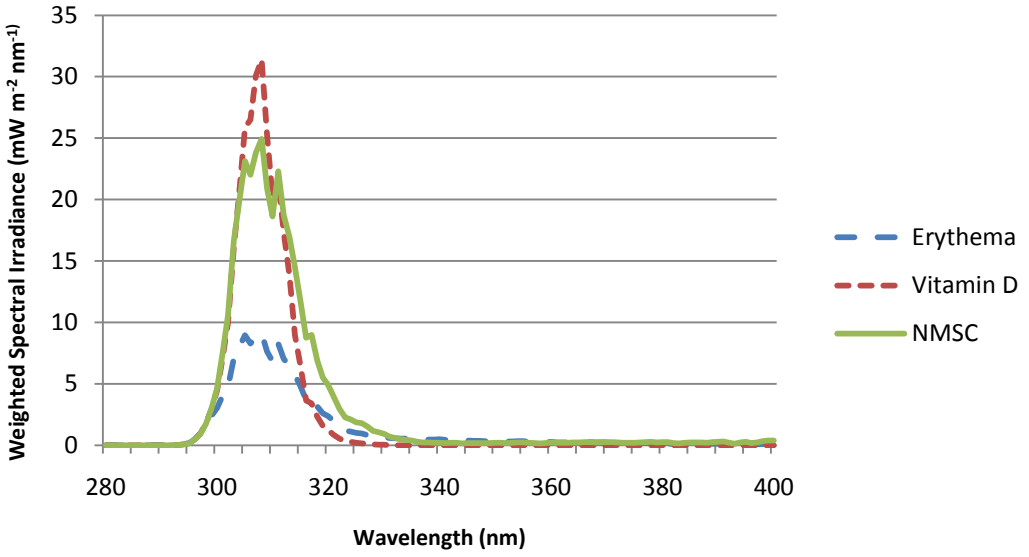

Figure 6.4. Weighted Solar UV Spectrum - Chilton, Oxfordshire, Clear Day, June 2011

6.2 UV index and personal protection

The World Health Organization, in conjunction with other organisations, developed the Global Solar UV Index (1-2: low; 3-5: moderate; 6-7: high; 8-10: very high; and 11+: extreme) to provide guidance on protection measures as a function of the solar irradiance, weighted for erythema (WHO, 2002). In the UK, it is rare that the UV Index exceeds 8. However, for destinations where a minority of the UK population may spend one or two weeks of recreation per year, the UV Index may exceed 11 (extreme) and at the equator it may reach 16. Visitors to mountainous or high-altitude regions are also exposed to higher UV levels. For every 1000m in height above the ground, the level of UVR irradiance exposure increases by approximately 10-15%, with reflection from snow additionally increasing UVR exposure (Blumthaler *et al.,* 1997; WHO, 2006).

If the UV Index is 2 or lower, no protection measures are advised. However, for 3 and above, it is recommended that a range of protection measures are used. The most effective is to avoid UVR exposure to the sun (however, see comments below about vitamin D synthesis). Shade may be used, but it is important to consider reflections and appropriate orientation of portable shade structures with openings. Clothing can be very effective for protecting covered areas of the body. A simple test of effectiveness is to see whether light is transmitted through the material – both when relaxed and stretched. A British Standard applies to the testing of clothing intended to be marketed as providing UVR protection (BSI, 2002). However, a recent assessment of summer clothing intended for children demonstrated the limitation of the test methodology (Khazova *et al.,* 2007). Hats can provide a high

level of protection, provided they shield the eyes, ears and the back of the neck from direct solar UVR exposure.

The use of sunscreen lotions as a UVR protection measure is not reliable. The test method for the sun protection factor (SPF) marking given on the packaging relies on a thicker layer of lotion than will normally be applied on a person. The SPF marking gives an indication of the protection largely against UV-B and is the ratio of the time to obtain a just perceivable erythema 24 hours after sun exposure with and without the sunscreen. Some manufacturers have adopted similar marking systems for UV-A protection. It is important that sun protection messages give guidance on the meaning of the protection level provided on the packaging. The actual exposure received will depend on the UV Index and the time of exposure, even if the lotion is applied as intended.

Appropriate sunglasses should provide shielding from exposure of the eyes to UVR from the side as well as the front. This can be challenging where prescription sunglasses are required. Sunglasses should provide adequate protection from UV-A and UV-B.

The CCRA Health Sector report (Hames and Vardoulakis, 2012) argued that higher summer temperatures could encourage people to spend more time in the sun (e.g. for leisure activities). While this may lead to higher levels of vitamin D in the body, it may also increase exposure to UV radiation and therefore contribute to an increase in the incidence of non-melanoma skin cancer. The large role that human behaviour plays in determining exposure to UVR, such as the total time people spend outdoors and how they protect themselves from the sun makes it very difficult to calculate the level of risk. Current climate projections (UKCP09) indicate a slight increase in net surface shortwave radiation (including UV) flux by the end of the century for southern England (up to 10% by the 2080s for the high emissions scenario), decreasing further north. The CCRA report concludes that "*Finally, the weakest overall evidence was related to the sunlight / UVB exposure metric, because of the uncertain projections of UVB exposure levels in the UK and the very limited quantitative evidence linking long-term UVB exposure of a relevant population to skin cancer. In addition, no quantitative evidence on the health benefits associated with increased exposure to sunlight could be identified.*" (Hames and Vardoulakis, 2012).

6.3 Climate effects on UVR

Climate change will influence UV radiation received at ground level through changes caused mainly to cloud cover and surface reflectivity (snow, ice, sand and water). Changes in aerosols and air pollutants in the future will also affect levels of UV radiation at ground level through absorption or scattering in the atmosphere. The sun's behaviour (such as sunspot activity) will also influence UV radiation. The amount of UV radiation reaching the Earth's surface depends also on the concentration of ozone in the stratospheric ozone layer, which protects life on Earth by absorbing UV radiation. However, thinning of the global ozone layer due to use of man-made chlorofluorocarbons (CFCs) which has occurred since the late 1970s, has resulted in increases in the amount of UV radiation reaching the Earth's surface.

While the depletion of stratospheric ozone over Antarctica has been widely studied, it has only recently emerged that similar depletion events have happened over the Arctic, lasting for several months each time, although not as regularly as over the South Pole region. 2011 saw the largest decrease in ozone so far over the North Pole region, it was comparable in extent and magnitude

with the ozone depletion over Antarctica, which happened during the boreal winter/spring time (Manney *et al*., 2011).

After the Montreal Protocol, which restricted the use of ozone depleting substances, came into force (1989), a gradual recovery of stratospheric ozone has occurred and ozone is expected to recover to pre-1980 levels before the mid 21st century (UNEP, 2010). However, there is now concern that the effects of climate change may slow down the recovery of ozone in the stratosphere and as a result this may affect levels of UV radiation at ground level. Recovery of stratospheric ozone is affected by changes in temperatures, circulation, and nitrogen and hydrogen ozone-loss cycles (Waugh *et al.*, 2009).

Changes in cloud cover, temperature and aerosols which are also influenced by climate change may affect UV radiation at ground level, such as at high latitudes, where increases in cloud cover and reduction of the area of snow or ice may lead to large decreases in UVR at the surface and to small increases at low latitudes where the UVR is already high (UNEP, 2010).

Detailed climate projections for the UK (UKCP09) contain only limited information regarding UVR, with the most relevant indicator being "downward surface shortwave flux". However, this term covers a wide range of the spectrum, including UV, visible and near-infrared radiation. For the whole shortwave range, the UKCP09 projections (high emissions, end of 21st century, 50% probability level) show an increase of up to 3% in the southernmost parts of the UK (up to 10 Wm^{-2}, with total flux being 345 Wm^{-2}). However, UKCP09 projections show a less pronounced increase in shortwave radiation in most of the northern parts of the UK, while a decrease in shortwave radiation is projected for small areas of western Scotland.

6.3.1 Recent trends in solar UVR exposure in the UK

Solar UV radiation has been monitored by the Health Protection Agency (HPA) at different latitudes within England and Scotland at six horizontal surface monitoring sites. Three are the former National Radiological Protection Board (NRPB, now part of HPA) sites in Chilton, Leeds and Glasgow and three other sites are at Met Office observatories at Camborne, Lerwick and Kinloss. The ground-based level of erythemally effective UV radiation (E_{er}) irradiance (280-400 nm) was measured using Robertson-Berger meter (RB-500 and RB-501) detectors. Changes in ground level E_{er} for these six locations in UK were investigated by Hunter *et al*. (2011).

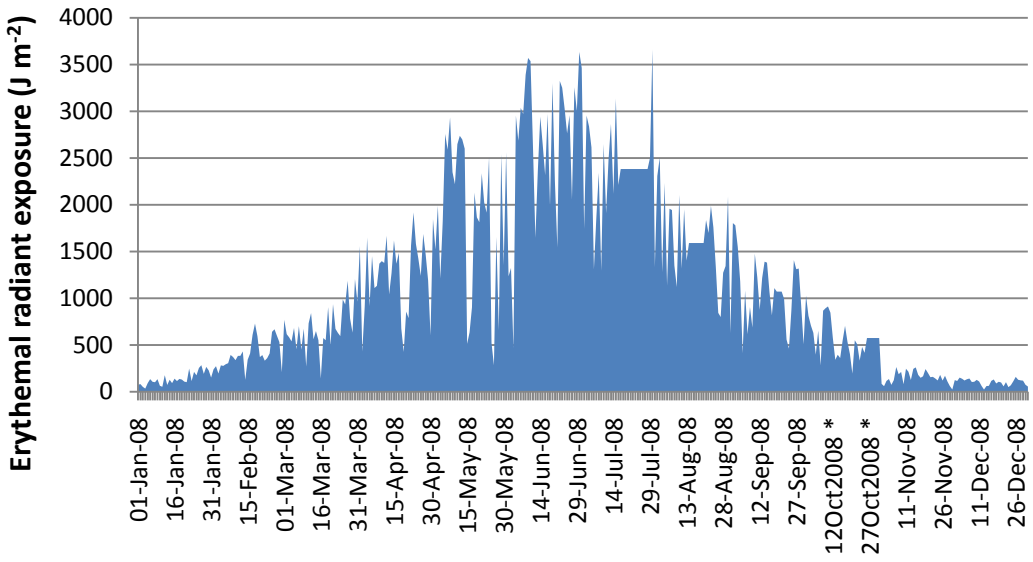

Figure 6.5. Daily variation in erythemal radiant exposure (J m^{-2}) in 2008 at Chilton, Oxfordshire.

As shown in Figure 6.5, the erythemal (sunburn) radiant exposure (H_{er}) for 2008 at Chilton in Oxfordshire was highest during June and lowest during December. This pattern is similar for all of the UK sites; the higher the latitude the lower the erythemal radiant exposure becomes (Hunter *et al*., 2011).

Figure 6.6 shows the yearly variation of total erythemal radiant exposure for the six monitoring locations in the UK. It should be noted that the year in which reliable and full data started to be collected varies by site, with the age of each site ranging between 13 and 20 years. The H_{er} data for all sites follow a similar yearly variation pattern. There was no significant upward trend before 1998, but a consistent rise until 2003 thereafter. Peaks were observed in 1995 and 2003 for total H_{er} recorded at these sites. This may be due to exceptionally clear sky during hot summers in these years, or reduced cloud cover.

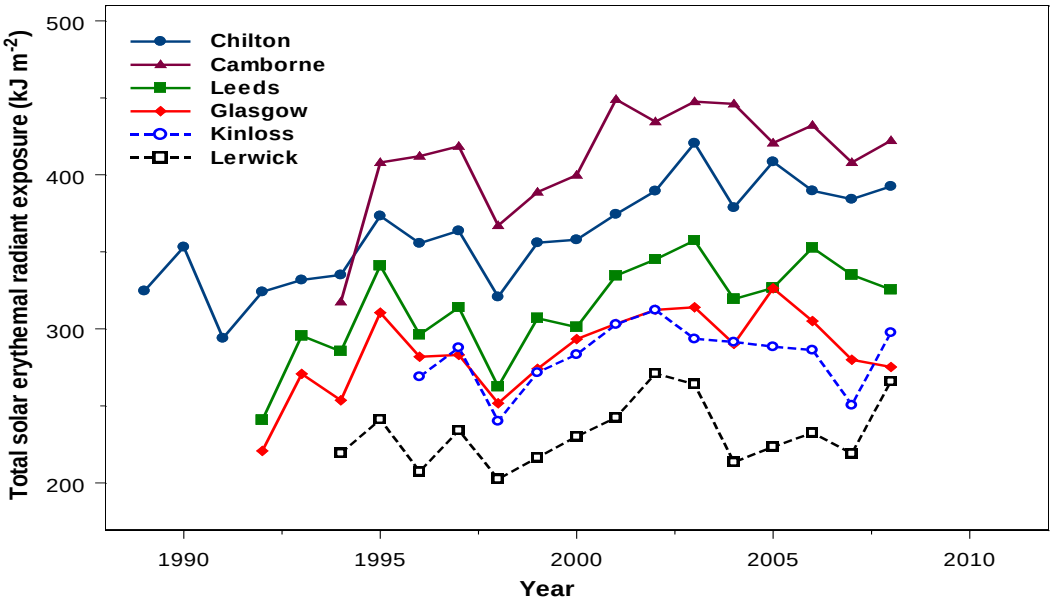

Figure 6.6. Total yearly erythermal radiant exposure data for the six UK sites.

The analysis of yearly erythemal radiant exposure values have shown statistically significant evidence that are consistent with a small but significant increasing trend between 1989 and 2008 in the annual integrated radiant exposures at four sites (Camborne, Chilton, Leeds and Glasgow), despite large inter-annual variability. There was also a statistically significant difference in slopes between sites. Overall, the observed H_{er} data in Figure 6.6 suggest a mean increase of 0.23 kJ m^{-2} $year^{-1}$ (95% CI: 0.01-0.45) between 1989-2008. Although significant evidence exists of upward trends for yearly H_{er} in the UK, in more recent years it appears that the observed exposure stabilises for most sites (Figure 6.6). Potentially influential factors affecting ground level UV radiation such as the total yearly stratospheric ozone and the total sunshine hours (as a proxy of cloud effects) to H_{er} were investigated (Hunter *et al*., 2011). However, there was a lack of clear evidence of any underlying dependence of changes of H_{er} on stratospheric ozone concentration and sunshine hours in the UK (Hunter *et al.*, 2011).

The amount of UV radiation reaching the Earth's surface depends on factors such as stratospheric ozone concentration, cloud cover, and air pollution. The effects of climate change on these factors is uncertain, which makes it difficult to predict changes in H_{er} associated with climate change. The level of UVR that reaches the Earth's surface can undergo large and rapid changes at any location; the UK is situated at a transition zone between increasing (southwards) and decreasing (towards Arctic region) UVR levels, making confident predictions difficult (Bais, 2011). The UV radiation data in the UK are still too variable and short-term to fully understand long-term trends. Hence it is very important to continue careful monitoring of UV irradiances and environmental variables, such as stratospheric ozone concentrations, that affect UVR, both from the ground and from satellites.

6.4 Health Impacts of UVR

An increase in the amount of UVR received at ground level has potential effects on human health, including increased incidence of skin cancer and cataract, as well as effects on the environment, e.g. animals and plants may be affected (UNEP, 2010). Furthermore, skin aging and suppression of the immune system are other known health effects of UVR exposure. Man-made devices such as industrial lamps and arc welding tools used for occupational work, and sunbeds used for cosmetic tanning are also known as an appreciable source of intense intermittent UVR exposure. The scientific evidence for the potentially harmful effects of UV radiation has been reviewed by various scientific committees (UNEP, 2010; WHO, 2006; WHO, 2003; ICNIRP, 2003; AGNIR, 2002; Norval *et al*., 2011; Lucas *et al*., 2010; 2008). On the other hand, UVR is essential for producing vitamin D in the human body, which has beneficial effects for skeletal health and may help in the prevention of certain diseases including cancers (Holick, 2007; McKenzie *et al*., 2009; Young, 2009; Epplin and Thomas, 2010).

6.4.1 Skin

The most serious adverse health effects for which exposure to UVR is a recognised risk factor are cutaneous malignancies (skin cancers). Over-exposure to solar UVR can increase the risk of both non-melanoma skin cancers (NMSC) - mainly basal cell carcinomas (BCC) and squamous cell carcinomas (SCC) - and melanoma skin cancers. UV-A penetrates to deeper layers of the skin than UV-B, while UV-B cause sunburn and increases the risk of developing skin cancer. Skin cancer risks are greatest in white people with fair complexions (light colour skin, red or blonde hair, and blue eyes) and sun-sensitive skins, and melanoma risks are much raised in those with many and atypical naevi (moles). BCC and SCC are relatively common although they are rarely fatal, but can be disfiguring and costly to treat. Malignant melanoma on the other hand is less common, but is the main cause of skin cancer death, particularly in young people in the UK. Findings from epidemiological studies indicate that the risk of non-melanoma skin cancer can be related to cumulative UVR exposure over a lifetime, whereas melanoma is more related to intermittent high levels of sun exposure (for example during holidays in sunny climates) and sunburn (Norval *et al*., 2011; Jung *et al*., 2010; Lucas *et al*., 2008; Lucas *et al*., 2006).

There is also evidence that short episodes of sun burning due to high UVR exposure at an early age are implicated as a major risk factor for melanoma and possibly basal cell skin cancer (Mackie, 2006). Higher numbers of naevi are associated with an increased risk of malignant melanoma. There is also growing evidence that childhood exposure affects the number of naevi (English *et al*., 2006; Oliveria *et al*., 2009).

Genetics (Albinism- inherited genetic condition)[3] also affect risk factors for skin cancer; if there is a family history of skin cancer, other family members are likely to develop skin cancer. Aging also increases a person's susceptibility to skin cancer, in part because of the cumulative exposure to sun, and also because of a weakened immune response.

Skin cancer is one of the commonest forms of cancer in the UK. Malignant melanomas are the most serious type of skin cancer and are rising in the UK. In 2008, there were 11,767 new registered cases of malignant melanoma and 98,800 new registered cases of non-melanoma skin cancer (NMSC), but

[3] (http://cancerhelp.cancerresearchuk.org/type/skin-cancer/about/skin-cancer-risks-and-causes)

registration is known to be incomplete for the latter (http://info.cancerresearchuk.org/cancerstats). Although NMSC are the most common skin cancer, mortality is higher from malignant melanoma. In 2008, there were 2,070 deaths from malignant melanoma in the UK compared to 491 from NMSC. Over the last thirty years, incidence rates of malignant melanoma in the UK have increased more rapidly than any of the other top ten cancers in males and females. Malignant melanoma incidence rates in the UK have more than quadrupled over the last thirty years. Figure 6.7 shows the age-standardised (referred to as the standardised population) incidence rate of malignant melanoma in both male and female for the UK. The male incidence rates have increased more than five times from around 2.9 diagnosed cases per 100,000 population in 1979 to 16.0 in 2008, while the female rates have more than tripled from 4.8 diagnosed cases per 100,000 population to 16.5 over the same period in the UK.

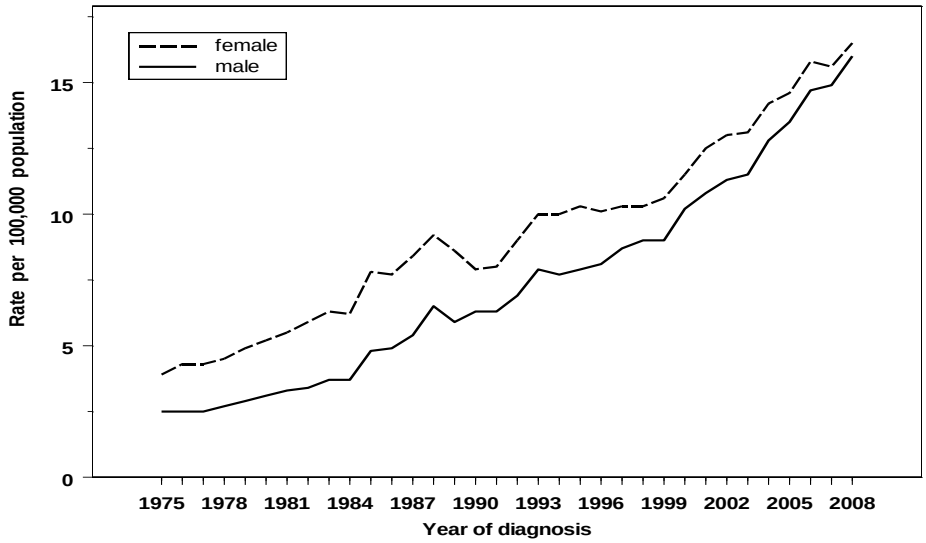

Figure 6.7. Malignant melanoma, age standardised incidence rates per year, UK, 1975 – 2008 (http://info.cancerresearchuk.org/cancerstats**)**

NMSC is common in the elderly; over 80% of NMSCs occur in people aged 60 years and over. Melanoma incidence also increases with age, and the largest increase is in the over 60s age group. However, the incidence is also high in young people aged 15-34 years old (over 900 cases diagnosed in this age group in 2008). On average, around 20 years of life are lost for each melanoma death (http://info.cancerresearchuk.org/cancerstats). Jung *et al*., (2010) also looked at the trends of NMSCs in Alberta, Canada, for the period 1988 to 2007. They concluded that NMSCs are linked to cumulative exposure to UVR over lifetime and rarely occur in people under 40 years of age. Their data suggested that the incidence rate has stabilised, or is possibly decreasing, from about the year 2000.

6.4.2 Eye

There is evidence that UVR exposure is a major factor in the causation of non-malignant SCC of the cornea and conjunctiva, such as cataract, pterygium (an overgrowth of the conjunctiva on to the

cornea) and pinguecula (small yellow growths in the conjunctiva) (Norval *et al*., 2011; UNEP, 2010; Lucas *et al*., 2006 & 2008). In addition, acute photokeratitis and photoconjunctivitis are also clearly UVR-induced, and retinal burns can result from high intensity exposure, such as looking directly at the sun. There is some evidence that chronic exposure of the eye to intense levels of UVR contributes to the development of cortical cataract (Norval *et al*., 2011). However, evidence for a causal role for solar UV radiation in age-related macular degeneration (a major cause of blindness) and ocular melanoma is conflicting. Age at exposure may be important when considering retinal damage due to the increased transmission of UV-A through the lens of eyes in children compared to adults. The extent to which UVR (UV-A or UV-B) exposure is an important risk factor for cataracts in the general population that does not receive chronic exposure to high levels of UVR is unclear, as is its relation to eye melanoma.

6.4.3 Temperature effect on carcinogenic potential of UVR

Some studies indicate that the projected future increase in surface temperature may also influence the relationship between UVR and skin cancer, by enhancing the induction of skin cancer and/or changing exposure behaviour (Norval *et al*., 2011). Van der Leun *et al*. (2008) showed a statistically significant influence of temperature on skin cancer induction risk using human data. The authors also reported that for the same UVR irradiance, each one degree Celsius increase in temperature resulted in an estimated 3% increase in the incidence of BCC, and 6% of SCC. Furthermore, high temperatures and humidity, as experienced in the tropics and as predicted for some areas of the world for the future, may increase the adverse health effects of UV-B radiation on human health, including suppression of immunity to infectious diseases and skin cancers (Ilyas, 2007).

6.4.4 UV-B and immune response suppression and effectiveness of vaccination

There is experimental evidence in animal models and human subjects of suppressive effects of UVR on the immune system (Norval *et al*., 2011; UNEP, 2010). Biological studies have shown that exposure to UVR can suppress the normal antigen-specific immune response to some skin tumours and to various pathogens. The significance for human health of UVR-induced immune suppression is not, however, clearly established at present (Norval *et al*., 2011). A link has been demonstrated between sun exposure and the reappearance of the symptoms of herpes simplex virus (HSV, cold sores) in a proportion of latently infected individuals (AGNIR, 2002). In addition, there is a risk of converting benign papillomas caused by various human papillomavirus (HPV, warts) types, to squamous cell carcinomas in immuno-compromised subjects in areas of the skin that are normally exposed to the sun.

6.4.5 Global burden of disease

The World Health Organization estimated that up to 56,000 skin cancer deaths a year worldwide are caused by excessive exposure to solar UVR (Lucas *et al*., 2006; 2008). Of these deaths, 46,000 are caused by melanoma and 10,000 by NMSC. Each year, excessive UVR exposure is responsible for the loss of more than 1.6 million DALYs (disability-adjusted life years) (Lucas *et al*., 2008). This represents 0.1% of the total global disease burden. Lucas *et al*., (2006; 2008) have also estimated that, worldwide, 5% of all cataract-related and 40-70% of pterygium-related disease burden are attributable to UVR exposure.

Lucas (2010) estimated the disease burden caused by UVR exposure and DALYs by country and by disease using country specific population-weighted average daily ambient UVR level. For the UK, she modelled the disease burden based for 2002 on an average daily UVR exposure of 1,576 J m^{-2} (1997-2003) and reported 1,700 deaths would be attributed to malignant melanoma, and 11 deaths and 5 deaths from SCC and BCC, respectively. The corresponding values in DALYs were 16,600 for malignant melanoma, and 80 and 130 for SCC and BCC, respectively. The DALY results in the UK for photoaging/solar keratoses and sunburn were 18 and 290 respectively. For cortical cataract, pterygium and reactivation of herpes labialis, the DALYs reported were 740, 7 and 67, respectively.

6.4.6 UVR exposure and vitamin D

Vitamin D is produced as a result of exposure of the skin to UVR (mainly UV-B) and through dietary intake. Vitamin D is important for bone health: deficiency results in rickets in children and osteomalacia in children and adults. Low vitamin D status is also implicated in the pathogenesis of osteoporosis and a wide range of non-skeletal diseases including colon cancer, cardio-vascular disease, tuberculosis, multiple sclerosis and type 1 diabetes, but the evidence is currently insufficient to ascribe causality (Ashwell *et al*., 2010). It has also been suggested that vitamin D may reduce the risks of prostate and breast cancers, but the evidence is weak (Norval *et al*., 2011). The International Agency for Research on Cancer (IARC) reviewed the scientific evidence on the relationship between low levels of vitamin D and various cancers (IARC, 2008). The conclusion was that low vitamin D status was more likely to be due to the cancer and not a cause.

The Scientific Advisory Committee on Nutrition (SACN) provides guidance on dietary reference values (DRV), aimed specifically at sectors of the population who are unlikely to achieve adequate levels of vitamin D through exposure to the sun in the UK (SACN, 2007). For 4-64 year olds, it was concluded that exposure to late spring, summer and early autumn sunlight should provide adequate vitamin D. During other seasons, the proportion of vitamin D effective UV-B is insufficient to generate sufficient vitamin D. Dietary supplementation was recommended for vulnerable populations, or those who do not expose their skin to the sun, such as the majority of pregnant and lactating women, those aged 65 years or more, infants and children up to 3 years of age, and those who cover their skin for cultural or religious reasons.

Since UV-B is a risk factor for various skin cancers and is considered the critical wavelength region for the production of vitamin D, it is important to balance the health risk and benefit. UV-A is thought to moderate vitamin D production (Webb *et al*., 1989). This has led to advice that the greatest health benefit from vitamin D production can be gained by exposing a proportion of the body (face and arms) to solar UVR at midday for about 10 to 15 minutes when the ratio of UV-B to UV-A is at its highest (AGNIR, 2002).

6.4.7 Relevance of behaviour

Assessing the UVR exposure to a horizontal surface is relatively straightforward. HPA (and its predecessor the NRPB) has been monitoring the solar UV and visible radiation across the UK for over 20 years. Measurements are made at approximately 2° increments in latitude from Camborne in Cornwall to Lerwick in the Shetland Islands. However, the measured data are not necessarily an accurate indicator of personal exposure. Therefore, it is important to consider individual behaviour

patterns, which include time of exposure to the sun, orientation of the body, and any protection measures used, such as shade, clothing, hats and/or sunscreen.

There is a trend towards indoor working (ONS, 2012), but there are critical groups that spend most of their working time outdoors. These include construction workers, some agricultural workers and beach workers. Recreational exposure to UVR is also highly dependent on behaviour. There will be those who spend most of their leisure time outdoors throughout the year through to some groups who will only receive significant solar UVR exposure during a one or two week holiday overseas. Holiday makers may implement protection measures guided by public health awareness campaigns, the activity of others and by ambient temperature. For example, in some countries the UV Index may be higher than the maximum experienced in the UK, but the temperature may be relatively low. In equatorial regions the high rate of change of UV Index throughout the day may also catch people unaware. Both of these situations could result in sunburn after relatively short exposure durations. It is possible that higher temperatures in the UK due to climate change may reduce the number of people taking holidays overseas in sunnier climates, although this will depend mostly on socioeconomic factors. Milder temperatures may encourage people to spend more time outdoors during most of the year, while extreme weather events, such as heatwaves and floods, will probably have the opposite effect (Dobbinson *et al*., 2008).

There will also be groups who receive little or no exposure to direct solar UVR due to cultural, religious or health reasons or confinement to indoor environments. Climate change is unlikely to have much impact on the solar UVR exposure of these people. The elderly have compromised mechanisms for converting UVR into vitamin D. Therefore, it may be necessary to provide vitamin D supplementation to address this, especially for those who do not receive sufficient UVR exposure.

At the time of writing, an EU Framework 7 funded project ICEPURE (http://www.icepure.eu/) is concluding and is expected to report on the link between environmental exposure to UVR and vitamin D status in Europe.

There have been significant improvements in sun protection behaviour of the population, following the introduction of the SunSmart public health awareness program in Australia. Similar campaigns have begun in the UK (www.sunsmart.org.uk).

6.5 Conclusions

Spring sun exposure when there is sufficient UV-B, may be important for replenishing vitamin D levels. There is anecdotal evidence that many people in the UK get sunburn at Easter, which tends to be the first opportunity to spend time outdoors for several days after the winter. However, the solar UV Index over that period is usually about 3, which would not be expected to cause erythema for the same people later in the year. Gradually increasing solar UVR exposure will result in hyperplasia, or epidermal thickening (Diffey, 2004) as an adaptive mechanism.

As solar UVR levels increase through the summer, the risk of erythema increases for those who are not adapted or who are particularly photosensitive due to skin type or medical conditions, such as lupus erythematosus. Sudden increased exposures by travelling to sunnier climates may be linked to an increased risk of malignant melanoma. However, this should not imply that developing the adaptation using a sunbed is recommended.

High temperatures on clear days tend to be good indicators of a high risk of erythema. However, with the cooling effect of wind, some people are misled and develop sunburn without realising the need for protective measures. Typically, there are only five totally clear (no cloud) days per year in the UK, and most of these occur during the winter months (Hooke *et al*., 2011).

The projected increases in temperature in the UK due to climate change are likely to encourage changes in behaviour that lead to more time spent outdoors. It is recognised that this may bring direct benefits, such as physical exercise, mental health benefits and possibly increased vitamin D production. However, it is important to consider the solar UV Index and the time of the year, and promote sun protection measures that minimise the risk of non-melanoma skin cancers (mainly related to cumulative UVR exposure) and malignant melanoma due to sudden increases in exposure levels (and possibly sunburn).

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7 Health effects of flooding, and adaptation to climate change

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Summary

- The Intergovernmental Panel on Climate Change (IPCC) states that it is likely that the frequency of heavy precipitation will increase in the 21st century in Europe and it is very likely that global mean sea level rise will contribute to increases in extreme coastal high water levels in the future (IPCC, 2012).
- Climate change is likely to affect river and coastal flood risk in the next decades. Some areas in the UK have been identified as particularly vulnerable to coastal flood risk, including South Wales, Northwest Scotland, Yorkshire and Lincolnshire (especially the Humber Estuary), East Anglia and the Thames Estuary.
- Our knowledge of the health implications of flooding has improved, particularly with regards to impacts on mental health and the implications for health from flood impacts on critical infrastructure (i.e., water supply and hospital services).
- All populations are at risk of the health effects associated with flooding; however, poorer communities are at higher risk of coastal flooding in the UK, while higher income households tend to be at higher risk of river flooding. Limited evidence indicates that the elderly are most at risk of flood mortality in the UK.
- The Natural Hazards Partnership, which includes HPA as a partner, offers the opportunity for better understanding of health protection and other emergency responses to reduce the impacts of floods by using enhanced cross government collaboration.

Public health recommendations

- Urgently consider developing a cross government flood plan to include health impacts, possibly mirroring the Cold Weather Plan for England (DH, 2011a) or the Heatwave Plan for England (DH, 2011b).
- Better identification of and information on each flood event with effective surveillance and monitoring systems.
- Ensure that hospitals and health centres in flood risk zones are protected from floods, with improved risk assessments, and other activities as described in the Safe Hospitals Project of the WHO (WHO, 2011).
- Ensure flood defences are maintained to the required defence standard and condition in the long-term. Sustainable planning should be undertaken to ensure that the population living in flood risk zones is reduced (and not increased).
- Support and strengthen the inter-agency Natural Hazards Partnership and its early warning mechanisms, facilitating sharing of tools such as its daily Strategic Hazard Assessments.
- Consider promoting measures to ensure the continuity of the NHS services and health care facilities including elderly care homes during floods to limit the impacts of climate change related risks.

Research needs

- Flood 'life-cycle' analysis will facilitate better identification of and information on each flood event with effective surveillance and monitoring systems to facilitate better understanding of health impacts on populations at risk, as well as climate change adaptation evidence based recommendations.
- Better understanding of causes and types of flood-related adverse health effects with improved understanding of the longer term health effects of flooding, particularly on mortality risk, mental health care for flooded populations, and for vulnerable groups. Living with Environmental Change (LWEC) has identified that an improved understanding of the health effects of flooding on individuals and communities is an important research priority which has been previously neglected within the research agenda (Moores and Rees, 2011).
- Research on the implications for persons with chronic diseases affected by the disruption to health services and infrastructure.
- Research on the causes and outcomes of population displacement via evacuation and relocation, including long term follow up of flooded households.

7.1 Introduction

Flooding is a regular occurrence in the UK and is associated with a range of impacts on health and welfare in addition to deaths from drowning. Floods damage local infrastructure, and recent events have indicated the vulnerability of UK populations to loss of water supplies and damage to health systems which also have implications for human health and health protection.

This chapter focuses on flooding and health. Although windstorms were reviewed in the last Department of Health/HPA assessment (HPA, 2008a), it was found that the impacts on health are limited to relatively few deaths and injuries each year, mostly vehicle related (Baker and Lee, 2008). The implications of future increases in drought events are discussed in Chapter 9, Water and food-borne diseases.

Flood risk is determined by many factors (environmental, technological, social and political) and the relative contribution of these factors will change over time. Changes in climate and local sea level are projected to be more significant towards the end of this century. The Environment Agency (EA) estimates that 5.2 million properties in England (one in six properties) are at risk of flooding. More than 5 million people live and work in the 2.4 million properties that are at risk of flooding from rivers or the sea; one million of these properties are also at risk of surface water flooding. A further 2.8 million properties are susceptible to surface water flooding (EA, 2009a). The combined effects of climate change and housing development pressure will increase the population at risk of flooding in England in the future, with the most significant changes likely to happen in the latter half of the century (EA, 2009b).

This chapter includes a qualitative update of the assessment of future risks to health and the implications for health protection.

7.2 Results and discussion

7.2.1 Summer floods of 2007 and other recent flooding events in the UK

The floods of 2007 were some of the worst observed in the UK in living memory and the impacts on health were wide-ranging. Previous flood events illustrate the vulnerability of the UK population to extreme weather. The combined rainfall of 24-25th June and 19-20th July 2007 in England and Wales was unprecedented; the affected areas registered over three times as much rain as the average for the same period in the previous year. Exceptional flooding occurred in many regions: South Yorkshire and Hull were worst affected in June 2007, followed in July by Worcestershire, Gloucestershire and the Thames Valley. The events were characterised by both fluvial (riverine) and pluvial (rainfall on water-logged ground) flooding (Pitt, 2008).

The main impacts of the 2007 floods included:

- Population affected: 55,000 properties were flooded; 7,000 people were rescued from the flood waters by emergency services (Pitt, 2008).
- Mortality: 13 people died (Pitt, 2008).
- 400,000 pupil school days were lost due to school closures (DEFRA, 2010).

- Impacts on critical infrastructure: 350,000 people lost mains water supply for 17 days; 42,000 people were without electricity for up to 24 hours; 10,000 people were trapped on the M5 motorway; and 500 people were stranded at Gloucester railway station (Pitt, 2008).
- Impacts on health care infrastructure: Tewkesbury hospital was evacuated and 20 patients were transferred to other hospitals (Whiteley, 2008).
- Economic impacts: the economic cost of the flooding was estimated at £3.2 billion, based on infrastructure damage (health and social costs were not included in this estimate) (DEFRA, 2010).

As a result of flooding in Cumbria in 2009, 1,500 people were evacuated from their homes or businesses, six bridges were lost, and one person died. As a result of flooding in Morpeth in 2008, 1,000 homes and businesses were affected and 250 families utilised rescue centres and temporary accommodation (DEFRA, 2011).

7.2.2 Health impacts of floods: update of current knowledge

The health effects of flooding can be described as direct or indirect. Direct health effects are those caused by the immediate effects of flood water, including drowning and physical trauma. Indirect health effects are the consequences of flooding and include the impacts from damage to infrastructure, water supplies, displacement and disruption to people's lives (Jonkman and Kelman, 2005; WHO, 2002). The health impacts from a flood continue to occur after the immediate event during the clean-up process, and may persist for months or years (WHO, 2002).

Deaths

Flood water creates an immediate risk of drowning. Over the last 10 years, floods in Europe have killed more than 1,000 people and affected over 3.4 million others (Jakubicka *et al*., 2010). Mortality risk is highest for flash floods. Fast moving shallow water is very dangerous, especially for children. In the US, many flood deaths are associated with vehicles entering flood waters (CDC, 2011). Dangers associated with floodwater include (EA, 2011):

- 15 cm of fast flowing water can knock a person over and 60 cm can float a car;
- Flooding can cause manhole covers to be displaced, creating hidden dangers such as holes in the road;
- Walking on sea defences or riverbeds can be dangerous, as can driving over bridges when water levels are high – both these activities can result in people or cars being swept away;
- Fallen power lines and trees can create potentially life-threatening hazards.

Worldwide, it is estimated that two thirds of flood deaths are due to drowning (Jonkman and Kelman, 2005). However, we do not have an accurate assessment of age-, gender- or cause-specific mortality for current flood deaths in the UK. The mortality associated with the 1953 east coast of England flood has been examined in some detail. Figure 7.1 illustrates the age distribution of deaths in Canvey Island (58 deaths of a total of 307 estimated deaths on land due to the flood in England) (Baxter, 2005; Greive, 1959). Autopsies showed that 34% died from non-drowning causes (hypothermia, strokes, heart failure, accidents). All six children below age 6 died from hypothermia.

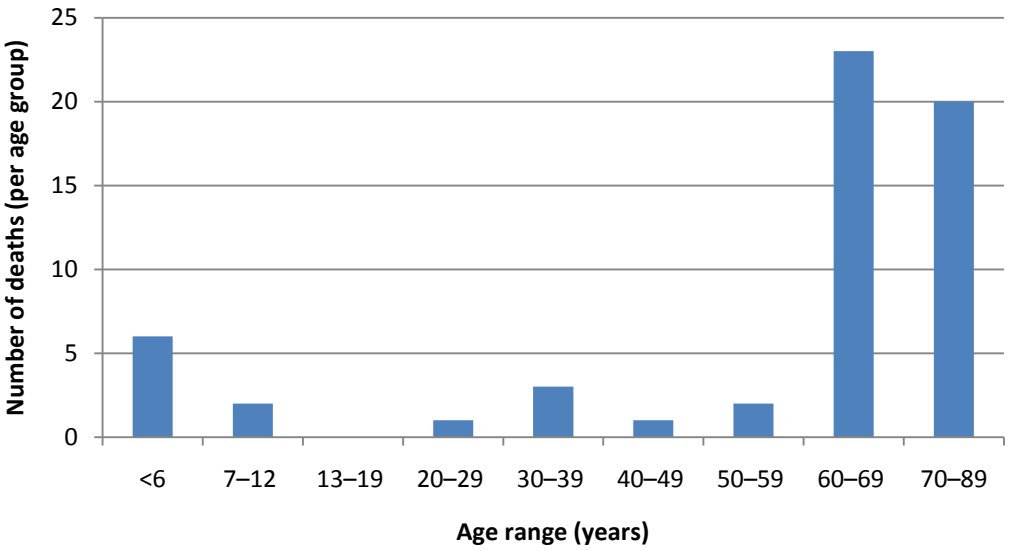

Figure 7.1. Flood mortality in Canvey Island due to the 1952 coastal flood by age group (based on Baxter, 2005, and Grieve, 1959).

In 1953, a lack of communication systems in rural areas and difficulty in accessing hospitals and medical resources contributed to the high mortality rate. At present, flood warning systems, communications and access to healthcare have been vastly improved so that we would not expect such high numbers of deaths if a similar flood event were to happen today.

The attribution of deaths to flood events can be complex. In formal disaster statistics, only the immediate traumatic deaths (i.e., from drowning) are recorded in official reports (Wynne-Evans *et al*., 2011). Deaths from injuries, related car accidents, and carbon monoxide poisoning during the flood clean up are also attributed to floods.

There is some uncertainty as to whether flood events are associated with a longer term effect on mortality in the flooded population (e.g. 6-18 months after the flood). A study of the Bristol floods of 1968 reported a 50% increase in mortality rates among those flooded compared to those not flooded during the 12 months following the event (Bennet, 1970). However, this finding has not been repeated. A study of mortality patterns in flooded areas (linked via postcode) in England and Wales from 1994 to 2005 found a relative reduction in mortality of 10% in years following flooding. Possible reasons to explain this finding include: lack of information on flood severity and lack of information on population movement from flooded postcodes (Milojevic *et al*., 2011). Further research is needed to ascertain the long-term impacts of flooding on mortality, taking into account population displacement via evacuation and relocation. Population displacement is complex, and requires the long term follow up of individual households.

Injuries

Flood-related injuries can be caused by direct contact with flood waters (Schnitzler *et al*., 2007), while people are being evacuated from flood waters and during the clean-up process (Jakubicka *et al*., 2010; WHO, 2002). Injuries may be sustained through contact with displaced animals, or through

sharp objects concealed by flood water (CDC, 2011). In many cases, injuries are not reported (e.g. hospital admission, visits to Accidents and Emergencies departments), and where they are reported they often cannot be identified as flood-related. The prevalence of injuries associated with flooding in the UK is unknown. In a survey of households following the 1988 floods in Nimes, France, 6% of households reported mild injuries related to the flood (Duclos *et al*., 1991).

Infectious disease

Flooding does not usually result in outbreaks of infectious disease in high income countries such as the UK (see also Chapter 9). Infections caused by flooding are rare in the UK as pathogens become diluted by flood water (NHS, 2010). Further, the HPA found no evidence of increased outbreaks of illness following the 2007 floods despite enhanced surveillance (HPA, 2009). Food can be a source of infection if it has come into contact with flood water, and HPA provides advice on food hygiene and hand washing (HPA, 2009). Drinking water can become contaminated by bacteria, sewage, agricultural waste or chemicals (CDC, 2008); in the UK, the HPA advises that mains water supplies are usually safe during flooding events (HPA, 2009).

Chemical contamination

Carbon monoxide (CO) poisoning is a serious health risk associated with flooding, occurring in the aftermath of the flood when generators or fuel-powered equipment are used indoors for drying or pumping out flood water (HPA, 2008b). Two deaths due to CO poisoning were reported following the 2007 UK floods (Pitt, 2008). CO poisoning post-flood/hurricane in the US includes several cases associated with indoor generator use (Sniffen *et al*., 2005; Van Sickle *et al.*, 2007; Cukor and Restuccia, 2007).

There is a health risk of chemical contamination of flood water, as flooding may displace chemicals from their normal storage place (CDC, 2004). Sources of contaminated floodwater include: storm water floods, overloaded sewers, hazardous landfill sites, waste water lagoons, and acid mine drainage (Euripidou and Murray, 2004). The HPA states that chemicals in flood water are likely to be diluted and probably pose little acute health risk (HPA, 2009). However, improvements in environmental sampling following flooding are needed.

Mental health

Flooding has negative effects on mental health and wellbeing (Ahern *et al*., 2005). A number of documents have been published since 2008 which acknowledge the detrimental impacts of flooding and other extreme events on mental health in the UK. Government reports include:

- The Mental Health Strategy: No Health Without Mental Health (HMG and DH, 2011)
    - Identifies the need to adopt public health approaches to tackle the mental health impacts of flooding.
- Healthy Lives, Healthy People: Our Strategy for Public Health in England (HMG, 2010)
    - Identifies health protection as a proposed outcome as well as coordination with emergency planning departments.
- New Horizons: A Shared Vision for Mental Health (HMG, 2009)
    - Identifies that flooding can have long-lasting impacts on mental health and wellbeing and highlights the need for cross agency working.

- NHS Emergency Planning Guidance: Planning for the psychosocial and mental health care of people affected by major incidents and disasters. Interim national strategic guidance (DH, 2009)
    - Identifies methods for preparing, planning and managing psychosocial and mental health services after a disaster.

The HPA has recently published a comprehensive report on the effects of flooding on mental health. The findings indicate that despite methodological complexities in analysing and comparing data, flooding can have profound effects on mental health and psychosocial resilience that may continue over extended periods of time (Murray *et al*., 2011). A study of the aftermath of the 2007 floods found that the prevalence of all mental health symptoms (psychological distress, probable anxiety, probable depression and probable post-traumatic stress disorder (PTSD)) were two to five times higher among individuals who reported flood water in the home compared to individuals who did not (Paranjothy *et al*., 2011).

A study of the psychological impacts of flooding in the UK found that, among flood-affected adults, 27.9% met criteria for symptoms associated with post-traumatic stress disorder (PTSD), 24.5% for anxiety and 35.1% for depression (Mason *et al*., 2010). Several factors were associated with greater psychological distress, including: vacating homes following a flood; previous experience of flooding; and poor health at the time of flood. A longitudinal study (a follow up of persons affected by the 1998 flood in Oxfordshire) found participants reported continuing psychological effects that they attributed to the experience of being flooded (Tapsell and Tunstall, 2008).

The 'Recovery Gap' is the period after which emergency response has ended and individuals must rely on the private sector for continued recovery efforts. The requirement for people to manage the recovery process themselves places unusual pressures upon them, and interactions with different organisations involved in the flood recovery process had an impact on whether participants were able to cope (Whittle *et al*., 2010). The provision of emergency and longer-term mental health care in planning, response and recovery is an important component of flood management (Murray *et al*., 2011). Further work is required to develop good practice embedded in mental health and all hazard plans.

Secondary stressors such as a lack of financial assistance, the process of submitting an insurance claim, parents' worry about their children, and continued lack of infrastructure can manifest their effects shortly after a disaster and persist for extended periods of time. Secondary stressors and their roles in affecting people's longer-term mental health should not be overlooked. In a recent review (Lock *et al*., 2012), some of the secondary stressors identified were:

- economic stressors such as problems with compensation, recovery of and rebuilding homes, and loss of physical possessions and resources;
- health-related stressors; stress relating to education and schooling; stress arising from media reporting;
- family and social stressors;
- stress arising from loss of leisure and recreation;
- stress related to changes in people's views of the world or themselves.

Vulnerable sub-groups

While all populations are at risk of the health impacts associated with flooding, certain groups are at higher risk of morbidity and mortality. Limited evidence indicates that the elderly are most at risk of flood mortality in the UK.

There is only limited evidence regarding the impacts of flooding on health by socio-economic status. However, there is a clear socio-economic gradient in the populations most at risk of coastal flooding in England, with poorer communities at higher risk (Walker *et al*., 2003); conversely, for river flooding, high flood risk areas tend to include higher income households (Fielding and Burningham, 2005). A review of inequalities associated with environmental risks in Europe found very little research on the distribution of flood exposures or flood impacts on health (Braubach and Fairburn, 2010).

Vulnerability is an important concept for targeting of public health interventions which may reduce the impacts of flooding. Table 7.1 summarises the qualitative evidence for groups which may be particularly vulnerable to the health effects associated with flooding. This information was compiled based on vulnerabilities to chemical incidents and was adapted to reflect populations which may also be vulnerable to flooding events (Edkins *et al*., 2010).

Table 7.1. ORCHIDS (Optimisation through Research of Chemical Incident Decontamination Systems) identified vulnerable groups, adapted for flooding (Edkins *et al*., 2010). ©WHO Regional Office for Europe.

Vulnerable group	Reasons for vulnerability
Children	• May become separated from parents or caregivers • May witness the death or injury of a close family member • May not have cognitive or motor skills to move away from danger or seek help if faced with stressful events • Pre-verbal children are unable to vocalise their symptoms • Immature immune systems can result in greater risk if exposed to infectious agents • Greater risk of anxiety reactions
Pregnant Women	• Women may be reluctant to accept treatment due to possible adverse health effects on foetus • Best treatment option for the mother may not always be the best treatment option for the foetus • Decreased immune response, may be more likely to become seriously ill than non-pregnant women • Reduced mobility in certain cases of advanced pregnancy
People with physical impairments	• Mobility aids such as wheelchairs, walking canes and walkers are relied upon by many physically impaired people; loss of these aids during a flood may result in a loss of independence • Emergency personnel may not have the skills required to transfer physically impaired people who cannot transfer themselves

People with sensory impairments	• May not be able to communicate using auditory or visual modes of communication, which are commonly relied upon during emergency responses
People with cognitive impairments	• May believe that authority figures are trying to harm them • May not have the same perception of risk as people without impairments • May be unable to express symptoms when receiving triage health care
Elderly people	• May have reduced mobility, impaired balance or reduced strength • Pre-existing health conditions (such as hypertension, heart disease, cancer, stroke or dementia) can result in decreased physical strength and weakened physiological response • Decreased immune response • Increased susceptibility to extremes in temperature • Possible accompanying sensory impairments • Possible delayed verbal and physical response times • Cognitive impairments may reduce the ability to retain information, understand what is happening and to follow rescue instructions; they may also cause the elderly to become disoriented or confused in unfamiliar surroundings • Possible loss of hearing aids, eyeglasses, dentures or prescription medication which may impede recovery process
People with chronic illnesses	• Likely to be reliant on medications to keep their illness under control (i.e., diabetes, asthma, and epilepsy); if medications are unavailable, people may suffer adverse health consequences
Tourists	• May be unable to speak the native language of the country of the flooding, which may result in difficulty getting help or understanding instructions • May be unfamiliar with local resources which can be relied upon in emergency situations
The homeless	• Substantial rate of mental illness among homeless populations; acute stress of flooding may exacerbate mental health problems • May have difficulty in reading or interpreting written instructions • Disproportionately greater risk of being disabled or being persistently ill
People with cultural and language-based vulnerabilities	• If unable to fluently speak the native language of the country, may have difficulty understanding instructions • Language barrier may prevent people from expressing needs to health care providers, possibly resulting in incorrect treatment or diagnosis • If unable to read written instructions, emergency responders may assume they are uncooperative • Vital components of messages may be lost in translation • May lack trust in authority figures or members of medical community • Differences in gender roles or gender-appropriate behaviour • May have own beliefs regarding health and treatment of illness

Water shortages in floods

Flood events have been associated with failures in the domestic water supply due to damage to the water supply infrastructure. This occurred during the Gloucestershire floods in 2007. A recent review found similar events in 11 countries in Europe (Armenia, Bosnia and Herzegovina, Georgia, Hungary, TFYR Macedonia, Republic of Moldova, Poland, Slovenia, Tajikistan, Turkey, and Ukraine (Caldin *et al*., 2012). Flooding in Cork, Ireland, in 2009 resulted in 18,000 homes being cut off from mains water supply; in total, approximately 300,000 litres of bottled water were distributed (Gavin, 2009). In 2006, flooding caused the contamination of an aquifer in Hungary and led to the loss of safe drinking water for 174,000 residents (Dura *et al*., 2010).

In 2007 in Gloucestershire, the failure of the Mythe water treatment works left 350,000 people without mains water supply for 17 days. Affected people were provided with a minimum of 10 litres of water per person per day (although most people received more) via bowsers, tankers and bottled water. The water provision proved to be insufficient after a long period of up to 17 days (Pitt, 2008). However, there was little evidence of health effects associated with the loss of water supply, probably due to the response measures that were implemented. The Sphere Project reports that a minimum of 15 litres per person per day is necessary for drinking, cooking and personal hygiene, dependent upon context (Sphere Project, 2011). The HPA has recently written a report on water shortages during and following extreme events (Carmichael *et al*., 2012).

Effects on health systems

Flooding can damage health care facilities directly or disrupt access to them (Meusel and Kirch, 2005). In a recent study reviewing flood preparedness and response between 2000-2009 among WHO Regional Office for Europe Member States, eight countries reported impacts of flooding on health facilities, including the flooding of two hospitals during the 2007 UK floods (Caldin *et al*., 2012). Issues related to the effects of flooding on health systems include increased patient load at health care facilities, disruption of power supplies, availability of clean water, damage to patient record systems, disrupted ambulance and outreach services, interrupted continuity of care, and potential hospital or nursing home evacuation (Caldin *et al*., 2012).

The Environment Agency (EA, 2009b) report that 7% of hospitals in England are built on a flood plain along with 9% of surgeries and health centres and 13% of Police, Fire and Ambulance stations. Further, they also assessed that other transport and utilities infrastructure were also vulnerable (Figure 7.2).

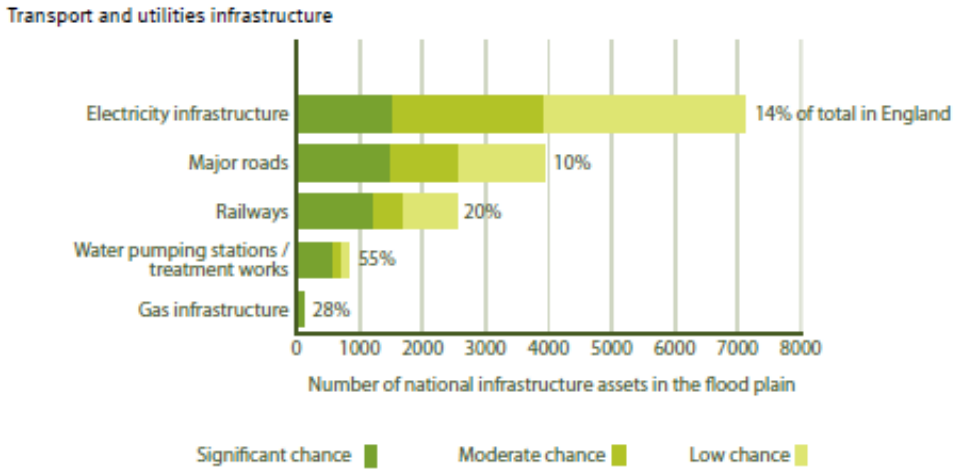

Figure 7.2. Vulnerable transport and utilities infrastructure in England (EA, 2009b)

However, little is currently known about the implications for population health of the disruption in health services during and after flood events. Planning and implementation of flood protection measures for health facilities buildings and access would be beneficial in facilitating health care. Recognition of these vulnerabilities is vital and reflects the call from the World Health Organization to ensure hospitals are safe from disasters (WHO, 2011). They state that "disaster damage to health systems is a human tragedy, results in huge economic losses, deals devastating blows to development goals, and shakes social confidence. Making hospitals and health facilities safe from disasters is an economic requirement, and also a social, moral and ethical necessity" (WHO, 2011).

Knowledge gaps in current health risks from flooding

The HPA and the WHO Regional Office for Europe have identified several gaps in knowledge on the health impacts associated with flooding, including the need for: further understanding of immediate and longer term mortality following flooding; information on the causes and types of flood-related injuries; further research on the specific health impacts of flooding on vulnerable groups; and further information on the disruption of health services and facilities during and following flooding (Caldin *et al*., 2012). In addition, risk communication has been identified as a key requirement with particular emphasis on how to communicate with the public in a time of power supply disruption and population movement.

7.2.3 Estimating future flood risk

Estimating the population exposure to flooding in the future is an even more complex problem, and as such, few studies have attempted this. Although national and regional population projections are available, population growth in coastal zones often follows a different pattern. In addition, there are a range of uncertainties which must be considered when calculating future flood risk, for example, the role of interventions such as flood defences, and whether these are likely to be maintained, replaced or deteriorate in future. Changes in land-use and the positioning of property in flood risk areas will also influence population exposure to flooding.

Anthropogenic climate change is projected to increase the frequency and intensity of heavy rainfall events. The Intergovernmental Panel on Climate Change (IPCC) states that it is likely (66-100% probability) that the frequency of heavy precipitation will increase in the 21st century in Europe and

it is very likely (90-100% probability) that global mean sea level rise will contribute to increases in extreme coastal high water levels in the future (IPCC, 2012).

UK Climate change projections (UKCP09) do not include specific flood projections, but indicate that although annual mean rainfall levels are not likely to show much change, across low, medium and high emissions scenarios for the UK, winter rainfall levels are likely to increase significantly, and summer rainfall levels are likely to decrease significantly (Jenkins *et al.*, 2009). All other things being equal, this would lead to increase in wintertime flooding and a reduction in summer flooding. Future actual flood risk will depend on a range of additional factors. The maintenance and strengthening of flood defences (river and coastal) will be the most significant determinant of future risk.

Box 7.1. The Climate Change Risk Assessment (CCRA) for the Floods and Coastal Erosion Sector

The Floods and Coastal Erosion Sector report of the CCRA assessed the impact of climate change on flooding risk for the UK (Ramsbottom *et al*., 2012). The model used in the analysis was the same as that used in the Environment Agency National Flood Risk Assessment, (EA, 2009a) which was carried out across all 69 river catchments and the coastline around England and Wales. To investigate the role of climate change, the drivers for the flood models were based on UKCP09 future climate scenarios, with and without projections of socio economic change, for the 2020s, 2050s and 2080s. The UKCP09 projects that the main climate drivers of flood risk (sea level rise, winter precipitation and storm rainfall intensity) will increase due to climate change. The analysis for future flood risk was carried out for projections of tidal and river flooding, but not for surface water flooding, due to a lack of information.

Baseline rates of flood risk were calculated, which indicated that about 6 million people (around 10% of the population) in the UK are at risk of flooding from rivers or the sea, and similar numbers from surface water flooding. About 3,000 km of UK coastline is currently eroding, which is around 17% of the total length. The Floods and Coastal Erosion Sector report indicated that climate change may lead to a doubling or quadrupling of river flooding in the UK by the 2080s; projected areas prone to river flooding with most people at significant risk under climate change (medium or high emissions, 2050s) include the South East of England, London, the East Midlands and North West England. Factoring in current population growth changes this picture slightly, while the areas with most people at risk still contain South East & London and East Midlands, the South West, Yorkshire and the Humber are now considered next in the ranking (Ramsbottom *et al.*, 2012). The report emphasises the many uncertainties and difficulty in projecting increases in river flood risk.

Since flooding is known to have direct and indirect consequences on health, separate analyses of deaths, injuries and mental health impacts associated with flooding were carried out in the Health Sector report of the CCRA (Hames and Vardoulakis, 2012; also see tables 7.2 and 7.3).

Estimating coastal flood risk

Coastal flood risk depends on both projections of sea level rise and changes in storm magnitude and frequency. Coastal flood models require detailed information on coastal morphology and projections

of sea level rise. The projected sea level rise for England is in the range 37.3 to 53.1cm by the end of this century (mean estimate 44cm) (Jenkins *et al*., 2009). Local sea level rise will be determined by additional factors such as land movement. This is particularly significant in Eastern England, where the land is subsiding. Several coastal areas have been identified as particularly vulnerable to climate change, due to increased risk of flooding and coastal erosion; these include: South Wales, Northwest Scotland, Yorkshire and Lincolnshire (especially the Humber Estuary), East Anglia and the Thames Estuary (Hall *et al*., 2006; EA, 2009a). The vulnerability to climate change in coastal communities is likely to be increased by social deprivation and low adaptive capacity (Zsamboky *et al*., 2011). (See box 7.1 on the Climate Change Risk Assessment.)

The uncertainty about future climate change makes decisions regarding long term investment in infrastructure difficult (Reeder and Ranger, 2010). Currently, London and nearby populations in the Thames region are protected by the Thames Barrier but this level of protection is likely to be reduced beyond 2030 due to sea level rise. The impacts of an unmitigated storm surge flood (a low probability but high risk event) would entail significant loss of life and other health implications associated with evacuation and damage to essential infrastructure. Adjustments to flood protection for London (including upgrades to the Thames Barrier) have been assessed by the Thames Estuary 2100 project (Haigh and Fisher, 2010). This involves a flexible approach, so that decisions are updated as more evidence becomes available and as risk factors (e.g. housing development pressures) evolve.

Estimating river flood risk

The Foresight report 'Future Flooding' (Evans *et al*., 2004) considered both climate change and other drivers of flood risk. The report concluded that the number of people living within a floodplain and the number of people at significant risk of flooding would increase in the future. The current assessment of river flood risk in the UK has not changed substantially since the previous assessment (HPA, 2008a). Based on the UKCP09 climate projections alone, it is anticipated that spring floods due to snow melt are likely to become less frequent (Jenkins *et al*., 2009). However, floods linked to sustained autumn and winter precipitation are likely to become more frequent in the future (Jenkins *et al*., 2009). More sophisticated modelling using catchment scale hydrological models indicate a less certain picture. The climate change impact on river flood risk was quantified in the CCRA (Ramsbottom *et al*., 2012; box 7.1).

Future flood health impacts due to climate change

There have been relatively few assessments that have quantified future flood mortality and morbidity attributable to climate change. The recent UK CCRA has estimated future mortality based on baseline mortality and morbidity rates from the literature and expert judgement (see Table 7.2). Hames and Vardoulakis (2012) estimate that climate change may lead to 8-49 additional flood-related deaths per year for the UK in the 2050s compared to current levels once population growth is included (Table 7.3).

Table 7.2. UK CCRA assessment of baseline mortality[1], relation between injuries and mortality, and relation between exposure and mental health (Hames and Vardoulakis, 2012).

		Deaths			Injuries[2]			Mental health[3]	
Event		**Baseline av. annual deaths[4]**	**Relation to exposure**	**Source**	**Ratio of deaths to injuries[4]**	**Baseline av. annual injuries**	**Source**	**Proportion of those flooded affected[5]**	**Source**
Floods	**Inland**	8	Proportional	Review of historical UK flood events (partly based on Defra/Environmental Agency, 2003) and EMDAT flash flood data for Western Europe; suggests deaths and injuries proportional to number exposed. Estimate based on expert opinion.	1:20	160	DEFRA/Environmental Agency (2003) & information 2005 Carlisle flood event. Estimate based on expert opinion.	30-40%	Reacher *et al.* (2000) & Tunstall *et al*. (2006)
	Coastal	3	Proportional	Recent flood events in North Wales and North West (as long series of sea level data), and previous literature. Estimate based on expert opinion.	1:20	60	No known information: assumed equal to risk for inland floods.	30-40%	Reacher *et al.* (2000) & Tunstall *et al.* (2006)
Storms[6]		7	Exponential relation to changes in mean sea level, which in turn influences exposure	'Violent Overtopping of Waves at Seawalls project'; 21 months of data. Estimate based on expert opinion.	1:20	140		Not assessed[7]	
Total		**18 deaths/ year**			**360 injuries/ year**			**30-40% of people exposed to floods[8]**	

[1] All health outcomes are amongst those at 'significant risk of flooding', defined as 1.3% chance of flooding in any given year (equivalent to a 75 year return period), with population at risk modelled in the UK CCRA flood and coastal erosion sector report. Due to data limitations, no regional estimates were made; all estimates are for the UK unless indicated.

[2] Specifically, injuries requiring hospital admission. The number of injuries is assumed to be directly proportional to the number of deaths.

[3] Estimates of mental health consequences (including projections) are for England and Wales only. A mental health 'event' is defined as a moving from a GHQ-12 (a Global Health Questionnaire) score of <4 to ≥4 as a direct result of a flood event.

[4] Risk of death and injury is a function of socioeconomic factors including age, sex and deprivation; however due to the low number of deaths, estimates are related to the entire population.

[5] Mental health effects believed to be associated with storm size, pre-existing health, sex, and ownership status of affected property. However, these factors were not considered in this assessment.

[6] Impacts attributable to 'storms' are not due to increased storm activity (which is, according to UKCP09 projections, expected to remain relatively constant) but rather due to increased wave activity during storms, associated with sea level rise.

[7] Mental health impacts due to storms are uncertain but as expected to be small compared to impacts due to floods were not estimated.

[8] Actual number of baseline mental health 'events' not reported.

Table 7.3. Projections of the additional impacts of flooding[1] and storms on mortality, injuries and mental health, in the UK, under plausible future climates.[2] (Hames and Vardoulakis, 2012)

Outcome	Time period					
	2020s		2050s		2080s	
	Baseline population[3]	Changing population[4]	Baseline population[3]	Changing population[4]	Baseline population[3]	Changing population[4]
Deaths	4-17	5-21	6-34	8-49	13-69	14-98
Injuries	80-340	100-420	120-680	160-980	270-1,380	290-1,960
Mental health 'events'[5]	3,000-4,000	4,000-6,000	4,000-7,000	8,000-13,000	5,000-8,000	13,000-20,000

[1] Projections assume no adaptation or deterioration of current flood defences.

[2] Climate scenarios are based on UKCP09 scenarios: for the 2020s (2010-2039) a medium emissions scenario is used; for the 2050s (2040-2069) and 2080s (2070-2099) low, medium and high emissions scenarios were used. Note that low, medium and high emissions correspond to IPCC B1, A1B, and A1FI scenarios. Within each emission scenario, lower, central and upper estimates were considered based on different probability levels.

[3] 'Baseline population' assumes there is no change in population between now and the future.

[4] 'Changing population' is based on the set of results assuming low, medium, and high population growth, EXCEPT for mental health where results are for high population growth only.

[5] Figures are for England and Wales only. It is estimated that inclusion of Scotland and Northern Ireland would increase estimates by around 10-15%.

7.2.4 Adapting to climate change and reducing flood risk

The UK's Committee on Climate Change Adaptation Sub-Committee (ASC) identified flooding as one of the biggest risks from climate change impacts on the UK population (Adaptation Sub-Committee, 2011). Land use planning is a key adaptation strategy in reducing flood risk; however, in their evaluation, ASC found only limited progress in reducing future flood risk (Adaptation Sub-Committee, 2011). Surveys of local authorities have found an overall increase in the area covered by buildings within areas at risk from flooding compared with change across locality as a whole (2001-2011) (Arup, 2011). This means that 12-16,000 new houses are being built every year in flood risk areas across England. However, there is some evidence that the new building developments in flood risk areas are becoming more resilient to flooding because of the specific flood protection measures taken (Arup, 2011).

The UK flood insurance system is in a period of change; in 2013, the 'Statement of Principles' between the Government and the Association of British Insurers (ABI) is due to expire. The UK is currently moving towards an increasingly individualistic, market-based approach to flood insurance, which could threaten to leave thousands of properties uninsurable (O'Neill and O'Neill, 2012). Access to affordable flood insurance is a critical adaptation measure to the increasing risk of flooding in the UK.

The work to assess, adapt to and mitigate flood risk in the future requires a multidisciplinary approach. To support such work the HPA set up a new Extreme Events and Health Protection Section (EEHPS). Its objectives are to further HPA's provision of impartial advice and authoritative information on extreme events and health protection. Its work considers all stages of the disaster cycle, i.e. planning, preparedness, response and recovery. In particular EEHPS has been tasked with enhancing the evidence base guidance to minimise the health impacts from flooding (HPA, 2011). In doing this work, it has been essential to develop cross agency communications of specialist skills and knowledge. An interagency partnership with the Met Office, Environment Agency, Flood Forecasting Centre, Ordnance Survey, Department for Environment, Food and Rural Affairs (Defra), Cabinet Office, British Geological Survey, National Centre for Atmospheric Science, National Oceanographic Centre, Centre for Ecology and Hydrology, UK Space Agency, Government Office for Science and the HPA has been formalised to make the Natural Hazards Partnership. As part of their work plan they prepare a daily Hazard Assessment on natural hazard risks in the UK. This early warning system links to those already in place, now consolidating the information in one place.

7.3 Conclusions and key vulnerabilities

7.3.1 Key findings

Climate change is likely to affect river and coastal flood risk in the coming century but its impact is highly uncertain and will depend on future decisions regarding coastal and river management. In the near term, floods are likely to continue to occur.

Coastal areas are likely to be more vulnerable to climate change due to rising sea levels, coastal wave activity, and accelerated erosion. The vulnerability to climate change is increased by social deprivation, geographic isolation and low adaptive capacity (Zsamboky *et al*., 2011).

Floods have significant impacts on human health, both short and long term. Our knowledge of the health implications of flooding has improved, but many gaps remain. Our understanding of vulnerable groups and the mental health effects of flooding has increased since the last edition of Health Effects of Climate Change in the UK 2008.

7.3.2 Implications for policy

Floods are a complex problem that requires multi-agency responses; the Natural Hazards Partnership is an example. Early warning is a key aspect of health protection along with other plans for climate change adaptation. The Flood Forecasting Centre is a joint venture between the Met Office and the Environment Agency which aims to provide alerts and warnings of possible flood risk for England and Wales. In addition, the newly created Natural Hazards Partnership's early warning system links to those already in place, consolidating the available information. An evaluation of

Environment Agency flood warnings (Fielding *et al*., 2007) found that most people did respond to flood warnings and take action they consider to have been 'effective'. However, there was some evidence that persons with disabilities, and the elderly were less willing or able to respond to warnings.

Better understanding of the causes and types of flood-related adverse health effects with improved understanding of the longer term health effects, particularly on mortality risk, is essential and requires further work to provide more effective cross government planning and preparedness.

Health sector engagement and awareness of risk, with reference to the number of hospitals and surgeries built on flood plains in England, is vitally important. Planning and implementation of flood protection measures for health facilities buildings and access would help assure continuing access to health care and reflects the call from the World Health Organization to ensure hospitals are safe from disasters (EA, 2009b; WHO, 2011).

Future flood risk will be influenced by flood defences and land use planning. With increasing pressure to develop, new housing developments continue to be proposed on floodplains (EA, 2009b; Smith and Petley, 2009). There is however considerable effort being undertaken, largely by the Environment Agency, to avert flood risk by identifying areas suitable for development, and restricting the positioning of new buildings in flood risk areas.

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8 Effects of climate change on vector-borne diseases

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Summary

- Vector-borne diseases are influenced in complex and often imperfectly understood ways by climatic and land use changes, and human activities. There is uncertainty regarding the distribution of tick and mosquito (arthropod) species and the pathogens they potentially transmit to humans. This makes robust quantitative predictions of the impact of climate change difficult, but it is likely that the range, activity and vector potential of many ticks and mosquitoes will increase across the UK up to the 2080s. The introduction of exotic species and pathogens is a possibility.
- These arthropods will be directly affected by several climatic changes (milder winters, warmer summers, wetter springs) in accordance with UKCP09 projections. Climate change adaptation strategies, including the creation and expansion of inland wetlands and coastal marshes (to mitigate flooding and sea level rise) and habitat defragmentation initiatives intended to assist wildlife adaptation may have a greater influence on arthropod distribution than the direct effects of climate change.
- The incidence of existing infectious agents, such as Lyme disease transmitted by ticks, is likely to increase. An increase in the number of mosquito species and the abundance of mosquitoes generally, with implications for transmission of arboviruses, such as West Nile virus is possible. Establishment in the UK of exotic ticks such as *Hyalomma marginatum* and mosquitoes such as *Aedes albopictus* will become more likely. In other parts of Europe these species transmit Crimean-Congo Haemorrhagic Fever virus and chikungunya virus, respectively. The risk from autochthonous transmission of malaria remains low.
- This chapter reviews key issues related to ticks and climate change, including evidence of expansion of native tick species, driving forces for change in their distribution, drivers for the introduction and potential establishment of exotic tick species, and the uncertainty and complexity of projecting risk for future tick-borne disease transmission.
- It also reviews the possible impacts of climate change and specifically climate change adaptation (wetland creation) on British mosquitoes and the implications for arbovirus transmission and malaria, as well as an assessment of the potential for establishment of exotic mosquitoes and the changing risk with climate change.

Public health recommendations

- Behavioural studies may help better prepare for current and future increased vector-borne disease risks, including effective “messages” to public health professionals, occupationally and recreationally exposed groups, and the general public to reduce such risks.
- There should be increased collaboration between public health and veterinary health sectors particularly in understanding, preparing for and dealing with zoonotic vector-borne diseases.

Research needs

- Research is required to understand better the contact that could occur between humans and arthropod disease vectors.
- Studies should be conducted to understand better the eco-epidemiological drivers that determine the distribution of UK's existing arthropod vectors and the pathogens that they might carry at finer spatial scales than is possible from current studies.
- Research is required to achieve better ongoing surveillance for the importation of exotic arthropod vectors and pathogens, and research that determines such factors as the competence of our existing UK arthropods for pathogen transmission seen elsewhere in Europe and globally.
- Field-based research should be conducted to understand the impact of environmental change and climate change adaptation strategies on disease vectors. A vector risk assessment should be included as part of environmental impact assessments when considering future habitat creation and management projects.

8.1 Introduction

Undoubtedly temperature and rainfall changes resulting from anthropogenic climate change will affect arthropod vectors and the pathogens they might transmit. Adaptation to climate change is now a regular discussion point in relation to how species of conservation concern will be able to cope with the changes in climate and weather events. The effects of these on arthropod vectors needs to be considered, as in many cases they lead to the creation of additional suitable habitat for ticks and mosquitoes.

Adaptation strategies include wetland restoration and expansion in rural areas, flood alleviation schemes in river valleys and urban areas, sustainable urban drainage programmes in new housing developments, green corridor initiatives in towns and cities and, through coastal realignment, the creation of salt-marsh and grazing marsh to mitigate the impacts of coastal erosion and storm surges. Allied to these adaptation strategies are biodiversity enhancement initiatives supported by government and wildlife organisations – for example, grants for environmental stewardship on farms and woodland management for biodiversity, and linkage of fragments of biodiverse-rich habitat on a national scale. Wildlife distribution is changing as a result of these initiatives – for example, deer numbers are increasing and consequently they are becoming more common in peri-urban areas.

These changes will alter the distribution and abundance of mosquito and tick species in the UK. Increased international travel, trade and transportation have led to the introduction and establishment of arthropod vector species (e.g. invasive mosquitoes) and their pathogens (e.g. chikungunya virus) in Europe in areas where they had not previously occurred. This chapter summarises the possible impacts of climate change (including adaptation strategies) on two sets of known/potential vectors: ticks and mosquitoes, and the pathogens they transmit.

A full review of the impact of climate change on native and potentially invasive ticks and mosquitoes and their associated pathogens has been undertaken here. It builds upon both published and unpublished work and where possible provides a quantitative risk assessment.

8.2 Ticks and Tick-borne disease

In Britain there are 20 native species of tick including 17 ixodid species in the genera *Ixodes, Dermacentor,* and *Haemaphysalis* (Appendix B for distribution, host preference and vector status). Fifteen of the seventeen ixodid species are in the genus *Ixodes.* Two additional species in two additional genera, *Hyalomma* and *Rhipicephalus* have arrived via migratory birds or quarantined pets, respectively. Currently, their establishment is doubtful but this could change in the future. The majority of tick species are specialist parasites of wildlife. Currently the most important tick and disease vector species in Britain is *Ixodes ricinus* (sheep/deer tick), a vector of Lyme borreliosis to humans (also Tick-borne encephalitis virus in continental Europe), and tick-bite fever and louping ill to animals. *Ixodes hexagonus* (hedgehog tick) is a potential secondary vector of Lyme disease, and both *Ixodes ricinus* and *Dermacentor reticulatus* have been suggested as potential vectors of rickettsiae. The two currently non-native species are known vectors of human pathogens elsewhere in Europe: *Hyalomma marginatum* (Crimean-Congo haemorrhagic fever virus) and *Rhipicephalus sanguineus* (*Rickettsia conorii*, the agent of Mediterranean Spotted Fever).

These ticks and tick-borne diseases are considered in more detail in the following four sections on: (8.2.1) climate change and other influences on the distribution of *Ixodes ricinus* (sheep/deer tick); (8.2.2) the range expansion and the effects of climate change on *Dermacentor reticulatus* and its vector status; (8.2.3) factors influencing the introduction of exotic tick species including climate change; (8.2.4) concluding with an overview of climate change and the tick-borne diseases of humans.

8.2.1 Climate change, other driving factors and Ixodes ricinus (sheep tick) in Europe

Ixodes ricinus continues to be reported in new locations and increased abundance in Europe. Climate change is among the causes for this. Higher spring and summer temperatures can directly affect the survival of ticks and influence their seasonal activity. It can also impact on the abundance of suitable hosts for them to acquire blood meals. These factors combined can increase the abundance of ticks and extend their range. Other factors related to human interventions, undertaken as adaptation strategies, and thus an indirect effect of climate change, can increase abundance of tick hosts and therefore ticks. This may include changes in woodland management practices or the introduction of habitat defragmentation initiatives for wildlife conservation.

Studies in Bosnia and Herzegovina and Czech Republic demonstrate an expansion in the altitudinal range of *Ixodes ricinus* over the last few decades. In Bosnia, the altitudinal limit for *I. ricinus* has increased from 800m.a.s.l. (metres above sea level) in the 1950s to 1180m.a.s.l. in 2010 (Omeragic, 2010). In the Czech Republic, the limit until the 1990s was 700m.a.s.l. but it has now increased to 1100-1270m.a.s.l. (Daniel *et al.*, 2003; Materna, *et al.*, 2005; Danielova *et al.*, 2006).

The increased altitudinal distribution has been associated with increases in temperature. In the Czech Republic, Danielova *et al*. (2010) reported that at 1000m.a.s.l, the mean annual temperature had increased by 1.4°C between 1961 and 2005, with a 3.5°C increase in temperature during spring and summer. Danielova *et al*. (2008) suggested that increased temperatures during January and February will also influence tick host survival, providing ample small mammal hosts for immature stages. Increasing temperatures are likely to positively affect *I. ricinus* populations at higher altitude by increasing the length of season for development (Danielova *et al*., 2006). Studies in Hungary compared the onset of autumn activity of the tick between the 1950s (Sreter *et al*., 2005) and 2000s (Szell *et al*., 2006), finding that autumn activity started and ended one month later and that tick activity (albeit low) was recorded during the winter months which was not observed in the earlier study. Climate does not act in isolation however. Ticks cannot physically ascend without a mobile host to transfer them to other favourable sites (Danielova *et al*., 2006). Higher temperatures provide deer with nourishment from vegetation over an increased proportion of the year, thus assisting the expansion of *I. ricinus*.

Increases in forest coverage and a change from managing forests for timber to complex ecosystems for wildlife allow expansion of tick ranges. Few *I. ricinus* occur above 700m.a.s.l. in the highlands of Scotland (Gilbert, 2010). Large parts of the UK (except montane habitats) are below 700m, so generally altitudinal expansion by ticks will have less impact on tick-human contact than is the case in parts of Europe.

There has been range expansion of *I. ricinus* to higher latitude in Northern Europe, particularly in Sweden, during the 1980s and 1990s (Jaenson *et al.,* 1994; Talleklint and Jaenson, 1998; Lindgren *et*

al., 2000; Jaenson *et al.*, 2009; Jaenson and Lindgren, 2011). This was linked to warmer winters with a reduction in the number of days below -12^{o}C during winter and prolongation of spring and autumn. The vegetation period (VP) has become longer (>180 *versus* <160 days) and snow cover days have become fewer (<125 *versus* >175 days) - these affect tick numbers directly and indirectly; the latter by increasing numbers of roe deer (the main adult tick host). Because *I. ricinus* occurs throughout the UK, climate change will not extend its range. However, climatic effects on tick and host biology may well extend the annual period during which *I. ricinus* is active.

Habitat structure also determines *I. ricinus* survival. An extended VP and expansion of deciduous woodland is important in northern latitudes, but in other parts of Europe, within the existing range of *I. ricinus,* there are a large number of afforestation and habitat connectivity initiatives that also appear to provide additional habitats for both ticks and their hosts. In Spain long- and short-term changes in climate have increased tick populations in some areas but reduced them in others (due to lower rainfall) (Estrada-Pena *et al.*, 2006), with connectivity between habitats also determining whether ticks are present (Estrada-Pena, 2002). It is likely therefore that the distance between patches and hence 'habitat fragmentation' is inversely related to the probability of the invasion and establishment of *I. ricinus* into new areas.

In the UK, agri-environment schemes provide habitat corridors between patches of extant habitat to encourage biodiversity and assist wildlife to adapt to climatic changes. These initiatives provide corridors for animal movements, and consequently tick movements, and refuges for browsing and resting (e.g. deer). An expansion in the range of *I. ricinus* in south-west England during the last decade has been suggested (Figure 8.1, Jameson and Medlock, 2010) and this may be due to the expansion of roe deer throughout the south-west. Unpublished UK field data from the HPA also suggest that *I. ricinus* are exploiting field margins (i.e. margins of arable land left for wildlife), with the extent heavily affected by neighbouring habitat (e.g. woodland versus arable), and the local movements and activities of deer. Woodlands are also being managed as mosaic habitats, with active grassland management of rides (i.e. track-side vegetation in woodland) within the forest, providing sunny path-side vegetation for a range of animals and plants, and specific management for butterflies. Within these rides, the occurrence of leaf litter, higher sward height, occurrence of bracken and bramble, and favourable aspect are associated with increased tick abundance (Medlock, 2009; Medlock *et al.*, 2012a). Urban green corridors are also facilitating movement of deer and ticks into urban areas and gardens (Jameson and Medlock, 2010; Dobson and Randolph, 2011). Since deer are important tick hosts the challenge will be to manage deer in urban areas. These changes are occurring in part in the effort to adapt habitats for climate change (Lawton *et al*., 2010). It must be ensured that biodiversity gain and climate change adaptation do not increase human tick exposure. Strategies are now being developed to manage habitats to reduce tick exposure whilst also ensuring biodiversity gain (Medlock *et al*., 2012a).

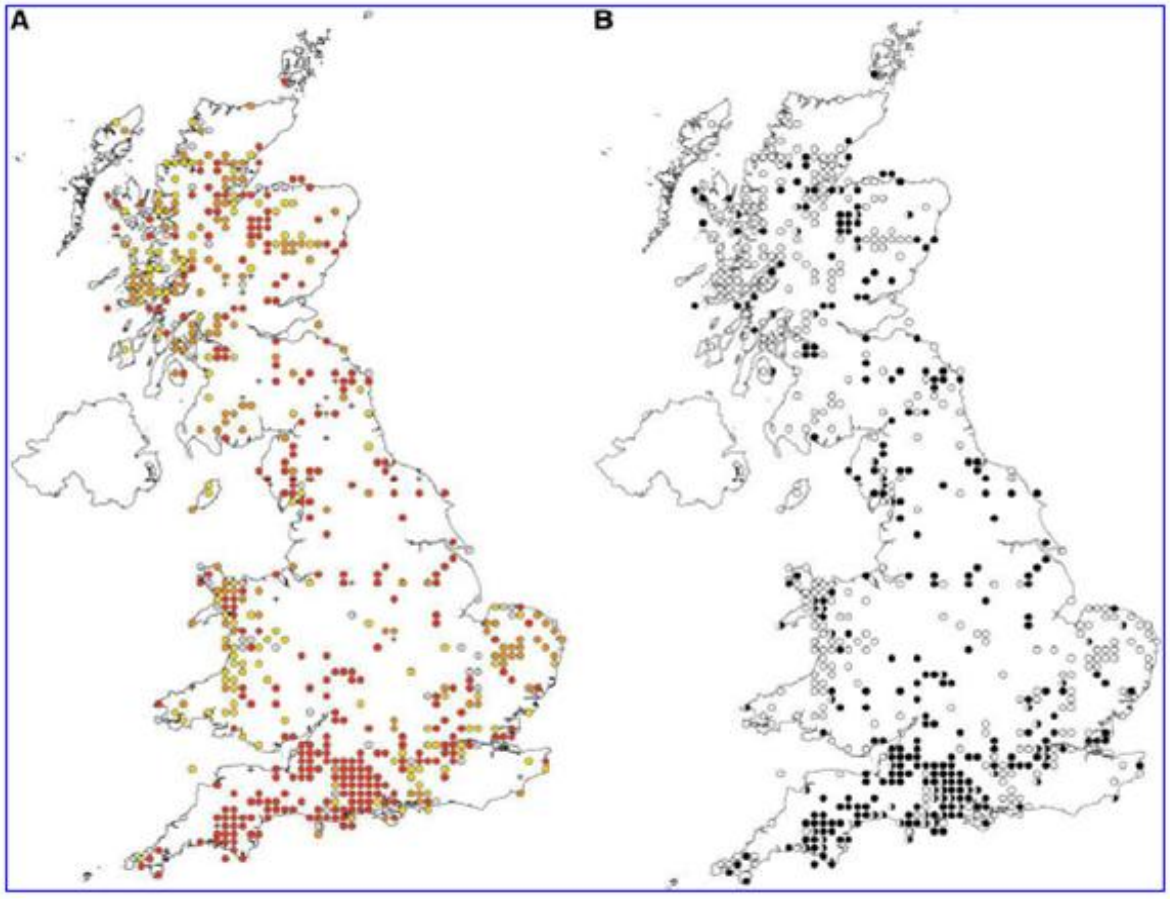

Figure 8.1. A) Distribution of *Ixodes ricinus* (sheep/deer tick) in Great Britain mapped at 10 km resolution. Red dots: 2005-2009, orange dots: 1990-2004, yellow dots: 1970-1990, grey dots: 1950-1969. B) Comparison of tick records submitted to the HPA for the period 2005-2009 and historical *Ixodes ricinus* mapped at 10 km resolution. Black dots: HPA, white dots: historical, black and white dots, both (Jameson and Medlock, 2011).

8.2.2 Dermacentor reticulatus – range expansion and climate change

The changes in the distribution of *Dermacentor reticulatus* are known to be linked largely to movements (natural and human-related) of host animals such as dogs, horses and sheep (Jameson and Medlock, 2011). Historical records of *D. reticulatus* are mostly restricted to western Wales and parts of Devon (Martyn, 1988), where populations still exist (Tharme 1993; Medlock *et al.*, 2011). Jameson and Medlock (2011) reported the first established population of *D. reticulatus* in Essex, with further field data confirming additional neighbouring foci (Smith *et al.*, 2011). In Germany, where numbers and distribution of *D. reticulatus* ticks are increasing, this species is found principally in areas of intense solar radiation (Dautel, 2006). Therefore this tick species might also be affected by climate change in Britain. South-eastern England is one of the warmest parts of the country (U.K. 1971-2000 climate data, U.K. Meteorological Office). UKCP09 climate projections show this region of the UK to have the greatest reduction in cloud cover and in some emission and probabilistic climate scenarios increased summer warming. Interestingly however, despite the apparent ease of movement on hosts there have been few new foci.

8.2.3 Exotic tick species – drivers for their introduction including climate change

Globally, the brown dog tick, *Rhipicephalus sanguineus*, is the most widely distributed tick species. It is a vector of Mediterranean Spotted Fever (*Rickettsia conorii*) in Europe. It is periodically imported into the UK by travelling dogs. It can complete its life cycle indoors. Warmer temperatures will reduce its generation time and mortality. Optimum conditions are temperatures of 20-30°C, with 85% relative humidity (RH), with progression through to the next stage (i.e. moulting) occurring >10°C. The number of generations per year increases as temperatures and RH approach their optima to up to 4 per year. *Rhipicephalus sanguineus* is not considered to be endemic in the UK, with reports currently linked only to quarantine kennels (Hoyle *et al*., 2001, Bates *et al.,* 2002, Jameson *et al.,* 2010). The importation of this tick on travelling dogs has until now been limited by the mandatory requirement for acaricidal treatment of dogs before returning to the UK. However since the start of 2012 these controls have been removed. In the absence of such controls, it is very likely that importations of this tick into the UK on travelling dogs will increase. It is also possible that indoor populations (in kennels, pet owners' houses) will become established. The influence of climate change, therefore, will become a more significant consideration in the future.

Hyalomma marginatum is the most important vector of Crimean-Congo haemorrhagic fever virus in Europe. It is known to be imported into the UK on birds migrating from Africa in the spring (Jameson *et al.,* 2012). It is not currently established in the UK due to unsuitable climate. Its nymphs require a minimum of 14-16°C to moult successfully with adults requiring a minimum of 12°C for activity (Estrada-Pena *et al.*, 2011). Even at 15°C the mortality of *H. marginatum* nymphs is expected to be high due to the longer time required for moulting. The mean daily temperature during spring/summer months is considered to be the main constraint on *H. marginatum* survival as endemic populations do occur in Russia where winter temperatures are lower than those recorded currently in the UK. In such regions the ticks spend the winter as adults. Only when winter temperatures fall below -20°C and the ground freezes, will this negatively affect adult tick survival. March-June are the key months for mass arrival of migratory birds from Africa. For countries where *H. marginatum* is abundant the average temperature around this time is 16-17°C. This mean daily temperature is not reached in the UK until June at the earliest. However, given predictions for an increase of 1-3°C in global temperatures, and between 1.5-4^{o}C for mean summer temperatures depending on the time period and emission scenario from 2020 to 2050 and beyond (UKCP09), it is possible that the future UK climate, particularly in central southern England (UKCP09), may become suitable for the establishment of imported *H. marginatum*.

8.2.4 Climate change and tick-borne diseases of humans

The ecological complexity of tick life-cycles and pathogen transmission means only qualitative assessments of risk are feasible. *Borrelia burgdorferi sensu lato*, the agent of Lyme disease, occurs in a range of wildlife species, and is transmitted primarily by *I. ricinus*. In Europe there are two main genospecies known to cause human disease. *Borrelia afzelii* occurs within small mammal-tick cycles, with high infection rates in wood mice (*Apodemus sylvaticus*), bank voles (*Myodes glareolus*) and yellow-necked mice (*Apodemus flavicollis*) (Humair *et al.,* 1993; Craine *et al.*, 1995; Hoodless *et al.*, 1998; Humair *et al.*, 1999; Hanincova *et al.*, 2003). *Borrelia garinii* occurs within bird-tick cycles, with high infection rates in pheasant (*Phasianus colchicus*) and ground-feeding passerines, like blackbird (*Turdus merula*) and robin (*Erithacus rubecula*) (Humair *et al.*, 1993; Hubalek *et al.*, 1996; Craine *et al.*, 1997; Hoodless *et al.*, 1998; Humair *et al.*, 1998; Kurtenbach *et al.,* 1998a; 1998b). Deer (e.g. Roe

deer, *Capreolus capreolus*) are not involved in transmission (Jaenson and Talleklint, 1992); however they are a key tick host and can be crucial in supporting tick populations. While pheasant become heavily infested and contribute to transmission of *B. garinii*, they also feed on a large number of nymphs which could otherwise bite humans (Kurtenbach *et al.*, 1998), and they can assist with the eradication of *B. afzelii*. Lizards are not competent hosts (i.e. they do not infect ticks) and are considered dilution hosts (i.e. reduce the infection rates of ticks). *Borrelia burgdorferi* infection in *I. ricinus* is maintained through moults, but transovarial transmission is less common, with less than 2% of resulting larvae infected. Thus, *B. burgdorferi* dynamics are complex, with the seasonal rates of infection in questing ticks dependent on a combination of tick activity, the local vertebrate fauna and their population dynamics, as well as climate.

Further complexities are also relevant here. For example, vole population dynamics are clearly related to beech masting (production of beech nuts) (Bennett *et al.*, 2010), which is dependent on sequential annual and seasonal weather events and climatic trends over several years. Beech mast is a key food for voles that in turn determines vole abundance. In the context of *Borrelia*, a rapid increase in certain rodent species can significantly affect the availability of tick hosts for larvae, immunological effects on the tick and the pathogen, and consequently tick infection rates. The annual release of pheasants, as well as the spread of deer, also affect tick population dynamics and in turn determine tick infection rates and genospecies prevalence. Many of these effects are driven by anthropogenic factors, and although climatic change may play a part, climate *per se* may not always be central to the transmission cycle.

Tick-borne encephalitis virus is common in central and eastern Europe, has also recently been reported in Scandinavia, but is not present in the UK. A similar virus, louping ill occurs in the UK; however the public health significance of this virus is questionable. Modelling studies have been conducted on the effects of current and future climate on TBE in Europe (Randolph, 1998: 2000, Randolph *et al.*, 1999). Foci of TBE transmission have been shown to be related to co-feeding of *I. ricinus* larvae and nymphs on the same host animal, which is determined by weather and climate. These studies predict that future climate will not lead to the incursion of TBE in the UK. Tijsse-Klasen *et al*. (2010) recently provided the first evidence of seven different species of *Rickettsia* in UK ticks, including *Rickettsia helvetica* in *Ixodes ricinus* currently in south-west England and parts of Scotland and *Rickettsia raoultii* in *D. reticulatus* in Wales. The human health risk posed by these pathogens is presently uncertain.

Although climate change is likely to increase the risk of the tick-borne diseases in the UK, it is not possible to make quantitative assessments of risk or the relative contribution of the direct and indirect effects of climate change and adaptation initiatives. Climate change adaptation strategies and other unrelated environmental changes (e.g. host expansion) may impact more on human tick-borne disease risk than the direct effects of climate change. Vulnerable sub-populations will include those occupationally (e.g. agricultural and forestry workers) and recreationally (e.g. walkers and outdoor sports enthusiasts) more exposed to ticks, particularly in areas where re-wilding initiatives are being implemented, as well as those regions where host numbers are increasing and where climate change is likely to improve the potential for the establishment of exotic ticks.

8.3 Mosquitoes and Mosquito-borne disease

There are currently 34 species of mosquito in Britain (Appendix C for ecology, host preference and vector status), including two reported in the last five years: *Anopheles daciae* (Linton *et al.*, 2005) and *Aedes geminus* (Medlock and Vaux, 2009). These include 6 species in the sub-family Anophelinae, all in the genus *Anopheles*, and 28 in the sub-family Culicinae in seven genera: *Aedes* (3), *Coquillettidia* (1), *Culex* (4), *Culiseta* (7), *Dahliana* (1), *Ochlerotatus* (11) and *Orthopodomyia* (1). Some develop in permanent waterbodies such as ditches and ponds (e.g. *An. claviger, Cq. richiardii*), while others occupy temporary freshwater pools in woodlands (e.g. *Oc. cantans, Oc. rusticus*) and flooded meadows (e.g. *Ae. cinereus*) or saline pools in saltmarshes (*Oc. detritus*) and grazing marsh (*Cx. modestus*). A few species occupy tree-holes (e.g. *An. plumbeus, D. geniculata*); while in urban areas others can use containers such as rainwater butts (e.g. *Cx. pipiens pipiens* biotype, *Cs. annulata*). One species also favours underground water in flooded basements, the foundations of dwellings, drains and underground railway tunnels (*Cx. pipiens molestus* biotype). There is also the potential for the importation of exotic mosquitoes, such as *Aedes albopictus*, which has invaded elsewhere in Europe.

The majority of British species bite humans, and at least a dozen species constitute a biting nuisance (Medlock *et al.*, 2005; 2012b). Potential nuisance species are associated with a range of aquatic habitats in rural, urban and coastal habitats. These mosquitoes, the diseases that they could vector and the potential impacts of climate change are considered in more detail in the following 9 sections on: (8.4.1) the potential impacts of climate change on British mosquitoes; (8.4.2) the impacts of adaptation strategies to climate change through environmental change; (8.4.3) the effect of wetland creation and expansion, and floodwater management on endemic mosquitoes; (8.4.4) mosquito-borne arboviral and (8.4.5) parasitic disease risk subsequent to climate change; (8.4.6) invasive mosquitoes in Europe and their public health importance; (8.4.7) assessment of the potential for establishment and seasonality of the invasive, *Aedes albopictus*, based on current conditions; (8.4.8) its recent trends in expansion and prospects for establishment in Europe and UK; and (8.4.9) the potential impact of climate change on the prospects for malaria transmission.

8.3.1 The impacts of climate change on British mosquitoes

The effects of the various predictions of climate change by 2080 on the distribution, abundance and activity of British and imported mosquitoes, and indeed the diseases that they could vector, will be complex and difficult to project. Different mosquito species will be affected at different stages of their life history and in different ways depending on their ecology and phenology. Climate change and the implementation of certain adaptation strategies, such as the reinstatement and creation of freshwater wetlands and coastal marshes as flood defences, will provide new habitat for mosquitoes and this may change future vector-borne disease risks, probably negatively, especially since there are currently no known mosquito-borne diseases of concern in the UK.

The impact of climate change on British mosquitoes was reviewed by Snow and Medlock (2006), and is summarised here. Climate change predictions with the medium emission scenario suggest an annual 10 year mean temperature increase for northern Europe relative to 1906-2005 of about 4^{o}C (2-6), and a summer mean temperature rise for the UK of 4.2^{o}C (2.2-6.8) by 2080 in parts of southern England to just over 2.5^{o}C (1.2-4.1) in the Scottish islands, with 'very hot' summers becoming more frequent (UKCP09). Such increases in temperature will directly impact the

development of all mosquitoes, inducing faster larval development, faster blood digestion, shorter intervals between generations, increased egg production and probably more generations per year. It may also decrease adult longevity and alter sex ratios of some species. Hotter summers may also encourage people to spend more time outdoors, increasing their exposure, especially to outdoor biting mosquitoes. A greater frequency of warm nights will encourage people to leave windows open leading to more frequent biting by indoor-biting mosquitoes. According to UKCP09, very cold winters are also predicted to become rarer in the UK. This could lead to a protracted biting season and promote the winter survival of immatures in species that are affected by ice-bound conditions, and survival of adults in species that are limited by cold temperature. It is also possible that aquatic habitats will become more favourable for immatures earlier in the spring, facilitating a longer season for development, and a reduced incidence of larval sites being eliminated by ice-bound conditions. Winters might also be wetter by 10-30% over most of the country according to UKCP09 central estimates, with an increased risk of the incidence of winter flooding. This is likely to create more temporary freshwater sites for mosquito breeding and a greater abundance of mosquitoes emerging in spring. During winter large permanent freshwater habitats are also likely to experience increased filling and (urban) underground aquatic habitats are more likely to become flooded.

Summers are predicted to be drier by up to 40% in the southwest, with a general south to north gradient by 2080 (UKCP09). This is likely to negatively impact on the aquatic habitats of some mosquito species, with smaller freshwater sites, the shallower margins of larger permanent freshwater sites and tree-holes all drying out more frequently. In contrast, other mosquito species might be favoured as larger pools become shallower and the velocities of rivers and canals decrease, thus increasing the extent of breeding sites. Drier summers might also increase the use of water butts in gardens, aiding container habitat species. UKCP09 further suggests an increase in the intensity of summer storms, leading to flash flooding on parched soils, which would be countered to some degree by increased temperatures and evaporation. Localised flooding is likely to aid some of the mosquito species that breed in flooded grasslands or are opportunist species (e.g. *Cx. pipiens, Cs. annulata*). The sea level rises and increased storm surges that are considered in the UKCP09, might also lead to the loss of salt-marsh. However this will be countered by the increased inundation of coastal areas and freshwater habitats by seawater, which could actually increase the extent of brackish habitats and the particular mosquito species that depend on them (e.g. *Oc. detritus*).

8.3.2 Adaptation to climate change through environmental change

It is likely that the effects of some climate change adaptation strategies will be as important in determining the future distribution and abundance of different mosquito species as the direct effects of climate change *per se*. The expansion of existing wetlands, their creation from arable land, and the creation of new salt-marsh to alleviate coastal erosion and flooding are important features of the UK environment sector's approach to adapting to climate change and its continuing goals to provide increased wetland habitat for wildlife and an outdoor space for human 'well-being'. For example, the Wetland Vision for England (Hume, 2008) outlines plans to restore existing wetlands and create new ones from areas currently under agriculture to improve resources for biodiversity, assist with alleviating coastal and inland flooding and re-connect extant nature reserves to help wildlife species adapt to climate change. However, such initiatives might have adverse consequences for mosquito-borne diseases (Medlock and Vaux, 2011). Developing the evidence-base is a crucial element in preventing mosquito-borne disease emergence and in aiding policy makers assessing

risks associated with wetland expansion. It is important to ensure that biodiversity gain and habitat restoration do not inadvertently elevate future vector-borne disease risks. The environment sector has recognised the need for an evidence-base to inform future wetland creation and management initiatives which could provide tools to keep mosquito populations at acceptable levels.

8.3.3 Effect of wetland expansion and floodwater management schemes on mosquitoes and mosquito-borne diseases in the UK

Wetland expansion schemes and the creation of salt marsh habitats are an indirect result of climate change since in part they are intended to assist climate-sensitive wildlife species to move to more favourable areas, whilst mitigating the effects of sea-level rise, coastal erosion and storm surges. Fens and ditches will be the main freshwater wetland mosquito habitats created. These will provide aquatic habitats for *An. messeae, An. claviger* and *Cq. richiardii*, and to a lesser degree *Cx. pipiens/torrentium, Cs. morsitans* and *Cs. annulata*. Of these, *Cq. richiardii* is currently the only known nuisance biting species, especially inside dwellings. *Anopheles messeae* and *An. claviger* do nevertheless bite humans (but are not generally associated with nuisance; Medlock *et al.*, 2012b) and are two of the most abundant and ubiquitous mosquito species in the UK around ditch, pond and fen habitats. Provided these habitats are managed as permanent wetlands, however, then a range of mosquito predators and competitors could be maintained to control them.

There are four main mosquito species associated with aquatic habitats in wet woodland, and woodland pools (*Ochlerotatus cantans, Oc. annulipes, Oc. punctor, Oc. rusticus*); often associated with nuisance biting, particularly *Oc. cantans* and *Oc. punctor,* and possibly also *Cs. annulata*. A particular problem in late spring and summer, there is evidence that some of these species may forage at a distance from their more usual habitat to find blood-meals and disperse to human dwellings. Ensuring that such habitats are not generated sufficiently close to human dwellings should be considered as part of habitat creation schemes to reduce biting nuisance and possibly future disease vector potential.

The primary nuisance biting species around brackish habitats are *Oc. detritus* and to a lesser extent *An. atroparvus*. The former is already subject to control programmes at certain sites in the UK (e.g. Dee Estuary, Sandwich). It is unclear whether the latter, the principal vector of malaria in 18th/19th century Britain is currently a significant nuisance species. Coastal re-alignment projects that potentially create such habitats should therefore be assessed on a case by case basis with respect to increasing the populations of specific mosquito species and biting nuisance.

In flooded grassland and in particular inundated, previously arable grasslands, the main colonising species are *Ae. cinereus, Oc. caspius, Cx. pipiens, Cs. annulata* (and in areas of permanent water, *An. maculipennis*) (Medlock and Vaux, 2011); none of which are significant daytime biting nuisances, except in areas of dense vegetation. People working around such habitats and animals that graze them or adjacent flood grasslands may become increasingly subject to nuisance biting. By contrast, in continental Europe the main mosquito species of flooded river valleys is *Aedes vexans*; a significant nuisance biter. This species is rare in the UK, and its range is not known to be expanding. In parts of the Thames Estuary however, *Culex modestus* has been found established across parts of north Kent and south Essex in coastal grazing marsh (Golding *et al.*, 2012). The reasons for its recent

discovery and establishment is not clear, however it is an important disease vector in continental Europe and requires further study.

Climate change adaptation strategies with their increasing drive towards wildlife gardening will result in an increased use of containers to collect rainwater in urban areas, which will potentially favour species such as *Culex pipiens pipiens* and *Culiseta annulata*. The former only bites birds, but the latter is a nuisance biting species throughout the year. The use of covers on water storage vessels should reduce most of these mosquito populations but would require householders to be made aware. Depending on the type of wetland habitat created by the specific climate change adaptation schemes that are adopted to promote sustainable urban drainage, the observations in relevant sections above would apply. If urban aquatic habitats become organically polluted then they are will also provide habitat for the urban pest species *Cs. annulata*. Similarly where urban flooding is a problem and this leads to underground flooding of, for example, cellars, sumps, lift shafts, and underground tunnels then additional habitat will be provided for another urban pest species, *Cx. pipiens molestus*.

8.3.4 Mosquito-borne arboviral disease risk with climate change

The autochthonous[1] transmission of pathogens between humans by mosquitoes has not been reported in the UK since the eradication of vivax malaria. The increasingly frequent incidences of mosquito-borne disease outbreaks elsewhere in Europe, however, suggest that assessment of the potential impacts of climate change on future transmission in the UK would be prudent.

In the UK the main potential enzootic vectors (i.e. bird-to-bird) for West Nile virus (WNV) are *Cx. pipiens pipiens/torrentium, Cs. morsitans* and *Cs. litorea* with the main potential bridge vectors (i.e. bird-to-human) being *Cx. modestus, Ae. cinereus, Oc. cantans, Oc. detritus, Oc. punctor, An. plumbeus, Cx. pipiens molestus, Cq. richiardii* and *Cs. annulata* (Medlock *et al.,* 2005). These species occupy a wide range of wetland types and could in future be implicated in transmission of WNV, especially given the ubiquity of the pathogen's enzootic vectors, and their preference for a variety of permanent wetland types and container habitats. Warmer summers and milder winters would favour the abundance of all of these mosquitoes. However, many already coexist with large bird populations and currently there is no confirmed evidence of WNV transmission to humans in the UK. Given the recent findings, areas where *Cx. modestus* occurs could present a higher risk for possible transmission. Creation of new wetlands that might attract both birds and mosquitoes should be a consideration when assessing the risk posed by bird-associated arboviruses. However for transmission of WNV to occur there will need to be a co-existence of infected birds, large numbers of mosquitoes biting both birds and humans as well as a susceptible human population. The rates of mosquito biting in the UK (except in a few locations, e.g. associated with sewage treatment works and saltmarshes; Medlock *et al.*, 2012b) do not currently compare with those where West Nile virus transmission occurs in the rest of Europe.

Sindbis virus has a similar enzootic cycle to WNV in Scandinavia involving some of the same bird-biting mosquito vectors but a bridge vector cycle involving predominantly *Ae. cinereus* and possibly also *Oc. cantans* and *An. maculipennis* s.l.. However the involvement of birds that are not common in the UK during the main mosquito season (i.e. fieldfare, redwing, song thrush, capercaille and black

[1] indigenous or local transmission in a region.

grouse) will probably limit transmission to humans in the UK. Tahyna virus outbreaks in central Europe are associated with floodwater mosquitoes, such as *Ae. vexans, Ae. cinereus*, *Oc. detritus* and *Oc. cantans*. There is no evidence of transmission of this virus to humans in the UK and if this were to emerge as an issue it would most likely be associated with flooded habitats and flooded river valleys. The main vector in continental Europe, *Ae. vexans*, is rare in the UK. The endemic European mosquito-borne arboviruses Inkoo virus and Batai virus are not considered important issues for human health. A full assessment of possible ecology and epidemiology of these mosquito-borne arboviruses in Great Britain has been published by Medlock *et al.* (2007a).

Exotic mosquito-borne arboviruses have been imported into Europe and become involved in local transmission to humans (e.g. Usutu and chikungunya viruses) or associated with returning travellers (dengue, yellow fever, Rift Valley fever viruses). Usutu virus is predominantly a bird virus and seldom infects humans (Vázquez *et al.*, 2011). Chikungunya, dengue and yellow fever viruses are transmitted primarily by *Aedes aegypti* and *Aedes albopictus*, both of which are invasive mosquito species in Europe, but neither occurs in the UK. It is, however, likely that the *Ae. albopictus* could survive in Britain (Medlock *et al.*, 2006) (see below). Both species are container-breeding and unlikely to be significantly affected by wetland expansion, but would benefit from warmer summers. Rift Valley fever virus occurs in Africa and Arabia and affects both humans and ruminants. Its incursion into Europe would be serious, but perhaps the only route of incursion would be through illegally imported infected ruminants. The main vectors are likely to be *Aedes vexans* and possibly mammalophilic/ anthropophilic forms of *Cx. pipiens*. Owing to the cloistered and urban nature of the latter, and the restricted and focal distribution of the former, considerable expansion of *Ae. vexans* would be required, for autochthonous transmission to become an issue, but this could be promoted by flooded habitats. This assessment assumes however that other endemic mosquito species (e.g. other *Aedes/Ochlerotatus*) might not become implicated in transmission.

8.3.5 Mosquito-borne parasitic diseases

Two parasitic infections of concern are transmitted by mosquitoes: *Plasmodium*, the agent of malaria, and *Dirofilaria*. Malaria is dealt with in section 8.4.9. *Dirofliaria* is a parasite of dogs and foxes and considered to be an emerging zoonosis in Europe, although the numbers of human cases are currently few. Although *Ae. albopictus* is believed to be competent to transmit the parasite, there is little data on the parasite's main mosquito vectors. The British climate might support transmission of *Dirofilaria* (Medlock *et al.*, 2007b) but given its currently limited public health significance, the limited number of imported canine cases and the uncertainty over the main mosquito vectors, it is not possible to assess the extent to which climate change or wetland expansion might change future transmission risk in the UK. It seems unlikely given the little current significance for human health and the few imported canine cases that this parasite will become important, even with climate change and wetland expansion.

8.3.6 Invasive mosquitoes in Europe: public health importance

The increased trade in used tyres has facilitated the global spread of a number of mosquito disease vectors to Europe from North America and Asia. Most notable is the Asian Tiger mosquito, *Aedes albopictus*, which was transported from the United States on a shipment of used tyres into Genoa, Italy in 1990. Over the past 20 years it has become established in most areas of the country below an altitude of 600 metres, and since 2000 has been reported in more than 15 European countries,

including in urban areas (ECDC, 2009; Valerio *et al.*, 2009; Medlock *et al*., 2012c). Generally temperate strains imported from North America that undergo diapause during winter as drought- and freeze-resistant eggs are found in Europe. These strains could survive in parts of northern Europe.

Aedes albopictus is a vector of dengue virus, and was also the primary vector of chikungunya virus in La Reunion in 2005-2007 and then Italy in 2007. During 2010, autochthonous cases of dengue virus were reported in France and Croatia in areas where *Ae. albopictus* was common. This species bites humans during the day, and is an economic concern in parts of urban Italy. Recent climate modelling by ECDC (2009) predicts further establishment of this species across Europe, including the UK. This dissemination is thought to be facilitated by public and private transport on highways; from Italy to southern Switzerland and southern Germany, and from Italy to southern France and north-east Spain.

Aedes albopictus has not been reported in the UK, but the importation in used tyres is possible. Surveillance for *Ae. albopictus*, particularly in the Netherlands, Belgium and Switzerland, has led to additional invasive mosquito vector species being found. *Aedes japonicus*, a species from North America, is now widely established in northern Switzerland (Schaffner *et al.*, 2003) and southern Germany (Becker *et al.*, 2010), and has been reported in France and Belgium. It is a biting nuisance, and although not considered a primary vector of human pathogens, field collected samples in the US have been found positive for West Nile virus (WNV), and it is a competent vector (i.e. experimental vector in the laboratory) of both WNV and Japanese encephalitis virus (Medlock *et al.*, 2012c).

In 2010, the primary yellow fever and dengue virus vector, *Ae. aegypti* was found in shipments of used tyres in the Netherlands. This followed reports of established populations of this species on the island of Madeira (Almeida *et al.*, 2007). This species was common throughout the Mediterranean basin until the 1950s, and there is no reason to suspect that it shouldn't become established in Europe again. It would be unlikely to survive in Britain, although climate change will increase the likelihood of survival. The remaining three species: *Aedes koreicus*, *Aedes atropalpus*, *Aedes triseriatus* have only been reported on a few occasions in Europe, but one is known to have established locally (*Ae. koreicus* in Belgium, Italy), and all three are disease vectors (e.g. *Ae. triseriatus* is a known vector of La Crosse virus in North America) (Medlock *et al.*, 2012c).

The distribution of invasive species will be dependent on the suitability of local climate. *Aedes albopictus* is adapted to more northerly climes. To assess risks it is important to develop climate-based models for establishment and seasonal activity that capture changes in climate suitability over time against a variety of modelled scenarios.

8.3.7 Assessment of the potential for establishment and seasonality of Aedes albopictus based on current conditions (1960-2000)

Analysis of the potential for survival and seasonal activity of *Ae. albopictus* in the UK has been undertaken using a model that simulates the factors crucial to the life cycle of *Ae. albopictus* (Medlock *et al.,* 2006). This has identified areas for potential establishment (incorporating annual rainfall and cold-month isotherms) and numbers of weeks elapsing between first egg hatching in spring, and the production of diapausing eggs in autumn (incorporating weekly temperature and photoperiod).

Potential for establishment

A basic assessment of the likelihood for establishment was made by combining input parameters on annual rainfall (to ensure sufficient filling of aquatic habitats) and mean January isotherms (to facilitate survival of diapausing eggs during winter). Specific input thresholds for the establishment of the mosquito were contingent on two climate parameters being met: a January isotherm (TJan) >0^{o}C and an annual rainfall (AR) >500mm. Sensitivity analysis also considered possible establishment at TJan 1^{o}C, AR 600mm; and TJan 2^{o}C, AR 700mm.

Highland Scotland and parts of northern England lie outside the 0^{o}C threshold (Figure 8.2). Even with a conservative threshold temperature (>2^{o}C), winter climate is already unlikely to limit the survival of eggs across much of England, Wales, Northern Ireland and lowland parts of Scotland. The lowest TJan reported in Scotland was -3.7^{o}C, still higher than the purported -5^{o}C thresholds for late summer expansions of the mosquito. According to UKCP09 winter mean minimum temperatures will increase across the UK by up to 1-2^{o}C by 2020, and 2-3^{o}C across Scotland and 4^{o}C in central and southern England by 2080. Similarly few areas of the UK (i.e., parts of Essex marshes, North Yorkshire coast) currently fail to reach the 500mm AR threshold suggesting that in addition to winter temperatures, annual rainfall is unlikely to be a limiting factor. If the AR threshold for the mosquito was instead 600mm then significant parts of eastern England may currently be too dry, however the majority of western UK receives >700mm AR, and UKCP09 median projections for changes in annual precipitation show very little change everywhere in the UK up to 2080, with the largest changes being from -16% to +14% but only in some restricted places, and more widely being closer to +10%, depending little on the emission scenario. Based on standard thresholds of 0^{o}C TJan and 500mm AR, the majority of the UK would support survival of eggs and provide sufficient rainfall to enable establishment of populations. In sensitivity analysis, even using conservative climate thresholds and the least favourable scenario large parts of western England would be suitable for the mosquito's establishment, with the UKCP09 projections suggesting a more extensive distribution.

Figure 8.2. Establishment zones for Ae. albopictus – combined analysis of (left) TJan 0^{o}C AR 500mm, (middle) TJan 1^{o}C AR 600mm, (right) TJan 2^{o}C AR 700mm

Possible seasonal activity

Long term establishment will depend on adult mosquito abundance sufficient to sustain viable populations. A seasonal activity model at a 1km resolution including two life history variables was developed: these variables were number of weeks from first egg hatching to either egg diapause or adult die off, based on environmental criteria involved in overwintering, spring activity and autumn diapause of the mosquito (see Table 8.1). Criteria for spring activity were applied to two scenarios (Table 8.1), each with a different autumn photoperiod threshold. A third scenario tested the projected die-off time for adult mosquitoes in late autumn/early winter, using a more conservative estimate of 9.5^{o}C as the threshold below which adults would succumb.

Table 8.1. Model criteria for overwintering and seasonal activity of *Aedes albopictus*.

Scenario and level of risk		Overwintering criteria		Spring activity		Autumn diapause	
		Jan T^{m}	R^{A}	*SprT*^{m} (^{o}C) 10-11^{o}C	*Spp* (hrs light) 11-11.5hrs	*CT* (^{o}C) 9-10^{o}C	*Cpp* (hrs light) 11.5-12hrs & 13-14hrs
Scenario 1	High risk Medium risk Low risk	0^{o}C	500mm	10 10.5 11	11 11.25 11.5	9.5 9.5 10	1313.5 14
Scenario 2	High risk Medium risk Low risk			10 10.5 11	11 11.25 11.5	9.5 9.5 10	1111.5 12

JanT^{m}: January mean temperature; SprT^{m}: Mean temperature threshold for activity in spring; Cpp: Critical photoperiod for autumn diapause, *AR: Mean Annual Rainfall; Spp: Spring photoperiod; CT: Temperature for cessation of egg/larval activity*

In large parts of England, for scenario 1 (medium risk) under current climate, at least 16 weeks would be expected to elapse between hatching of overwintering eggs in spring (from week 17-19 April/May) and the production of diapausing eggs in autumn (weeks 36-37 September) (Figure 8.3). More prolonged activity would occur throughout south-east England, the Severn and Mersey basins, with 18 weeks in London and the south coast ports. For scenario 2, under current climate conditions all periods of activity increased by four weeks (April-October), compared to scenario 1. With respect to scenario three in relation to adult die-off, biting mosquitoes may be on the wing for up to six months, with a prolonged activity (26-32 weeks post hatching of overwinter eggs) occurring in coastal areas of England and Wales (from Liverpool south/east to Ipswich) and inland areas of the London basin, the Solent, Somerset and Gower. The southern ports, where eggs may be imported on used tyres, are the most suitable areas of the country for the survival and prolonged seasonal activity of *Ae. albopictus* in the UK.

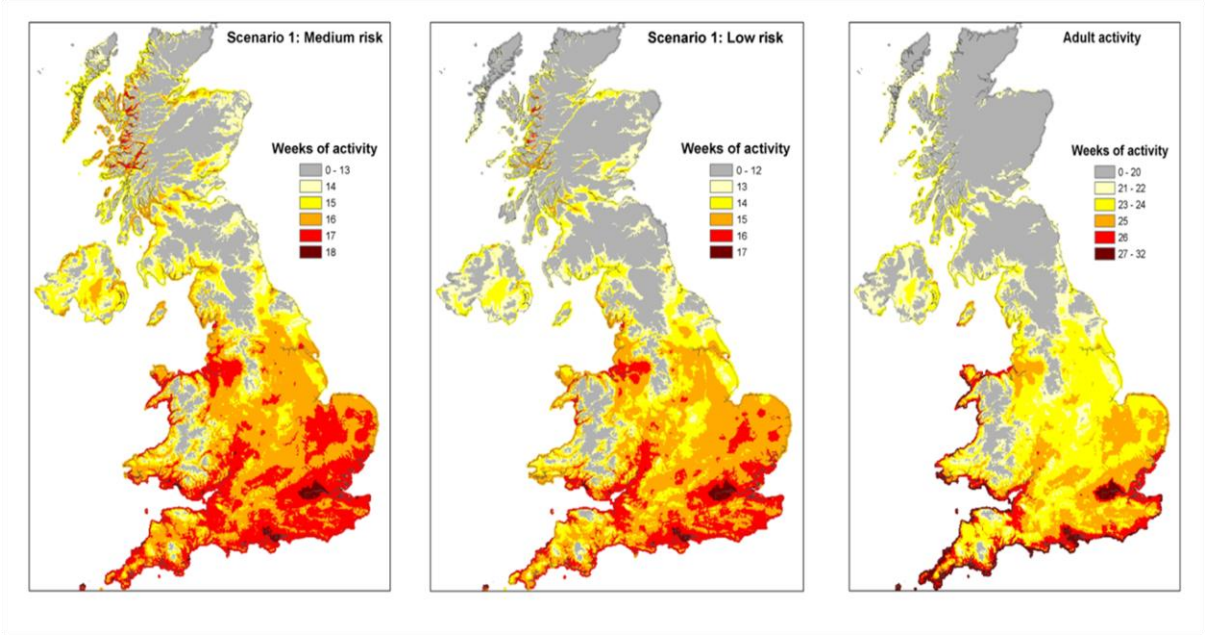

Figure 8.3. Predicted seasonal activity of Aedes albopictus in the UK

Sensitivity analysis using daily 5 km resolution climate data (aggregated to weekly) supplied by the UK Meteorological office for five years (1995, 1996, 1997, 1999, 2000) to simulate seasonal activity during individual years demonstrated no marked differences in seasonal activity or survival predictions compared with using 1971-2000 climate average data (Medlock *et al.*, 2006). The UKCP09 projections to the 2080s suggest future range expansion if *Ae. albopictus* were imported into the UK.

Conclusion

The model suggests the current UK climate could support the establishment and prolonged seasonal activity of *Ae. albopictus*. Preliminary consideration of key UKCP09 climate projections regarding winter mean temperatures and annual precipitation suggest that the areas of the UK that could support establishment will increase, especially northwards into currently less favourable regions. These aspects are investigated in more detail in the following section.

8.3.8 Climate suitability for the Aedes albopictus in Europe: recent trends and future scenarios

Recent climate change may have contributed to movements and establishment of *Ae. albopictus* in Europe (Caminade *et al.*, 2012). An ensemble of regional climate models (RCM) was employed to assess how climate suitability for the mosquito might change in the near future (Appendix D). Four types of model were created: model (1) uses the establishment criteria based on winter temperatures and annual rainfall after Medlock *et al.* (2006), model (2) uses establishment based on mean annual temperature after Kobayashi *et al.* (2002), model (3) the Multi Criteria Decision Analysis (MCDA) after ECDC (2009) and model (4) a seasonal activity model after Medlock *et al.* (2006).

Recent climatic trends

Model 1 assessed overwintering of *Ae. albopictus* in regions where European winters are suitable based on climate for 1960-1989 (Figure D1(a), Appendix D). Most of western Europe, including most of the UK except highland regions appear to be possible overwintering areas for *Aedes albopictus*. Annual rainfall has generally increased over Northern Europe, and there has been a significant decrease in the number of frost days in winter. Figure D1(b), Appendix D, shows the regions of potential overwintering over the last 20 years (1990-2009), for which temperature and rainfall has significantly changed. Suitable areas for the mosquito (white shading) have increased in north-west Europe and northern UK.

Assuming that the mosquito has previously been introduced, Models 2-4 (Figure D2, Appendix D) project changes in climate suitability for *Ae. albopictus* based on the 3 different methods:

- Model (2): In comparison with 1960-1989 (Figure D2a) and 1990-2009 (Figure D2b) there has been a dramatic increase in the suitability of southern England and Wales for *Ae. albopictus*. This is also the case for the Benelux countries.
- Model (3): Between the two time periods (Figures D2c, D2d) there is an increase in suitability for the Benelux countries, but this is not so pronounced for the UK, although suitability in eastern England is higher in the later time period.
- Model (4): with regard to seasonal activity, the potential period of activity has shown to be extended for large parts of southern UK from 1960-1989 (Figure D2e) to 1990-2009 (Figure D2f).

All three models highlight that climate suitability for *Aedes albopictus* has significantly increased over southern UK as well as the Benelux countries during the last twenty years compared to the previous thirty years.

Future climate scenario

In Model 1, future scenarios based on regional climate model projections highlight similar overwintering trends for the period 2030-2050 to current day (Figure D3, Appendix D). With respect to the recent climatic context (1990-2009) there are significant changes in suitability in continental Europe but these are less pronounced in the UK and northern France.

The future climate suitability of *Aedes albopictus* is shown in Figure D4 (Appendix D) based on the ensemble mean of the RCMs projections again based on the 3 different methods.

- Model (2): the future simulated trends are relatively similar to those trends recently observed, with an increased risk over north-western Europe including the UK (Figure D4a).
- Model (3): this approach provides similar results to Model 2, with a higher risk simulated over southern England (Figure D4c). Changes in the north are linked to increased temperature and precipitation. The impact of future climate change upon *Ae. albopictus* suitability might then result in its spreading over north-western Europe.
- Model (4): Figure D4e highlights the period of activity of the mosquito. The activity is simulated to lengthen over southern England, as well as the near continent, with an extension of two weeks predicted.

The increase in suitability over southern England, northern France, central and western Europe, the Balkans (and decrease over southern Spain and Portugal) is generally a common feature across all RCMs scenarios. All RCMs simulate increased risk covering a large area of southern UK based on model (2) (Figure D5a) whereas only half of the RCMs within the ensemble simulate this feature according to models (3) and (4) (Figure D5b, D5c, Appendix D). Note that model (4) (based on Medlock *et al.*, 2006) provides the most realistic pattern (hatched) with respect to observed presence of *Ae. albopictus* over western Europe (ECDC, 2009).

8.3.9 Impact of climate change on malaria transmission

Malaria is transmitted by inoculation of the parasite during feeding by anopheline mosquitoes (genus *Anopheles*), which breed in both fresh and brackish water. Three hundred to six hundred and sixty million clinical cases occur globally each year and the 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.

Domestic malaria (predicted using the biological approach)

Malaria was common in marsh communities in Southern England between the 16th and 19th centuries (Dobson, 1997) and some indigenous malaria occurred at the beginning of the 20th Century. Those areas most badly affected included the Fens, Thames Estuary, South-East Kent, the Somerset levels, the Severn Estuary and the Holderness of Yorkshire (Shute and Maryon, 1974). Malaria declined progressively from the 1820s due to a number of factors. Drainage schemes in 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 mosquitoes to locate a human blood meal. Cattle numbers rose and cattle 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 treatment and control. All reported cases of indigenous malaria in the 20th century were vivax malaria, except for one case of falciparum malaria in Liverpool.

Mosquito vectors and malaria transmission

There are six species of anophelines in Britain 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 British 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 feed on people in their houses. *An. atroparvus* can 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 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 relatively rare and unlikely to bite large numbers of people. Another possible vector is *An. plumbeus,* which has a widespread distribution including London. It 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).

Malaria transmission requires that a potential vector should feed on someone carrying gametocytes, the stage of the parasite that is capable of maturing and becoming infective within a mosquito. Between 9-24 days (depending on the temperature (Boyd, 1949)) after taking an infectious blood meal containing gametocytes, a vector mosquito will be able to transmit the infection to anyone that it bites. Since there are a few hundred imported vivax cases in the UK each year, and most of these are amongst 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 extremely unlikely that vivax malaria will be transmitted in the UK under current and future climate because of the limited distribution of the vectors.

More than one thousand imported cases of falciparum malaria are reported in the UK each year, mostly from West Africa. Many of these people live in London (Williams *et al.,* 2002) and other urban areas in the South of England, areas where *An. plumbeus* occurs. 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) many will have circulating gametocytes in their bloodstream for several weeks. Gametocytes may not be completely eliminated by chemotherapy (Targett *et al.,* 2001). The peak in imported malaria cases coincides with the period when *An. plumbeus* is most abundant in the UK (Williams *et al.*, 2002). However, it is unlikely that *An. plumbeus* will be responsible for local transmission since it is a relatively rare mosquito and will bite few people. We would therefore not expect more than a few cases of autochthonous malaria in the UK over the next 50 years.

Malaria and climate

P. vivax is better suited to the British climate than is *P. falciparum*. It requires lower temperatures (by 1-2^{o}C) than *P. falciparum* to develop in mosquitoes. *Vivax* parasites, unlike *falciparum* parasites, 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^{o}C; the current season for potential transmission in the UK would be between June and September.

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

Impact of temperature changes

Here the risk of *vivax* malaria in the UK is modelled for *An. atroparvus* (see Appendix E for model explanation). Maps of malaria suitability under recent climate (average 1961-90) and a range of future climate scenarios (Figures 8.4 and 8.5) show the number of months that *vivax* malaria, if it

were introduced, could persist each year in different parts of the country based simply on mean weekly/monthly temperatures. These maps do not account for changes in precipitation, humidity or the availability of mosquito breeding sites, but these may not be critical for the UK because the risk of malaria transmission will be highest near extensive areas of wetland, which provide numerous breeding sites and are not so affected by small changes in rainfall.

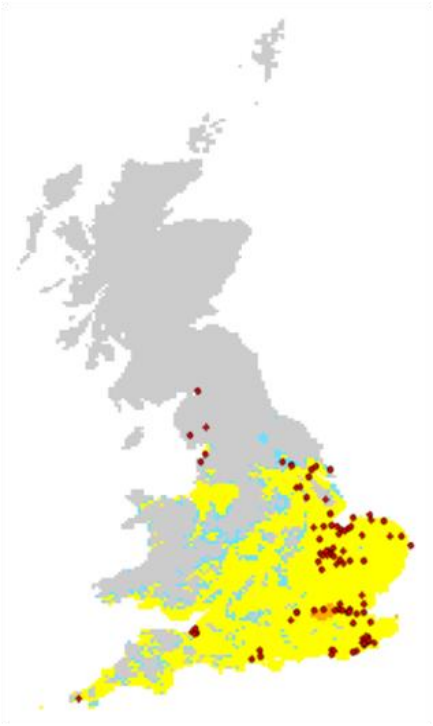

Figure 8.4. Areas of the UK where the climate could support vivax malaria. Shading represents the number of months where vivax malaria could be transmitted (grey =0, blue =1, yellow =2, orange =3). Red circles show malaria cases in the 19th Century. Based on the UKCIP for 1961-90.

The present distribution corresponds very well with past records of the distribution of malaria in England (Fig. 8.4) (Nuttall *et al.,* 1901). Thus, we are confident that our temperature-malaria model is robust. Under all climate-change scenarios, the risk of transmission is predicted to increase in the South of England, spreading northwards to the Scottish Borders.

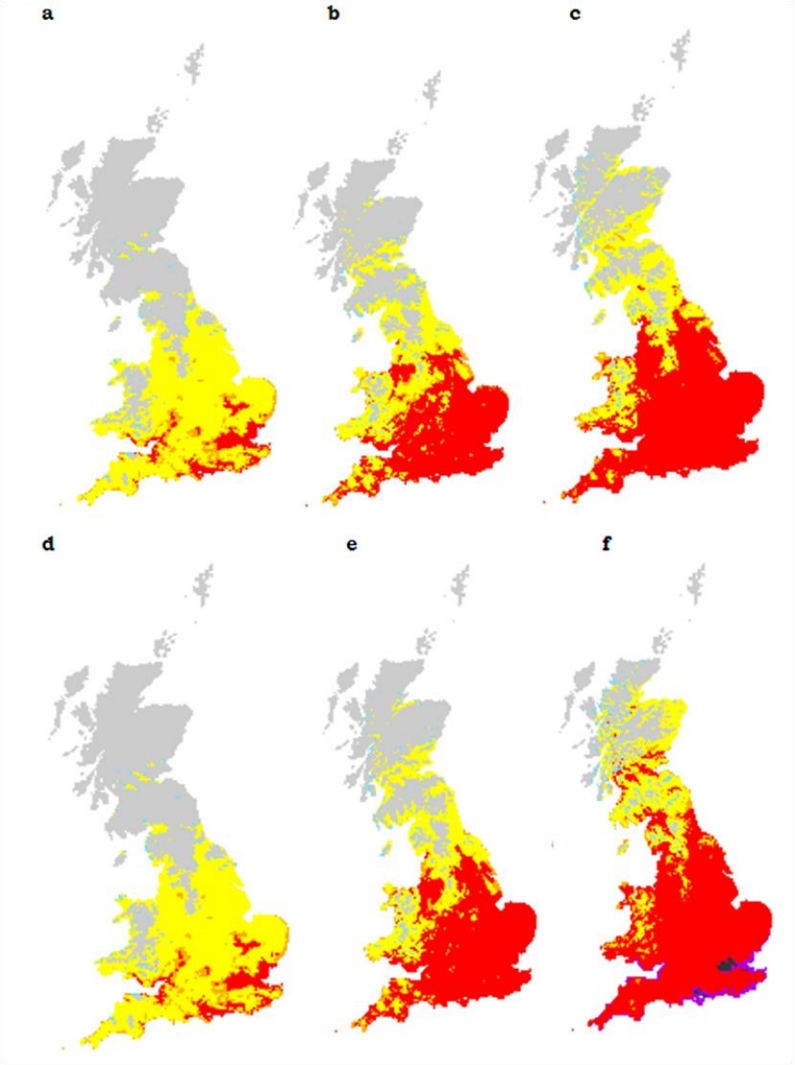

Figure 8.5. Projected future risk maps for vivax malarial transmission under a medium-low (a, b and c) and a medium-high (d, e and f) climate change scenario. Maps show risk for the period 2020s (a and d), 2050s (b and e) and 2080s (c and f). Based on UKCIP02.

At present, in only a few months in the south of the UK are temperature conditions permissive for transmission of *P. vivax* by indigenous vector mosquitoes. Although such transmission occurred in the past, it is a minor threat currently because living conditions have improved considerably. If the climate becomes warmer, conditions for transmission become more favourable, and last for longer. It is certain that our present standards of living, as well as rapid treatment of cases and surveillance systems will mitigate this increasing threat to a large extent, but not necessarily wholly in high risk areas. It should be noted that these assessments were based on UKCIP02 and it was not possible to update these for this report. It is not likely that the outputs will have changed significantly with UKCP09 and the conclusions have not changed

Impact of habitat changes

An. atroparvus is largely restricted to salt-marshes. At present there are 42,251 ha of salt-marsh in Britain, with the largest areas, 8,525 ha, along the Greater Thames Estuary in Essex and Kent

(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 saltwater, may result in less salt-marsh. Elsewhere, gradual saltwater intrusion into coastal lowlands may increase breeding sites for *An. atroparvus*. With summer droughts, there may 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 change will allow new vector species to become established in Britain. This would be most serious if it involved better European vectors of *vivax* malaria, such as *An. saccharovi*, *An. labranchiae*, *An. superpictus* and *An. sergentii*.

8.4 Conclusions

The status of vector-borne disease has changed dramatically in Europe during the last ten years. The impacts of climate change adaptation on arthropod vectors should be considered in disease projections, rather than only considering direct effects of temperature and rainfall changes. In light of the strategies to adapt to climate change, including changes in land management, there exist possible future conflicts between biodiversity‑enhancing strategies and vector-borne disease that require an evidence-based approach. Adaptation strategies may impact on vectors and associated pathogens more significantly than changes in weather and climate alone.

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Appendix B

British tick species, their distribution, host preference and vector status.

Species	Distribution	Host	Vector status
Ixodes arboricola (tree-hole tick)	Mostly England/some in Wales/one site in Scotland	Great Tit (*Parus major)*/Blue Tit (*Cyanistes caeruleus)*	
Ixodes caledonicus (Northern bird tick)	Northern England/Scotland	Pigeons/Corvids	
Ixodes frontalis (Passerine tick)	England	Ground feeding passerines	Avian tick-related haemorrhagic syndrome
Ixodes lividus (Sand Martin tick)	England	Sand Martin (*Riparia riparia*)	
Ixodes rothschildi (Puffin tick)	SW England/ W Wales	Puffin (*Fratercula artica*)	
Ixodes unicavatus (Cormorant tick)	Across Britain	Cormorant (*Phalacrocorax carbo*) /Shag (*P. aristotelis*)	
Ixodes uriae (Seabird tick)	Shetlands to Cornwall	Seabirds	
Ixodes acuminatus (Southern rodent tick)	Scillies/coastal Cornwall/Devon	Small rodents	
Ixodes apronophorus (Marsh tick)	Norfolk Broads/Wicken Fen	Water Vole (*Arvicola terrestris*)	
Ixodes canisuga (Fox tick)		Badger (*Meles meles*)/Fox (*Vulpes vulpes*/domestic dog	
Ixodes ventalloi (Rabbit tick)	Scillies/Lundy	Rabbit (Oryctoladus cuniculus)	
Ixodes trianguliceps (Shrew tick)	Across Britain	Small mammals/humans (but rare)	*Anaplasma phagocytophilum*
Ixodes vespertilionis (Long-legged Bat tick)	SW England/N Wales	Horseshoe-bats (*Rhinolophus*)	
Ixodes hexagonus (Hedgehog tick)	Across Britain	Hedgehog (Erinaceus europaeus)/humans/ companion animals	*Borrelia burgdorferi* s.l./ TBE (lab competency/field caught)
Ixodes ricinus (Deer/Sheep tick)	Across Britain	Wide range including humans	*Borrelia burgdorferi* s.l./*Anaplasma phagocytophilum/ Babesia divergens/ Babesia microti* Louping ill - tested positive for Rickettsia (*R. helvetica*)
Dermacentor reticulatus (Ornate Cow tick)	Wales/Devon/Essex	Domestic dog/sheep/ cattle/horses/ occasionally humans	Tested positive for Rickettsia (*R. raoultii*)
Haemaphysalis punctata (Coastal Red tick)	SE England/Wales	Passerine birds/sheep/cattle/ humans (but rare)	
Argas reflexus (Pigeon tick)	Cambridge, England	Domestic pigeon (*Columba livia domestica*)	
Carios maritimus (Marine argasid)	Offshore Islands W Wales	Seabirds	
Carios vespertilionis (Blyborough tick)		Bats	

Appendix C

A summary of biological, behavioural and disease parameters relevant to selected key British mosquitoes (based on Medlock and Vaux, 2011).[2]

Species	Aquatic habitat	Overwintering stage & voltinism	Biting preference	Nuisance status Potential vector status
Anopheles claviger	Shaded pools, ditches and ponds, particularly those with floating or marginal vegetation, or the margins of ditches sheltered under trees	Larvae (instars II-IV) in arrested development. Bivoltine	Readily bites humans, also rabbit and bovid	Absence of bird biting records suggest limited vector of WNV or SINV. Not considered main malaria vector in UK historically.
Anopheles maculipennis s.l.	*An. messeae* prefers clean, permanent, standing water supporting algae. *An. atroparvus* similar habitat but can tolerate high salinities.	Both species overwinter as nulliparous, inseminated females. *An. messae* undergoes diapause in cool shelters. *An. atroparvus* prefers warmer animal shelters and takes bloodmeals throughout winter.	Both species feed on animals, but not significantly on birds.	Historical vectors of malaria in Britain.
Anopheles plumbeus	Tree-holes, also found in containers such as tyres	Overwinter as IV instar larvae. Bivoltine	Mammals, inc. humans, also birds	Putative malaria vector, local nuisance
Coquillettidia richiardii	Vegetated ditches, requires species for plants	Univoltine. Overwinter as larvae. 1st instars June-Sept; all other instars present all year.	Mainly on humans and other large mammals, but also birds, rabbits and amphibians.	Putative vector of WNV. Biting nuisance but limited to a peak in July/August.
Aedes cinereus / Aedes geminus	Reed-bed, flooded meadows, ponds, ditches, marshes.	Univoltine. Remain in egg stage for 6 months; Eggs require 8-12 soakings.	Readily bites humans, cattle, and birds.	Putative vector of WNV. Bridge vector of SINV in Scandinavia, and potential vector of TAHV.
Ochlerotatus cantans / Ochlerotatus annulipes	Shaded woodland pools, with eggs laid in dried up hollows subject to flooding.	Univoltine. Eggs laid in damp leaf litter June-Sept; eggs require cold temperatures to	*Oc. annulipes* bites humans and cattle. *Oc. cantans* bites cattle, rabbits, humans, birds, and	*Oc. cantans* a potential vector for WNV, SINV, and TAHV.

[2] mosquito-borne viruses Tahyna (TAHV), West Nile (WNV), Sindbis (SINV)

		stimulate hatching in spring.	horses.	
Ochlerotatus punctor	Woodland pools, especially those lined with dead leaves.	Univoltine. Adults peak in June. 4th instar larvae found in December, but pupation deferred until April.	Aggressive biter of humans. Also cattle, and birds.	Putative bridge vector of WNV.
Ochlerotatus detritus	Brackish lagoons and saltmarsh, also freshwater	4th instar larvae. Multivoltine	Mainly cattle and humans. Some birds	Putative WNV. Aggressive biter; can require control interventions
Ochlerotatus caspius	Coastal and freshwater flooded habitats		Humans and large mammals	Potential Rift Valley fever vector
Culex pipiens s.l.	*Cx. pipiens pipiens* in natural and artificial water. At WWF wheel ruts, shallow standing water, and containers. *Cx. pipiens molestus* usually in flooded underground chambers.	*Cx. pipiens pipiens* - Multivoltine. Inseminated females hibernate, and lay eggs in spring following a blood-meal. *Cx. pipiens molestus* is non-diapausing	*Cx. pipiens pipiens* bites birds. *Cx. pipiens molestus* is mammalophilic, but also feeds on birds.	*Cx. pipiens pipiens* is an important enzootic vector of bird-associated viruses (WNV, SINV). *Cx. pipiens molestus* is a potential bridge vector of WNV
Culiseta annulata	Range of habitats including containers, ponds, ditches, marshes, in sunlight or shade.	Multivoltine. Overwinters without diapauses.	A broad range of hosts including humans, birds, rabbits, pigs and no doubt other mammals/livestock.	Aggressive human biter. Putative vector species - implicated as a potential bridge vector of WNV & TAHV.
Culiseta morsitans	Fresh or slightly brackish ponds, ditches, and pools – shaded or open.	Univoltine. Eggs hatch following immersion by autumn or winter rainfall; eggs can survive desiccation; larvae can withstand freezing.	Feeds exclusively on birds.	Ornithophilic nature makes it suitable as an enzootic vector of bird-associated viruses (WNV, SINV).

Appendix D

Climate suitability for the *Aedes albopictus* in Europe: recent trends and future scenarios.

Datasets

A high resolution (25km^2) gridded climate dataset has been developed for Europe based on station measurements (Haylock *et al*., 2008) within the EC FP6 ENSEMBLES project framework (Van Der Linden and Mitchell, 2009). Observed climate datasets (EOBS hereafter) including rainfall, temperature, minimum and maximum temperatures, available over Europe for the period 1950-2009 at daily and monthly temporal resolution, were employed to estimate the recent climate envelope of *Aedes albopictus* in Europe.

Regional scenarios for climate change impact assessments require finer spatial scales than those provided by global climate models (GCM) which have a coarse resolution (about 300 km). The ENSEMBLES European project provides improved regional climate models (RCM), at spatial scales of 25 km, for both recent past (1961-2000) and future climate scenarios (1950-2050). Models covering the European domain with a regular 0.25° step consistent with the observation grid were retained. Two ensembles of simulations have been carried out, the Control experiments (SimCTL) and the scenario experiment (SimA1B). In the SimCTL experiment (1961-2000), all RCMs are forced at their boundaries by the ERA40 reanalysis (the 'best guess' of the observations which uses both modelling and different sources of observations through data assimilation, see Uppala *et al.*, 2005). Observed external forcing (greenhouses gases, solar, volcanic, aerosols) is applied to all RCMs. In the SimA1B experiment (1961-2050), the RCMs are forced at their boundaries by a general circulation model (GCM) with a coarser resolution (about 300km) forced by the SRESA1B emission scenario (median scenario in terms of CO_2 emissions, see Nakicenovic *and* Swart, 2000). Different GCMs are used to drive the regional climate models according to this plan: http://ensemblesrt3.dmi.dk/

The 10 selected RCMs (and the related operational centre which ran the experiments) are: C4IRCA3 (Met Éireann, Ireland), CNRM-RM4.5 (CNRM, Météo-France), DMI-HIRAM5 (DMI, Denmark), ETHZ-CLM (ETHZ, Switzerland), ICTP-RegCM3 (ICTP, Italy), KNMI-RACMO2 (KNMI, Netherlands), METO-HC(Met Office, UK), MPI-M-REMO (MPI, Germany), OURANOSMRCC (OURANOS, Canada), SMHIRCA (SMHI, Sweden).

Only the SimA1B future scenario ensemble is considered in this study. Simulated precipitation and temperature outputs for each RCM have been mean bias corrected with respect to the EOBS dataset over the 1990-2009 reference period.

Model construction

Establishment criteria (detailed previously) were defined as totally suitable (AR >700mm, JanTm >2°C), with unsuitable overwintering conditions for a low scenario (defined as 600mm< AR< 700mm and 1°C < Tjan < 2°C), medium scenario (500mm< AR< 600mm and 0°C < Tjan < 1°C), high scenario (AR < 500mm and T_jan < 0°C).

Model (2): Establishment criteria based on mean annual temperature after Kobayashi et al. (2002)

A further climate threshold detailed in Medlock *et al.* (2006) was derived by Kobayashi *et al*. (2002), whereby totally suitable conditions are defined for mean annual temperature above 12°C. A high,

moderate and low risk is then defined for mean annual temperature ranging between 11-12°C, 10-11°C and 9-10°C respectively. The selection of these thresholds was derived on the basis that Ae. albopictus is relatively well established in Japan for mean annual temperature above 11°C, the establishment being more stable for annual temperature above 12°C. Areas in Northern America where annual temperature is above 11°C also strongly corresponded to the observed pattern of the distribution of *Ae. albopictus* in the USA. This method is relatively simple but limited as it does not take into account climatic changes that can occur during the seasons, and extremes.

Model (3): Multi Criteria Decision Analysis (MCDA) after ECDC (2009)

This is based on the Multi Criteria Decision Analysis (MCDA) that was developed in the ECDC (ECDC, 2009). Annual rainfall, January and summer (June-July-August) temperatures were first transformed into an interval ranging between 0 and 255 using sigmoidal functions. These sigmoidal functions were defined following expert advice. For annual precipitation, suitability is dropped to zero when rainfall is lower than 450 mm, and maximum (255) when precipitation is higher than 800 mm; for summer temperature, the suitability is zero when temperatures are lower than 15° C and higher than 30° C, and maximum between 20° C and 25° C; for January temperature, the suitability is zero when temperatures are lower than -1° C, and maximum when temperatures are higher than 3° C. The 3 parameters are then linearly combined (arithmetic average) to define the suitability for *Aedes albopictus*. The suitability is finally arbitrarily rescaled to range between 0 and 100.

Model (4): Seasonal activity model after Medlock et al. (2006)

Finally, we employed the GIS based method developed by Medlock *et al*. (2006). This method combines the standard overwintering criterion with weekly temperatures and photoperiods to simulate the weeks of activity of *Aedes albopictus* between the onset of hatching and the autumn egg diapause.

Model outputs

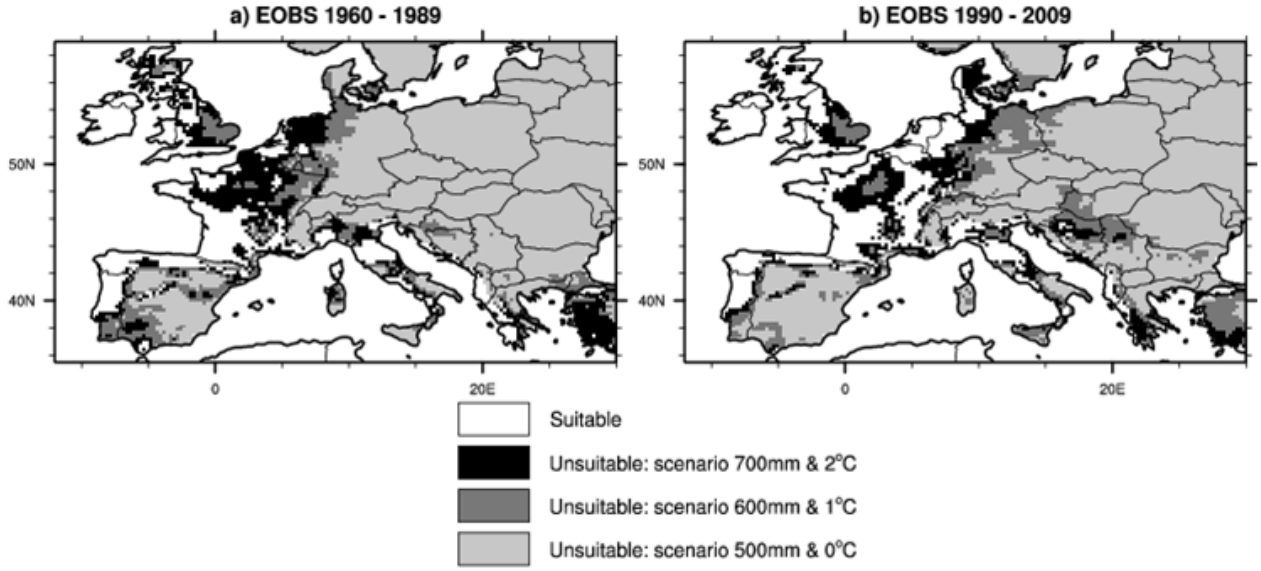

Figure D1. Overwintering capacity of *Aedes albopictus* to survive based on mean observed January temperatures and annual rainfall. This is carried out for the period 1960-1989 (a) and 1990-2009 (b) based on the EOBS dataset. White areas depicts regions for which climate is suitable for the mosquito. The different grey and black shadings depict regions of unsuitability according to different climatic thresholds. The light gray shading depicts strictly unsuitable areas

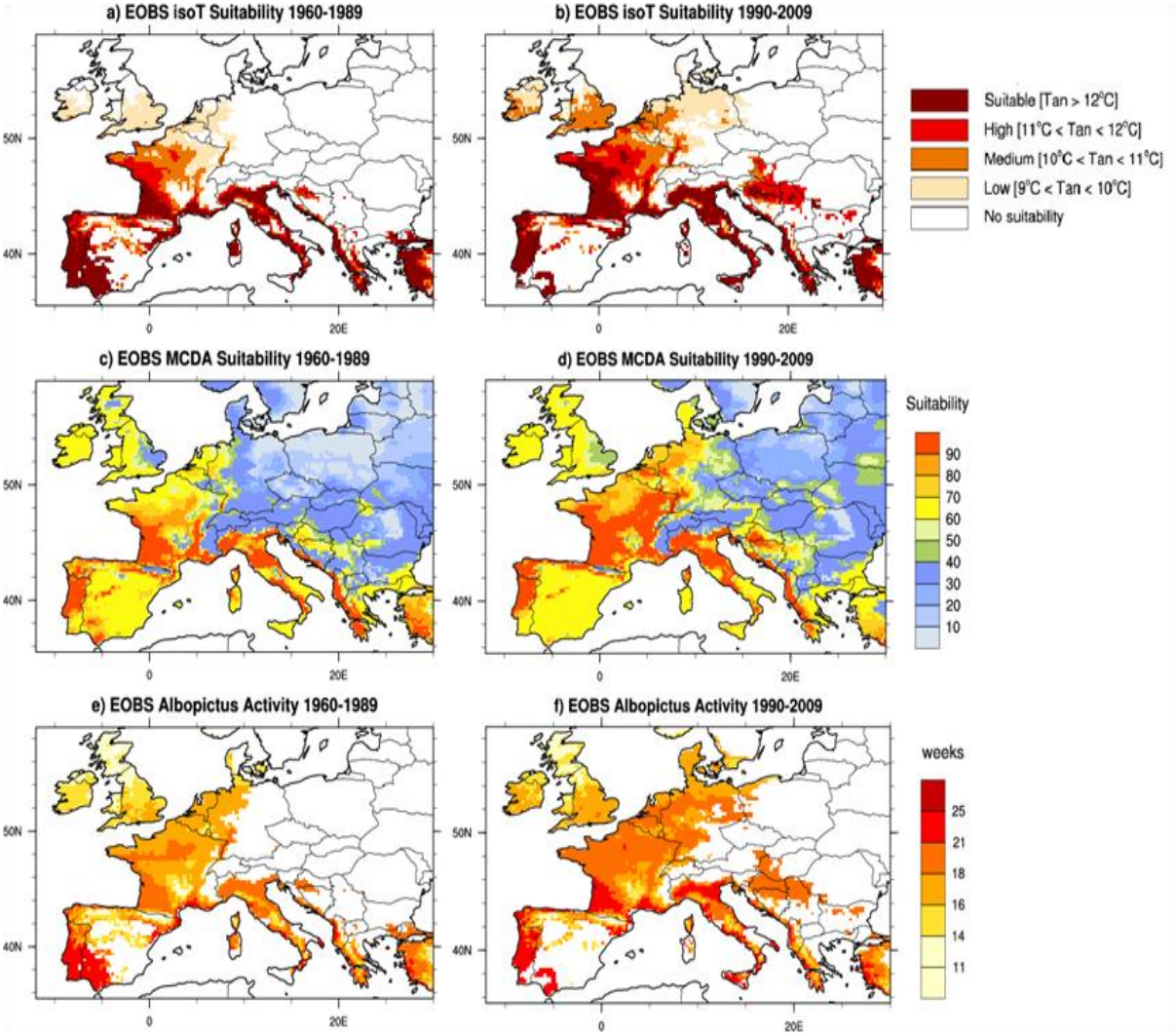

Figure D2. Observed climate suitability of *Aedes albopictus* based on different methods (rows) and for two different time periods (columns). Upper row: the climate suitability is calculated based on annual mean temperatures for a) 1960-1989 and b) 1990-2009 (an overwintering zone is defined based on annual rainfall above 500mm and January temperatures above 0°C). Middle row: the climate suitability (ranging between 0 and 255) is based on the MCDA method developed in Schaffner *et al.* (2009) (using annual rainfall, January and summer temperatures). This is carried out for c) 1960-1989 and d) 1990-2009. Lower Row: Weeks of adult mosquito activity for e) 1960-1989 and f) 1990-2009 based on the method developed in Medlock *et al.* (2006).

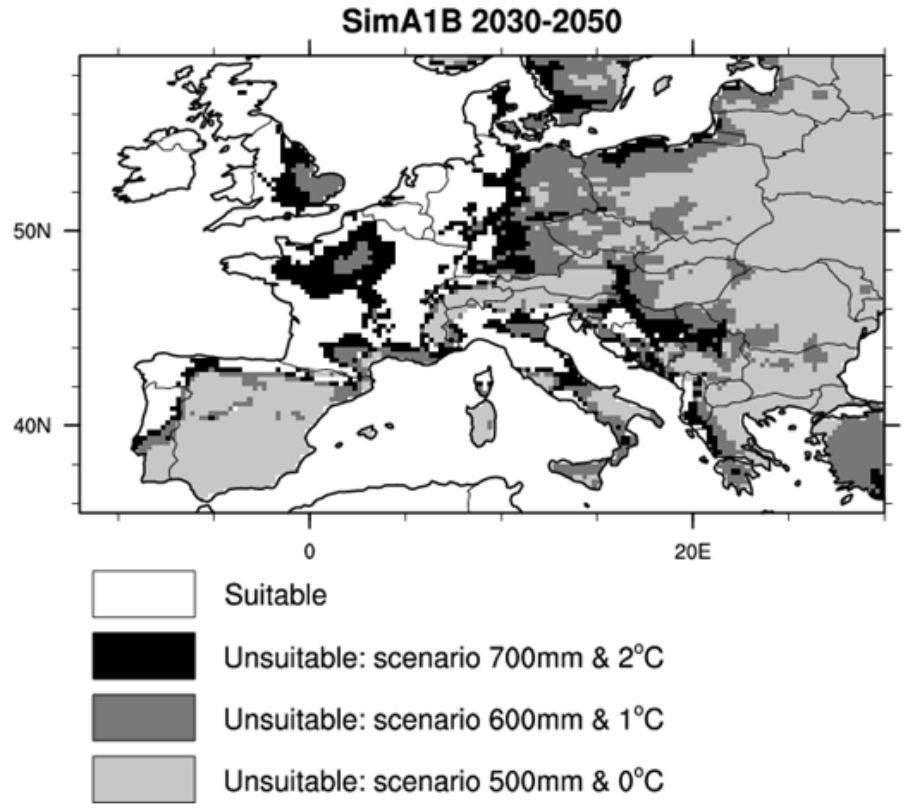

Figure D3. Future overwintering capacity of *Aedes albopictus* to survive based on mean observed January temperatures and annual rainfall. This is carried out for the period 2030-2050 based on the SimA1B scenario experiment (ensemble mean of all RCM experiments). White areas depicts regions for which climate is suitable for the mosquito. The different grey and black shadings depict regions of unsuitability according to different climatic thresholds. The light gray shading depicts strictly unsuitable areas (lower scenario).

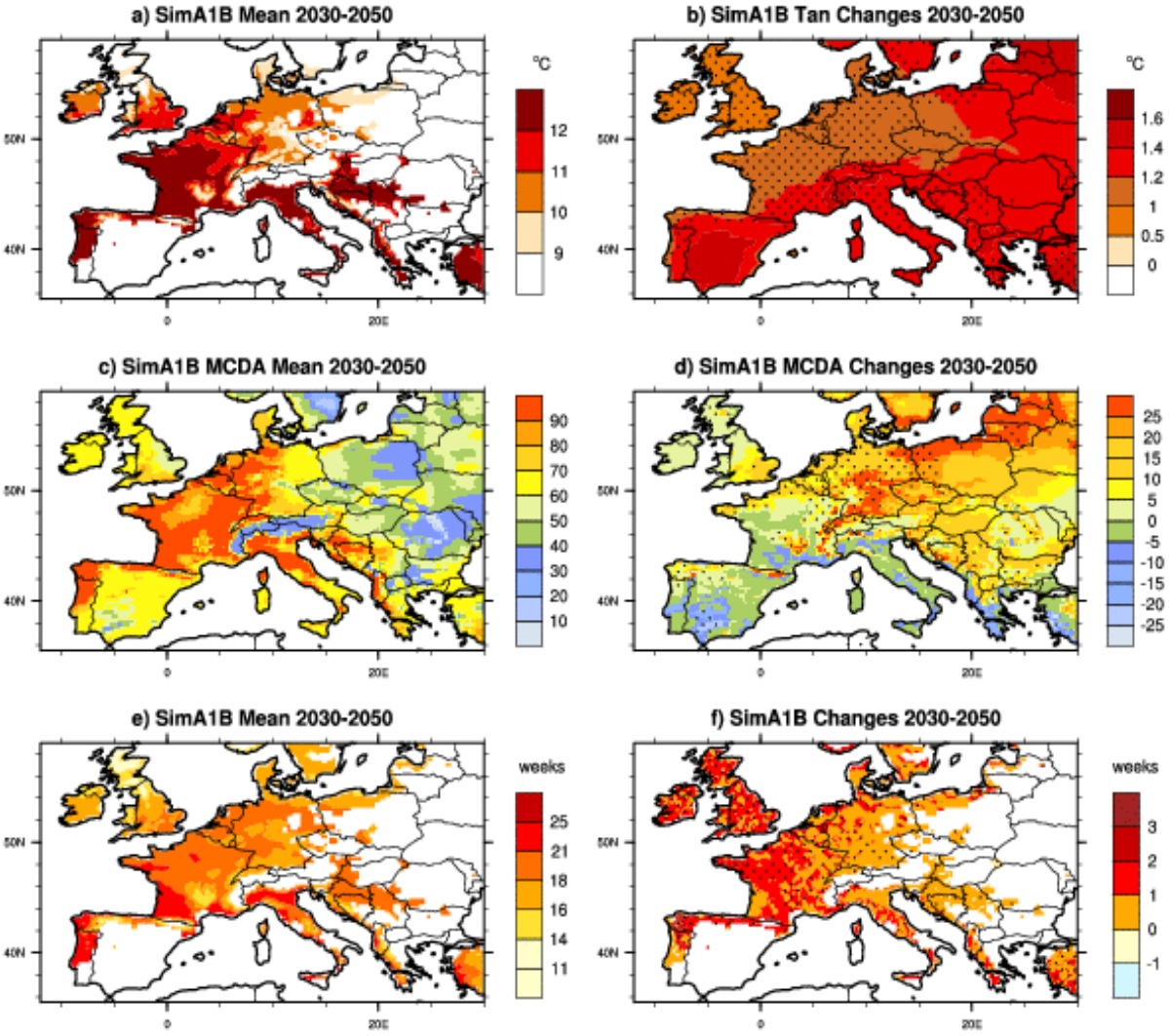

Figure D4. Future climate suitability of *Aedes albopictus* based on different methods (rows). The left column depicts the mean suitability based on the ensemble mean of all RCMs driven projections for 2030-50. The right column shows the future changes (2030-50) with respect to the 1990-2009 climatology. The black dots depict the areas where the simulated mean changes are greater than two times the inter-model ensemble standard deviation (regional climate models ensemble spread). a) Mean future climate suitability based on annual mean temperatures. b) Annual temperature future changes. c) Mean future climate suitability based on the MCDA method. d) Future suitability changes based on the MCDA method. e) Weeks of adult mosquito activity for 2030-50. f) Changes in adult mosquito activity (weeks) for 2030-50

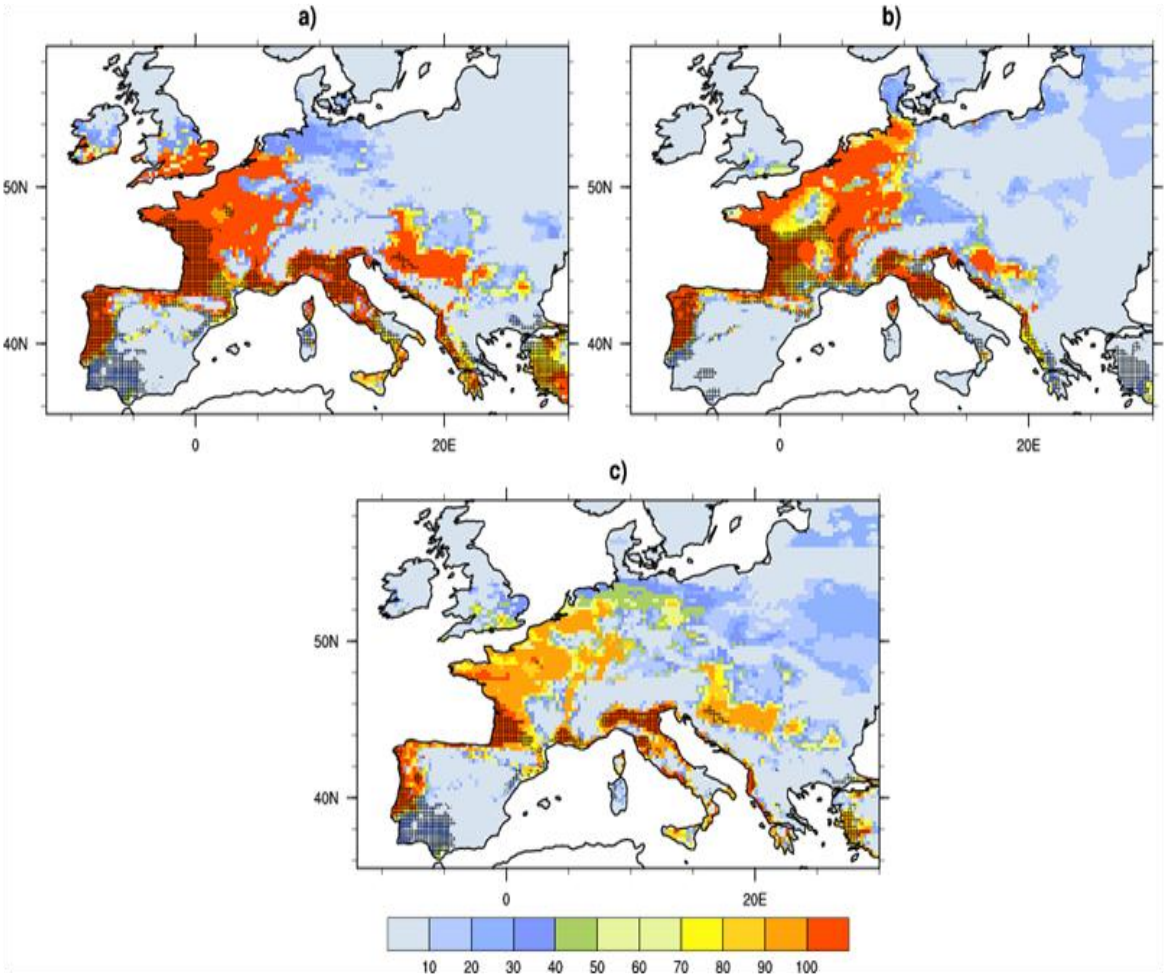

Figure D5. Regions of possible suitability for the *Aedes albopictus* mosquito according to different time periods and climatic thresholds. The horizontal and vertical striped pattern depict suitability for the period 1960-89 based on the EOBS climate observations. The coloured shading depicts the percentage of models agreeing on the mosquito suitability/presence for the period 2030-50 based on the SimA1B RCM ensemble. a) Suitability areas are defined for annual rainfall above 500mm, annual temperatures above 11°C and January temperatures above 0°C. b) Suitability is defined for MCDA output values above 80%. c) The suitability is defined for adult mosquito activity above 20 weeks.

Appendix E

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

The following text explains the derivation of the maps in Figures 8.4 and 8.5, using a biological approach.

The analyses to produce the maps of European *vivax* malaria in Figure 8.4 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:

$$R_o = (ma^2bp^n)/(-ln\ (p)r)$$

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;

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

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:

$$u = f_1/(T-g_1) \text{ days}$$

Where $\boldsymbol{f_1}$ is a thermal sum, measured in degree days, representing the accumulation of temperature units over time to complete the cycle = 36.5°C, $\boldsymbol{g_1}$ 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).

$$n = f_2/(T-g_2) \text{days}$$

Where $\boldsymbol{f_2}$ is a thermal sum, measured in degree days, representing the accumulation of temperature units over time to complete the development = 105 degree days,

$\boldsymbol{g_2}$ 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.

9 Water and food-borne diseases under climate change

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Summary

- Most water, food-borne and enteric pathogens show seasonal variation. The seasonal, environmental, social and climate drivers for many of these pathogens are poorly understood. Seasonal drivers may be directly or indirectly influenced by climate. If an association with climate exists then this implies that incidence may alter under climate change.
- For some pathogens, particularly *Salmonella* and *Campylobacter*, there are intervention programmes in specified animal species at relevant stages of food production at the UK or EU level that are likely to affect more human case numbers (reduction) than those from the current predicted climate change (increase).
- Climate can affect human behaviour, such as food consumption and preparation practices, which can increase the risk of food-borne diseases. In addition, warmer weather and milder winters will allow pathogens such as *Salmonella* to grow more readily in food and will favour flies and other pests that affect food safety.
- A significant proportion of many enteric infections (e.g. salmonellosis) derive from foreign travel. These can be related to work, holidays, visiting families or migration from overseas. Infections from these sources are likely to increase, although not necessarily as a result of climate change.
- The most important mechanisms to prevent and control food- and water-borne diseases are early detection, surveillance and monitoring, horizon scanning, risk assessment, management, communication and preparedness for potential outbreaks.
- Climate change is likely to elevate food prices. As healthy food is often more expensive this may reduce the nutritional quality of dietary intakes and hence the nutritional status of some population groups.
- The safety of food and water is tightly controlled at the National and EU level. This provides the UK with resilience to changes associated with climate and the potential to adapt to the challenges of climate change. There is a need to ensure that existing measures are maintained and strengthened.

Public health recommendations

- Ensure that current measures for protecting against food- and water-borne infections are maintained, strengthened and harmonised to improve the public health infrastructure throughout Europe.
- Strengthening of surveillance and monitoring systems may contribute to adaptation to climate change by detecting local and geographical changes and analysing trends in food- and water-borne diseases.
- Communicating risks related to food and water safety to the industry and public (e.g. the degree to which raw meats are contaminated with *Salmonella* and *Campylobacter*).

- Preventing people from bathing in contaminated coastal and inland waters can be achieved by timelier monitoring and reporting of contaminated beaches, better signage indicating risks, and clearer presentation of overall beach status.

Research needs

- Climate change is likely to alter human behaviour which will have a range of impacts including altering the types of food individuals consume, changing the way that food is prepared, and affecting the frequency with which they bathe in inland waters. There is little research on how these human behaviours will change in the future.
- Our understanding of how food- and water-borne diseases are affected by current climate variability is limited, making it difficult to ascertain the likely impacts of climate change. Studies to examine the factors (drivers) that contribute to seasonal and long term changes in the occurrence of the main enteric pathogens using complex systems approaches are required to model the impacts of climate variability, human behaviour, agricultural systems and other factors affecting transmission.

9.1 Introduction

A review of the range and type of organisms causing food and water-borne diseases provides rather a daunting picture of the diverse sources, environmental reservoirs and transmission routes for gastrointestinal pathogens (Nichols, 2010a) (Table 9.1). However, many of these organisms involve relatively small numbers of cases, often acquired on travels to developing countries. Worldwide, the disease burden from water, sanitation, and hygiene was estimated to be 4.0% of all deaths and 5.7% of the total disease burden (in Disability Adjusted Life Years) occurring worldwide, based on diarrheal diseases, schistosomiasis, trachoma, ascariasis, trichuriasis, and hookworm disease. The burden is largely preventable and should be a priority for global public health policy (Pruss *et al*., 2002). Although the burden in developed countries is less, there are still outbreaks due to contaminated drinking water. For food-borne diseases there is also a significant disease burden (Flint *et al*., 2005), particularly in developing countries, and although estimating the burden is difficult, the World Health Organization has created an initiative to estimate the burden of disease related to food (WHO, 2008). A recent review of infectious intestinal diseases (IID) in the UK (which includes food-borne, waterborne, hygiene and person-to-person related infections) identified that there are around 17 million cases and one million GP consultations per year for IID (Tam *et al*., 2012).

The latest UK climate projections (UKCP09) until the end of the 21st Century are for warmer and drier summers and more extreme weather events, including storms, high winds and heavier rainfall in the winter. This chapter focuses on how local changes in weather patterns associated with climate change may affect the incidence/prevalence of food and water-borne diseases in the UK, how international changes in water availability may affect public health in the UK, and what preparations need to be made to adapt to these changes.

The latest UK climate projections (UKCP09) indicate that climate change in the UK is likely to have some impact on rainfall and the consequent availability and quality of water, which can be contaminated by animal and human faeces following heavy rainfall. Estimates of annual precipitation show very little change overall, but with increased rainfall in winter (up to 33%) along the western side of the UK and a small (few percent) decrease over parts of the Scottish highlands. In the summer estimated rainfall is down by about 40% in parts of the far south of England. For longer term scenarios, there may also be a rise in sea levels resulting from the thermal expansion of oceans and ice-cap melting, which may have an impact on land used for agriculture.

Food is also an essential requirement for human health and changed weather patterns will have both local and global impacts on food production and food security (nutrition and food safety), including in developed countries. Food produced under changed climatic conditions will result in altered use of pesticides, fertilizers and irrigation water, and may lead to new crop and livestock species and altered means of production. There may be increases in food prices that will lead to the consumption of food with lower nutritional quality. Some of the microbiological changes to risk may result from changing food consumption as a result of altered supply chains or new technology for food processing. Climate change could also contribute to the emergence of pathogens that are not currently common.

Advice on assessing national vulnerability, impact and adaptation assessments has been produced by the European Centre for Disease Prevention and Control (ECDC) (Lindgren and Ebi, 2010) along with a knowledge base and quantitative microbial risk assessment tools for food and water-borne

diseases. The potential health impacts in Europe have also been reviewed (Semenza and Menne, 2009).

9.2 Methods

There is a need to predict potential health outcomes that might be expected from changes in climate over the next few decades. For conditions like heat events it is possible to model expected risk against UKCP09 projections of changing climatic factors. This would help characterise and initiate appropriate adaptation strategies. For food- and water-borne diseases a number of other drivers influence infection (e.g. population growth, economic activity, technological change, altered animal husbandry, food supply chains, food imports, and travel patterns). Current public health initiatives with *Salmonella* and *Campylobacter* should result in a decline in these pathogens over coming decades, both in the UK and within Europe. For this chapter, the literature was reviewed for evidence of the impacts of climatic events such as floods and droughts on water and food-borne diseases, as well as the impacts of seasonal and other regular climatic changes (e.g. El Niño) on gastrointestinal infections. The evidence from this provides indications of links between weather/climate and gastrointestinal infections, and informs a view of how climate change might impact on the incidence of gastrointestinal diseases in the UK.

For food and water-borne diseases, the modelling is complicated by the large number of organisms responsible for these illnesses, and for many the mechanisms through which they may be affected by current climate variability are poorly understood. This makes the prediction of future burden of illness difficult. It is also worth recognising that in the future climate change will only be one of a number of issues affecting food and water-borne illnesses. For example in the future, food systems are likely to be very different due to factors such as increasing global affluence and the challenges of feeding a global population rapidly approaching 9 billion. It is also worth recognising that currently food and water are highly regulated systems in developed countries. Therefore, any consideration of climate change impacts should rightly consider the capacity of public and private organisations to adapt to any changes that occur.

9.3 Impacts

9.3.1 Types of food and water related disease

Drinking water from public supplies in England and Wales is of good quality. Sources are regulated by the Environment Agency, the quality by the Drinking Water Inspectorate, the cost by OFWAT (The Water Services Regulation Authority), and outbreaks linked to the supplies are investigated by the Health Protection Agency and local Environmental Health Departments. Drinking water from smaller private water supplies is generally of poorer quality and the infrastructure and management are frequently sub-optimal. The way water is used within the home and other buildings may be an issue in the future if increased ambient temperatures lead to more cases of Legionnaires' disease through growth of *L. pneumophila* in taps, shower heads and other areas that are able to produce an aerosol.

The recreational use of natural bathing in coastal waters is an important part of life, and climate change could have an impact on bathing water quality and on behaviour. The levels of faecal contamination in sea water are thought to be correlated with pathogen risk, and some studies have estimated significant disease burdens from sea water bathing (Brinks *et al*., 2008). Sea water can

also be subject to algal blooms that can include toxic dinoflagellates and diatoms which can cause health problems through shellfish poisoning (Nichols, 2010b), but can also cause respiratory and systemic symptoms (Durando *et al*., 2007). Inland lakes and ponds can similarly be subject to cyanobacterial blooms that can occasionally cause illness (Stewart *et al*., 2006). Such blooms may change in timing and location under climate change.

Water used in food production plays an important part in agricultural productivity, and the microbiological quality of water used by animals, irrigation water and water used for washing crops can contribute to the contamination of foods. In investigating the impact of climate and other drivers for change it is useful to have an understanding of the range of food and water related diseases that can be encountered (Table 9.1), and although some infections are common (e.g. *Campylobacter* and *Salmonella*) the animal sources, vehicles and routes of transmission can be complex.

Table 9.1. Types of water, food and gastrointestinal related disease (modified from Bradley,1970).

Disease type & route	Organism examples
Water-borne by consumption through passive transmission of the agent	*Vibrio cholerae, Salmonella* Typhi, *Shigella* spp., VTEC, *Cryptosporidium* spp., *Dracunculus medinensis*
Water-borne by inhalation through passive transmission of the agent in aerosols	*Legionella* spp., *Ostreopsis* spp., *Mycobacterium avium*
Water-borne by surface exposure (skin, eye, ear, wound) through bathing in contaminated water, flooding	*Cyanobacteria, Pseudomonas aeruginosa, Naegleria fowleri, Acanthamoeba spp., Aeromonas spp., Mycobacterium marinum, M. kansasii, Leptospira* spp.,
Water-borne by injection through contamination of injecting fluid	*Clostridium novyi, C. botulinum. Mycobacterium* spp.
Water-borne by perfusion through contamination of water for dialysis	*Microcystis aeruginosa, Schizothrix calcicola, Anabena floss-aquae*
Water-borne by contamination of devices such as contact lenses, respirators, endoscope washers	Environmental *Mycobacterium* spp., *Acanthamoeba* spp.
Water-borne by contamination of seafood	Dinoflagellate shellfish poisoning, ciguatera poisoning, *Vibrio vulnificus, V. cholerae*
Water-borne by recreational bathing in natural water such as hot springs, freshwater and seawater	*Salmonella* spp., *Campylobacter* spp., *Naegleria fowleri*
Water-borne by recreational bathing in man made swimming pools, hydrotherapy and spa pools	*Cryptosporidium* spp., *Legionella pneumophila*, *Pseudomonas aeruginosa*
Water-borne by occupational exposure, particularly in agriculture	*Schistosoma* spp*., Leptospira* spp.
Water washed diseases through Insufficient water for washing	*Chlamydia trachomatis, Shigella* spp*., Sarcoptes scabiei*
Water-borne parasites that complete their lifecycle in man but do not cause GI disease	*Dracunculus medinensis*
Drought resulting in Insufficient water for crops, animals or to drink, resulting in malnutrition and starvation	*Shigella* spp., *Vibrio cholerae*
Flooding related diseases	*Leptospira* spp., *Salmonella* Typhi, *Vibrio cholerae*,
Damp related and linked to living in conditions where it is damp	Respiratory symptoms related to fungi
Water based infections where the pathogen completes it's lifecycle in water	*D. medinensis, Schistosoma* spp.
Water vectored diseases transmitted by insect vectors that breed in water	Yellow fever virus, dengue virus, West Nile virus, *Wuchereria bancrofti, Plasmodium* spp., *Onchocerca*
Drowning related Infections following partial drowning	*Aeromonas* respiratory infection
Food-borne through organisms derived from agricultural	*Salmonella* spp., VTEC, *Campylobacter* spp.,

Food-borne through contamination from the environment or food manufacturing	*Listeria monocytogenes*
Food-borne infections caused by organisms that do not cause diarrhoea	*Toxoplasma gondii, Mycobacterium bovis, Listeria monocytogenes*
Food-borne through intoxication caused by organisms producing toxin through growing in food	*Clostridium botulinum, C. perfringens, Bacillus cereus, Staphylococcus aureus*
Food-borne through toxic organisms growing in a crop	*Claviceps purpurea*
Organisms causing chronic gastrointestinal infections without diarrhoea	*Helicobacter pylori, Mycobacterium avium* subsp. *Paratuberculosis*
Direct contamination of food from humans	*Staphylococcus aureus*
Acute or chronic disease caused by fungi growing on mouldy crops	*Aspergillus* spp., *Cladosporium* spp.
GI parasites that do not complete their lifecycles within man but cause disease	*Anisakis* spp., Pseudoterranova spp.
GI parasites that complete their lifecycle within man but are not acquired orally	*Schistosoma* spp.
Food-borne parasites that complete their lifecycle within man but do not cause GI disease	*Trichinella spiralis*
Syndromic diseases with no associated pathogen but may be infectious in origin	(Crohn's disease, Brainerd diarrhoea)
Gastrointestinal diseases caused by organisms that are not readily cultivable	*Tropheryma whipplei*
Gastrointestinal illness resulting from the diet and normal bowel flora	(Diverticulosis)
Gastrointestinal illness resulting from the disruption of the normal bowel flora	*Clostridium difficile*
Food-borne by contamination of crops with irrigation water	*Shigella* spp., VTEC.
Food-borne through water as a food component or contamination of foods in manufacturing or retail	*Salmonella* Typhi, *Shigella* spp., *Cryptosporidium* spp.
Opportunistic food or water-borne infections in people with impaired immunity	*Mycobacterium* spp.

9.3.2 Drought

Water availability (access to drinking water) is one of the most important factors in human survival, and events in the past can highlight some of the problems that can occur when supplies are compromised. Drought in developing countries caused by the failure of rains can lead to agricultural collapse, famine and death on a large scale if emergency supplies are not provided from donor countries and organisations. It is important to understand the sorts of infections associated with droughts in developing countries in order to identify potential effects in the UK. Developed countries can encounter problems with overuse of reserves, low groundwater, and redirection of surface supplies, and these can cause restrictions on the water supply.

Changes in disease associated with climatic change have been associated with the El Niño Southern oscillation and La Niña (Warner and Ore, 2006). Drought associated with El Niño has been implicated as one of the factors in the emergence of Nipah virus in Malaysia (Chua, 2010). An outbreak of St. Louis encephalitis virus (SLE) in Florida in 1990 followed a severe springtime drought, which facilitated amplification of the SLE virus among the *Culex nigripalpus* and a portion of the wild bird population (Shaman *et al*., 2003). Modelling of human West Nile virus infections in Mississippi has suggested that transmission is greater in times of drought (Wang *et al*., 2010) and this has also been seen in California (Reisen *et al*., 2009), although climate may have different effects in different areas (Landesman *et al*., 2007). Chikungunya virus infections were associated with drought in coastal

Kenya (Chretien *et al*., 2007). Drought has contributed to Konzo outbreaks associated with people using short-cut methods of cassava processing (Mlingi *et al*., 2011), and to outbreaks of scurvy in Afghanistan (Cheung *et al*., 2003).

Infections and disease in the UK associated with drought are rarely important because drought is less severe than in many countries. However, an examination of outbreaks of water-borne disease in the 20th Century in the UK used a case-control study of rainfall before the outbreaks and in the five previous years (Nichols *et al*., 2009). The study found a significant association between disease outbreaks and heavy rainfall in the previous week and low rainfall in the three weeks before that.

Box 9.1. Drought in Yorkshire

A drought caused a shortfall in drinking water supply in Yorkshire in 1995. The reservoirs feeding Calderdale and Kirklees were at around 12% of their maximum capacity (one year reservoirs) and the demands were significant. The rainfall for the area was 46-50% below the long term averages, and the Met Office estimated that a rainfall as low as this occurs once in 200 to 500 years. Planning for rare weather events needs to factor in climate change, as the chance of a once in 500 year event may change to become more frequent. The interventions in this incident included adoption of a hosepipe ban, tankering of water from the Kielder reservoir in the Northumbrian Water area to the Eccup reservoir supplying Leeds, changing temporarily the rules for using compensation water to keep streams flowing, the possible use of standpipes, rota cuts, disused boreholes, Tees-Ouze transfer and improved leakage control. Up to 600 tankers per day transferred water into local reservoirs. The limitations on tankering were the distance the lorries had to travel, the space and organisation for loading and unloading, the availability of tankers (including transferring them from other European states). This was the first use of large scale tankering for this purpose in the UK and involved around 34 thousand cubic meters per day (tcmd) in a 24 hour operation.

Standpipes were the least preferred option because they are subject to vandalism, are inconvenient to use, hygiene is difficult and they create hardship for the elderly. However, some industries preferred the option of domestic use of standpipes to measures which would cut off water to industrial users for a day at a time. Rota cuts planned to cut off water zones on a 24 hour off / 24 hour on basis and the target for these measures was a 25% reduction in water use. However, cutting off of supply zones puts all distribution water at risk of contamination and a general boil water notice would have been required. Even in protected zones (e.g. hospitals) it would have been necessary to boil all drinking water. More frequent cuts were thought to be a worse option because the amounts of water saved would have been less and there would have been more stress on the system including more burst pipes. The switching of supplies on and off can cause disruption of sediment in the distribution system, causing water to fail some chemical standards (e.g. iron, manganese, aluminium and turbidity), making the water unwholesome temporarily and requiring relaxation of acceptability standards. Special measures were planned to help large livestock farms, the fire services, schools, hospitals and nursing homes. Other issues that needed to be addressed included economic issues, central heating and dishwashing, food production and retail, nursing homes, renal dialysis and dentists. Tankers would be provided for the fire services and bulk storage tanks for nursing homes. There was vandalism of water storage tanks associated with schools and

nursing homes.

A number of issues were highlighted in relation to food safety. Under the Food Safety Act, premises selling food are obliged to provide potable water for reasons of hygiene, and must also provide potable water under the Health and Safety at Work Act. Evidence from the Registered Nursing Homes Association suggested that nursing homes should be included with hospitals and hospices as institutions which should be protected from rota cuts. The rate of water use was estimated to be around 240 litres per resident per day (mostly from laundry). In the event rain arrived before many of the stringent interventions were introduced and the crisis subsided with no detectable impact on health surveillance data. This incident caused reputational damage and highlights the problems that such an incident can create. The forecasts for the rest of the 21st Century suggest lower rainfall in summer months but higher rainfall in winter months. Water companies should be able to plan for these changes.

9.3.3 Floods

Flooding can manifest in a number of forms, including storm surge, flash flood, flood plain inundation, rapid snow melt, and river overflow. In developing countries flooding can lead to a lack of reliable potable water supplies and disruption of sanitation services, with malnutrition, displacement and higher vulnerability of the population. This increases the risk of infectious diseases such as cholera, typhoid fever, diarrhoea, acute respiratory infections and measles. In developed countries the health impacts are mostly non-microbiological, including drowning, car accidents, injury, electrocution, asphyxiation, animal bites etc., and for people whose dwellings are affected there are issues of stress, cleaning, over-exertion and depression (Ahern *et al*., 2005; Du *et al*., 2010) (see also Chapter 7). The expected microbiological problems such as enteric infections are usually not much different from normal in developed countries, although large outbreaks of cholera (Sur *et al*., 2000) and leptospirosis (Gaynor *et al*., 2007; Hajat *et al*., 2005; Lau *et al*., 2010) linked to flooding can be important in developing countries that are largely agricultural. An outbreak of norovirus was associated with exposure to floodwater in Austria (Schmid *et al*., 2005), and there was an increase in leptospirosis in the Czech Republic following extensive flooding in 1997 and 2002 (Zitek and Benes, 2005). Flooding also appears to have caused an increase in a variety of infections in Italy (Marcheggiani *et al*., 2010). Sewage overflow is a risk at the start of flood incidents, particularly in flooded houses, but the exposure risks can be subsequently lower as a result of dilution.

The expected lower summer rains in predictions based on UKCP09, along with higher winter rains and extreme weather means that winter flooding in the UK may be more common in the future. Patz *et al*. (2008) have predicted increases in extreme weather events in parts of the US as a general feature of atmospheric warming. Such flooding events may have significant health effects but the infections related to these are not likely to be dramatically different in 50 years time from those when flooding occurs now if they are occurring in the winter.

Box 9.2. Flooding in Tewkesbury

Exceptional flooding occurred across the UK in June and July 2007 and affected Northern Ireland around the 12th June, the Midlands and East Yorkshire by 15th June, followed by Gloucestershire, Herefordshire, Worcestershire around the 25th June, and had also affected Oxfordshire, Berkshire and South Wales by the end of July. There was heavy rain across Gloucestershire on 20th July 2007 that was equivalent to two months rainfall in one day. This caused extensive flooding with the Teme and Avon rivers at the highest levels ever recorded in some sites. Tewkesbury came to national prominence when it suffered some of the worst flooding in British history. The city is surrounded by a floodplain that is frequently affected by flooding but this generally causes little damage to property, although there were severe floods in 1947 and 1960. The Severn and Avon rivers meet at Tewkesbury and were overwhelmed by up to five inches of rain over five days. The four access roads to the town were rendered impassable by flooding, leaving an embankment that was once a railway line as the only non flooded route for pedestrian or cycle access.

The Mythe water treatment works flooded for the first time in 100 years and there was a consequent loss of potable tap water to around 350,000 people in Tewksbury, Cheltenham and Gloucester over a two week period. Half a metre of flood water covered the site, with buildings, offices and equipment flooded, and the flooding prevented staff from returning for three days. EA staff, fire and rescue services and other organisations quickly put up temporary barriers around the site and restored it to normal service as quickly as possible. The works were out of action for 17 days as a result of the flooding. More than 50 million litres of bottled water was provided to those affected. Following the floods more permanent defences were built around the site and extra pumping equipment installed. The overall cost of flooding at Mythe was estimated at £25 - £35 million, with costs to householders of £25 million. The rescue efforts were thought to have been the biggest in peacetime Britain and the loss of drinking water supply had some similarities to the low water levels in the Yorkshire drought.

The Walham sub-station to the north of Gloucester provides electricity to half a million homes across Gloucestershire and South Wales. It is built on raised ground in the River Severn floodplain. It was necessary to construct 1,000m of flood defence to protect the site. Work on temporary defences to protect the site from flooding was conducted in extremely difficult conditions with EA staff working alongside the fire and rescue services, local authorities, utility companies and the military. Work was completed just in time to avert a major shutdown of the site which could have left half a million homes without power. Power to 42,000 homes from Nearby Castle Mead sub-station was cut whilst temporary defences were put in place. More permanent flood defences have now been constructed around both Walham and Castle Mead sub-stations.

The emergency response involved the Civil Contingencies Committee (CCC) meeting at COBR (Cabinet Office Briefing Rooms) and the HPA initiated a Level 4 Incident in accordance with the Incident Emergency Response Plan (IERP).

Water supply and electricity industries need to ensure there are effective long term plans to protect the many other sites at risk from flooding. This severe flood event should not have been unexpected. Flood maps show these and many other critical sites are vulnerable to flooding. The 2007 floods should be a wake-up call for the water, sewage, gas and electricity industries and others (e.g.

hospitals, care homes, schools, health centres, prisons, police/fire/ambulance stations) to re-assess their flooding risks as flooding is likely to become more common with predicted changes in UK climate.

9.3.4 Heavy rainfall and drinking water

Heavy rainfall can lead to the contamination of drinking water systems. A drinking water outbreak of *Cyclospora* and *Cryptosporidium* in Turkey followed a period of heavy rainfall (Aksoy *et al*., 2007). An outbreak of Hepatitis A in a military camp in Korea followed contamination of the stream supplying drinking water following a period of heavy rain (Lee *et al*., 2008). Analysis of cholera outbreaks in developing countries has shown heavy rainfall to be an important risk factor along with flooding and population dislocation (Griffith *et al*., 2006), and cholera prediction using climate forecasting is becoming increasingly feasible (Anyamba *et al*., 2006; Constantin de *et al*., 2008; Hashizume *et al*., 2010). Severe enterovirus infections have been linked to heavy rainfall in Taiwan (Jean *et al*., 2006).

In developed countries cholera and typhoid are less prevalent and the impacts of heavy rainfall are consequently different. A drinking water outbreak in Finland followed the contamination of a borehole with spring floodwater (Miettinen *et al*., 2001). An outbreak of norovirus associated with oysters in France was linked to contamination of oyster beds by a period of heavy rainfall and overflow of a water treatment works (Doyle *et al*., 2004). In the UK outbreaks of cryptosporidiosis have been linked to heavy rainfall affecting public supplies (Atherton *et al*., 1995; Bridgman *et al*., 1995; Willocks *et al*., 1998) and possibly a private water supply or contaminated surface water associated with a farm visit following heavy rain (Hoek *et al*.,2008). The largest outbreak of cryptosporidiosis recorded in the UK was associated with a supply with a river source where there was prior heavy rainfall (Harrison *et al*., 2002). An *E. coli* O157 (VTEC) outbreak associated with a small stream crossing a beach followed a period of heavy rain and animal manure was thought to be the source (Ihekweazu *et al*., 2006). A VTEC O157 outbreak in Ireland was associated with a private water supply (Mannix *et al*., 2007) and emphasises the potential for contamination of such supplies from surface water. Lake *et al.* examined the relationship between the monthly cryptosporidiosis rate, and the weather and river flows in England and Wales between 1989 and 1996 (Lake *et al*., 2005). There was a positive relationship between the cryptosporidiosis incidence rate and maximum river flow in the current month between April and July. A study of drinking water outbreaks in the 20th Century showed more frequent heavy rainfall in the week before the outbreak, and lower than average rainfall in the three weeks prior to this, compared to control years (Nichols *et al*., 2009). This suggests that changes in rainfall pattern could influence the burden of disease related to drinking water as a result of increased dry periods and occasional periods of heavy rain. The main burden of this excess is likely to be in those with private water supplies, as these have sources that are more influenced by surface water than do public supplies. There has been an improvement in the arrangements for monitoring water quality in private supplies following the Private Water Supplies Regulations in 2009 and improvements in management may reduce disease resulting from these supplies in the medium term. In addition the public supplies generally have better plans for dealing with changes in source water quality than do private supplies, which are commonly contaminated (Richardson *et al*., 2009) and the microbiological quality of which is more influenced by recent

rainfall. Some groundwater may deteriorate in microbiological quality with lower summer rains through the lower water table and reduced dilution of sewage effluent in rivers.

The widespread contamination of groundwater by sewage following heavy rainfall in South Bass Island, Ohio in 2004 resulted in a mixed pathogen outbreak that affected 1,450 residents (Fong *et al*., 2007).

Prediction based on UKCP09 climate projections and the recognised associations between low and heavy rainfall and water-borne outbreaks suggests a possible increase in outbreaks associated with private water supplies as a result of lower summer rainfall, although improved regulation may be a counteracting factor. It is thought that the risk associated with public drinking water supplies will be largely covered by interventions that have been implemented over the last decade to reduce the risks from Cryptosporidium, and there is unlikely to be a change resulting from altered climatic conditions other than those due to water shortage or flooding.

9.3.5 Bathing in coastal and inland waters

Bathing in natural waters carries with it a risk of infection from pathogens contaminating the water which derive from animal, bird and human sources and those of environmental origin. The diseases linked with bathing in contaminated seawater are gastrointestinal (diarrhoea and vomiting), respiratory (colds), eye, ear and skin diseases. Coastal water is contaminated from rivers, particularly following periods of heavy rainfall when untreated sewage from Combined Sewer Outfall (CSO) overflows, and when water is washed off farmland containing animal waste. The demonstration of illness associated with bathing is difficult. Evidence for faecal contamination of coastal waters is strong and there are broad indications that the more contaminated the water is by faeces or sewage the greater is the chance of symptomatic illness associated with bathing in it.

Outbreaks linked to bathing have included enterovirus infections (echovirus 30 and coxsackievirus A1) among travellers in Mexico (Begier *et al*., 2008), a VTEC outbreak among people who had occupied the same part of the beach on the same day (Harrison and Kinra, 2004) and another VTEC outbreak affecting people on holiday in Cornwall, all of whom had stayed at different places locally (Ihekweazu *et al*., 2006). The onset dates were consistent with a point source. The outbreak was caused by cattle faeces and heavy rainfall causing contamination of a freshwater stream which flowed across a beach. There have been outbreaks of respiratory disease in Spain and Italy associated with bathing in waters contaminated with blooms of the marine dinoflagellate *Ostreopsis* (Barroso *et al*., 2008; Durando *et al*., 2007).

Experimental bathing beach studies have been developed as one way of examining the risks related to bathing by getting information on bathers' exposure to faecal indicators and relating the indicator counts to disease as measured by pre-swim and follow-up questionnaires. The first randomised study was conducted over four summers in four UK resorts and 1,216 adults took part (Kay *et al*., 1994). Similar bathing beach studies have been conducted in the Great Lakes (Wade *et al*., 2006), Sydney (Corbett *et al*., 1993) and elsewhere. While the methodologies differ and the indicators linked to gastrointestinal illness show different associations, the broad link between water contamination and self reported illness remains. This relationship between indicators and disease has been used to establish WHO guidelines for recreational waters (Kay *et al*., 1994) and EU legislation. There is a need to avoid risk perception bias (which can result from bathers having a

perception of what they think the study is investigating) in such studies as this has been noted particularly with skin related symptoms (Fleisher and Kay, 2006). There is also a need to take into consideration the other causes of gastrointestinal illness (e.g. particular food types) and the risk behaviours associated with these (Fleisher *et al*., 1993). The standards established by these studies and promoted by WHO have been used to estimate gastrointestinal and respiratory illness burdens (Brinks *et al*., 2008; Turbow *et al*., 2003) and to provide an evidence base for recreational water use (Kay *et al*., 1994). In Southern California between 689,000 and 4,003,000 swimming related gastrointestinal illness episodes and 693,000 respiratory illness episodes were estimated to occur each year and it was estimated that 71% of infections occurred when the water quality standards were satisfactory. There is a large variation in confidence limits associated with this work and a degree of scepticism about the reliability of these estimates.

The associations between water quality and human symptoms have been repeatedly reported in bathing beach studies and the transmission of pathogens that cause gastroenteritis is biologically plausible, but putting a number on how many cases of diarrhoea are associated with bathing in coastal waters is difficult.

Options for reducing the health risks associated with bathing are largely down to reducing the input of faecal contamination to coastal waters or stopping people from bathing. Reduced contamination can be achieved through improvements in sewage treatment, storm water management, control of farm wastes, tackling diffuse sources and depositing contaminated waters further out to sea. Preventing people from bathing at the wrong time and place can be achieved by more timely monitoring (including rapid methods) and reporting of contaminated beaches, better signage indicating risks (particularly beaches regularly failing the standards), and clearer presentation of overall beach status. The interventions to improve bather risks have included the Bathing Water Directive 2006 and its implementation by the Environment Agency. Reduced summer rainfall could also encourage more people to go to the beach.

Inland waters are also subject to faecal pollution and reduced summer rainfall may reduce faecal inputs in summer, based on UKCP09 projections. However, inland lakes may have reduced summer volumes and may be more subject to cyanobacterial blooms. While these can be a problem for drinking water providers (Codd *et al*., 2005), there is no evidence that there is a significant public health burden associated with cyanobacteria in the UK and recreational exposure to blooms are usually controlled locally by Environmental Health Departments using signage. It is likely that any change in blooms as a consequence of climate change would not have much public health impact.

Based on UKCP09 estimates coastal water quality in the summer months may improve, with rivers having lower CSO contamination as a result of reduced summer rainfall, but possible higher contamination in the winter. There have been improvements in bathing water quality over recent years (European Environment Agency, 2009), and these make it difficult to provide reliable estimates of changes in disease burden due to changes in climate.

9.3.6 Food-borne disease

Climate change will lead to a number of environmental effects which may affect the way our food is grown and processed along the entire food chain. These may alter the levels of pathogens and chemicals in food through for example changing use of irrigation water, altered pesticide spraying

regimes or elevated chance of bacterial reproduction during home preparation. Climate change may also directly influence food choice (e.g. elevated consumption of salad during warmer summers).

To investigate the potential impacts of climate change upon food-borne disease it is important to recognise that food is a global commodity. In the UK some of the food available is home grown and some imported. For example in the UK in 2010 60% of vegetables consumed were home grown as opposed to only 12% of fruit (DEFRA, 2011). This means that climate change in other counties will have an impact on some of the food consumed in the UK.

Furthermore it is important to recognise that food-borne disease does not respect international borders. An example of this is that 14% of infectious intestinal disease (IID; includes food-borne and from other transmission routes) is thought to have been acquired abroad (Adak *et al.,* 2002). Food-borne infectious diseases usually have a short incubation period. Chemical and other harmful substances ingested in food can lead to food-borne diseases which manifest themselves over longer timescales. The impacts of climate change upon each will be considered in turn.

Infectious Intestinal Disease

A recent review of IID in the UK identified that there are around 17 million cases per year (5). IID are caused by a variety of organisms and the estimated contribution from each is presented in Table 9.2.

Table 9.2. Incidence rates of IID in the UK. Adapted from (Tam *et al*., 2011).

Organism	Cases per 1000 person years (95% CI)[1]
Bacteria	
C perfringens	1.5 (0.5 to 3.9)
Campylobacter spp.	10.9 (7.4 to 15.9)
E coli O157 (VTEC)	0.3 (0 to 4.3)
Enteroaggregative *E coli*	5.9 (3.4 to 10.2)
Salmonella spp.	0.6 (0.2 to 2.4)
Protozoa	
Cryptosporidium	1.2 (0.4 to 3.9)
Giardia	2.0 (0.7 to 5.6)
Viruses	
Adenovirus	10.2 (6.8 to 15.4)
Astrovirus	5.3 (3 to 9.4)
Norovirus	47.0 (39.1 to 56.5)
Rotavirus	12.7 (8.7 to 18.4)
Sapovirus	26.1 (20.1 to 33.8)

[1] Where more than one detection of method was used the results for the one with the greatest incidence is presented

It is likely that most of the cases due to bacterial infection will be food-borne, but only a minority of the protozoa and viruses will be food-borne in origin (Adak *et al*., 2002). IID which are most likely to be affected by climate change are those which are currently affected by existing climate variability, often exhibit strongly seasonal patterns (Figure 9.1) and may also vary in incidence in response to short-term climate variability.

In terms of climate change, most research has focused on the impacts upon *Salmonella* and *Campylobacter* infections. This is because, in addition to their public heath importance, there is much evidence that these infections are influence by existing climate variability especially temperature (Lake *et al*., 2009). Therefore, under a warmer climate, incidence of these infections may change.

Salmonella infections

There is much evidence that *Salmonella* is sensitive to climate variability and infections are more common in the summer. Even stronger evidence emerges from a number of studies that have shown that during periods of warmer weather *Salmonella* infections are elevated (Fleury *et al*., 2006; Kovats *et al*., 2004; Naumova *et al*., 2007; Nichols, 2010c). There is also a clear biological understanding of the associations with temperature because the organisms can grow in food kept at ambient temperature and are more likely to reach the numbers that can initiate infection during warmer periods (D'Souza *et al*., 2004). The logical extension to this observation is that in a warmer world, *Salmonella* infections will increase. However, the numbers of cases are currently declining in Europe because intervention has proven effective through the vaccination of animals, increased biosecurity and slaughtering out. Additionally, there is evidence that we are becoming more tolerant to the effects of temperature as a society, and over time the influence of temperature on *Salmonella* infections is decreasing (Lake *et al*., 2009). It is therefore inappropriate to predict *Salmonella* cases against estimated future temperatures when there are currently active changes in interventions at the European level and case are on the decline.

It is reasonable to assume that with a warmer climate there could be an increase in cases of *Salmonella* as the bacteria increases its multiplication rate in warmer weather. However, a full assessment of how the disease might change over the next few decades has not been undertaken. This would also need to include the observation that *Salmonella* cases are currently falling as a result of an EU intervention to reduce *Salmonella* contamination of chicken flocks.

Campylobacter infections

Campylobacter infections are also associated with climate variability and a number of studies have shown positive associations with temperature (Fleury *et al*., 2006; Lake *et al*., 2009; Louis *et al*., 2005). However, the situation with *Campylobacter* is more complicated as peak occurrence does not occur during the warmest time of the year (it occurs between mid-June and mid-July). Biologically there is also a less clear understanding of why *Campylobacter* is associated with temperature as the organism does not usually grow outside animal intestines. The transmission of *Campylobacter* to humans is complex ecologically with many hosts and possible transmission routes (Kovats *et al*., 2005). Suggested mechanisms include human behaviour, fly populations (Guerin *et al*., 2008; Hald *et al*., 2004) and hypothesised transmission from faeces or contaminated meats to ready to eat foods (Ekdahl *et al*., 2005; Nichols, 2005). Despite the large body of evidence, the drivers for *Campylobacter* seasonality remain elusive (Kovats *et al.,* 2005; Louis *et al.,* 2005). This makes the prediction of future cases difficult without complex systems analysis to model the relationship between climate variability, behavioural and other factors affecting transmission (Kovats *et al.,* 2005).

Although *Campylobacter* infections have been associated with elevated temperatures our understanding of why this occurs is currently limited. Therefore, it is not possible to predict that cases will rise. *Campylobacter* typing could improve the understanding of disease transmission, which might improve predictions of the impact of climate change.

Other infectious intestinal diseases

There are a number of other IID for which there is evidence of relationships to existing climate variability. *Listeria monocytogenes* is more common in the summer and might be affected by changes in climate. While the organism can grow at cool temperatures, it is able to grow faster at warmer ones (Lianou and Sofos, 2007) and could therefore increase with elevated ambient temperatures. *Vibrio vulnificus* infections can be serious and life threatening. The occurrence of V. *vulnificus* infections has been associated with increased water temperatures (Kim and Jang, 2010; Paz *et al*., 2007). Shellfish contamination by *V. vulnificus* is influenced by water temperature and salinity and counts can increase following flooding (Motes *et al*., 1998). However, there is no indication that UK coastal waters are likely to reach the temperatures where *V. vulnificus* will emerge as a problem as a result of climate change. Shellfish beds can be subject to faecal contamination, resulting in outbreaks of viral infections, particularly norovirus. Bacterial contamination is removed through depuration[1], whereas viral contamination is less readily removed. The contamination of shellfish beds with sewage during the summer may decrease as a result of lower summer river flows, but increase in the winter. Shellfish can also be exposed to dinoflagellate blooms that cause amnesic shellfish poisoning, azaspiracid[2] shellfish poisoning, diarrhoeic shellfish poisoning, neurotoxic shellfish poisoning and paralytic shellfish poisoning (Nichols, 2010b). One of the causes of food poisoning is the incorrect storage of food. Outbreaks linked to *Staphylococcus aureus, Bacillus cereus* and *Clostridium perfringens* are likely to increase with increased ambient temperatures.

Many other IID could be affected by climate change through indirect mechanisms such as changes to animal husbandry or alterations to ecological systems. However, there is currently little evidence on which organisms are most likely to be affected. There are a variety of different mechanisms through which changes to pathogen prevalence could occur (Food and Agriculture Organization, 2008), such as changing animal husbandry affecting animal to animal transmission, or new weather patterns altering the survival of pathogens in the environment. Given this complexity, prioritizing systems and pathogens of most concern is nearly impossible (Food and Agriculture Organization, 2008). Climate change is most likely to affect pathogens with low infective doses (e.g. enteric viruses, Shigella spp., enterohemorrhagic *E. coli* strains and parasitic protozoa) and significant persistence in the environment (e.g. enteric viruses and parasitic protozoa). Pathogens with well shown stress tolerance responses to temperature and pH (e.g. enterohemorrhagic *E. coli* and *Salmonella*) may also enhance their competitiveness under climate change (Food and Agriculture Organization, 2008).

In the UK, warmer waters may increase the frequency of dinoflagellate blooms and contaminated shellfish. These may be additionally affected through changing rainfall patterns altering river flows.

[1] purifying

[2] any of several organic compounds with a complex polycyclic structure, responsible for the toxicity of some mussels.

There are a number of other IIDs in the UK and for many of these there is little information on what the effects of climate change may be.

Other food-borne disease

In addition to IID, climate change may also impact on other forms of food-borne disease. Examples include changes in heavy metal concentrations or pesticide residues in food. Within agriculture, one direct impact of climate change may be variations in seasonal patterns and abundance of pests and diseases. Altered use of pesticides (including herbicides and fungicides) is likely as a response to this (Boxall *et al*., 2010). These responses will differ between crops and between geographical locations. This is exemplified by Chen and McCarl (2001) who examined the likely influence of climate change upon pesticide usage in the United States. Overall, their results indicated that pesticide usage would increase under climate change, but the effect varied by crop and location. Some areas / crops would see pesticide increases, other areas / crops pesticide decreases. The impacts of climate change will not be restricted to crops but may lead to changes in the way that livestock are managed. As an example, elevated temperatures may lead to the presence of new pathogens, vectors, or hosts in livestock (Harrus and Baneth, 2005), resulting in higher use of biocides and veterinary medicines (Kemper, 2008). These could potentially lead to higher concentrations of their residues in food.

Climate change may also affect the transport of contaminants into food such as volatile and dust-associated contamination. The bioavailability of heavy metals may be altered by changing environments and soil properties (Boxall *et al*., 2010). Flooding is a well known mechanism to transport chemicals onto agricultural land and the occurrence of this is likely to increase (Boxall *et al*., 2010). Climate change might affect transport rates but also the nature of the material being transported. For example, after hurricanes Katrina and Rita, the US Geological Survey found evidence that some mobilised flood sediments were derived from the reworking of old, highly contaminated urban soils (Plumlee *et al*., 2007).

9.3.7 Nutritional impacts

There is little research on how climate change may affect the nutritional content of food consumed in the UK (Lake *et al*., 2012). The nutritional content of dietary intakes is mainly governed by the types of food that individuals consume. Many factors affect individual food choices but price is one of the most important. Several assessments have examined the impact of climate change upon world food prices, with most focussing upon grain. These suggest little change, or a small reduction, in grain prices up to a global temperature rise of 3^{o}C. After this, prices will start to rise as production falls (Easterling *et al*., 2007). However, many of these assessments do not consider probable increases in extreme weather events, likely to increase under climate change. When these are taken into account, food prices are likely to be higher than the published assessments. If food price rises occur then individuals may shift to lower cost food items.

Healthier food is often more expensive than less healthy food and so rising prices often result in less healthy food choices (Cummins and Macintyre, 2006). Of particular concern is the observation that food with a high energy density (usually more processed foods with high sugar and fat contents) is often cheaper than its less energy-dense counterparts. Such foods are also less affected by food price rises as food is a smaller component of the total cost. Therefore, climate change induced rising

food prices may reduce the nutritional quality of dietary intakes and lower the nutritional status of some population groups. It could also increase the risk of obesity (Lake *et al*., 2012).

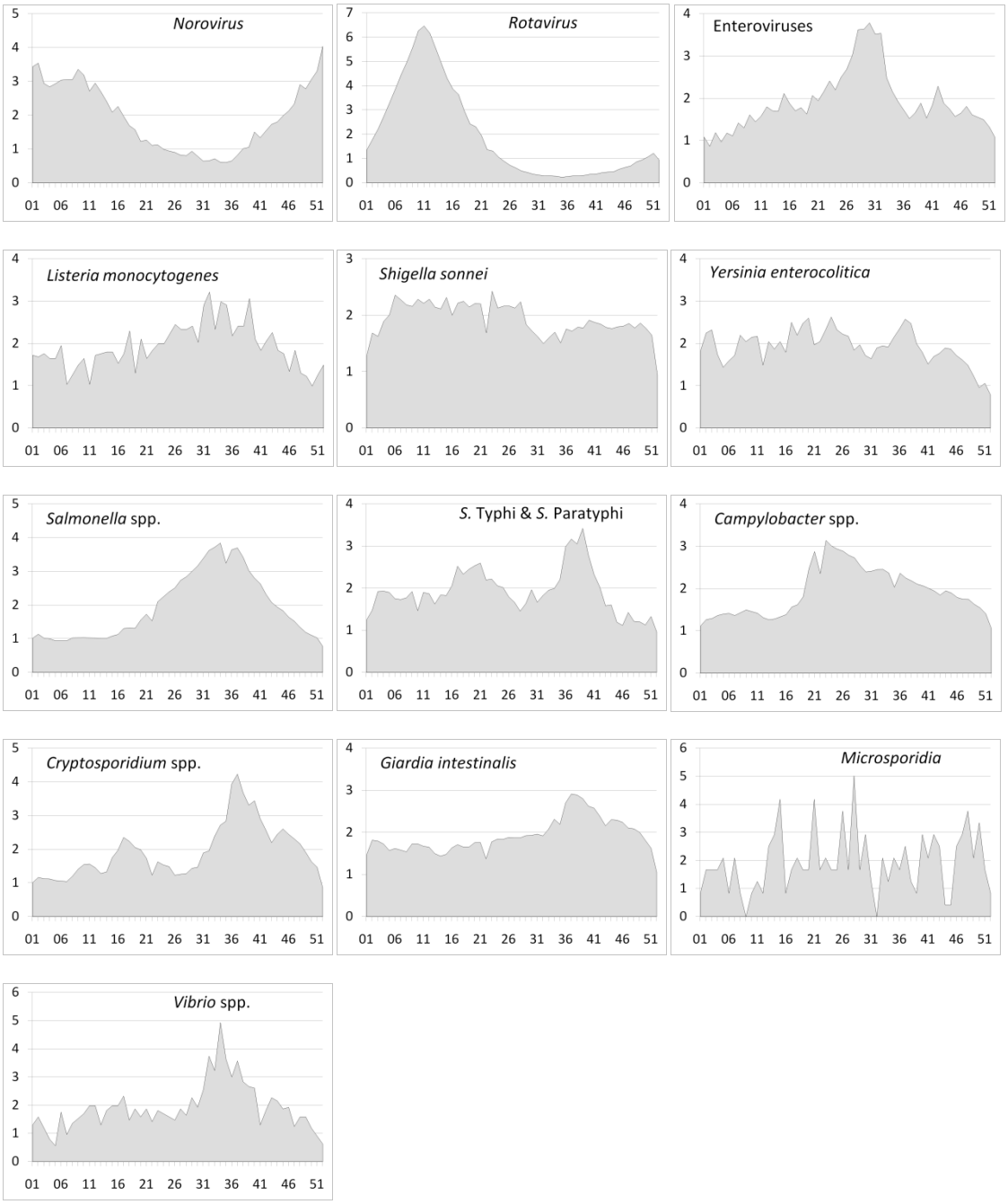

Figure 9.1. Seasonal distribution of common enteric pathogens in the UK (1989 to 2010). the x axes show week of year (1989 to 2010) and are all identical in range; the y axes show cases per week as a percentage of total and the range varies according to species.

Climate change will lead to shifting food belts, implying that food consumed in the future will be sourced from different parts of the globe (Easterling *et al*., 2007). This is important because the geographical source of food may affect its nutritional quality due to different varieties grown, varying soils and growing conditions, differing methods of harvesting, processing and storage. An

example of this is the element selenium which may have a protective effect on several types of cancer. Between 1970 and 2000 there was a 50% reduction in UK dietary selenium intake (Adams *et al.,* 2002) coinciding with a shift of grain importation from the selenium-rich soils of Canada to the relatively selenium-poor soils of the UK. This has led to daily selenium intakes in the UK population being below recommended levels (Finley, 2007). Therefore, climate induced shifts in food production could lead to changes in the nutritional composition of our food.

9.3.9 Legionella – the environment, water in buildings and distribution systems

Legionnaires' disease is predominantly associated with water in buildings, although the 54 related species can be isolated from a wide variety of natural environments (Lee and Nichols, 2010). The occurrence of community acquired pneumonia has lead to an examination of the occurrence of disease under different climatic conditions. A study of cases in the Philadelphia area showed increased illness associated with wet periods and raised humidity (Fisman *et al*., 2005). A similar study in England and Wales found associations with temperature and humidity (Ricketts *et al*., 2009) possibly indicating better survival of *Legionella* in aerosols or greater growth. There is probably still under-ascertainment of this disease and improved diagnosis and follow up could yet improve our understanding of a wider spectrum of sources.

It is reasonable to assume that with a warmer climate there could be an increase in cases of Legionnaires' disease over the next few decades as a result of warmer houses and warmer water in natural environments and a greater need for cooling equipment, although this has not been modelled yet.

9.4 Discussion

9.4.1 Adaptation to food-borne disease

The permitted levels of many disease causing agents in food are set on an international basis through the FAO/WHO Codex Alimentarius Commission (Food and Agriculture Organization, 2006). This produces internationally agreed standards for concentrations in food. Consequently any changes to the levels of disease causing agents in food would have to occur within regulatory limits. Additionally processes within agriculture and food processing are controlled to minimise the risk of food-borne disease. Examples include the EU Food Hygiene Regulations (EU, 2004). All these have the potential to prevent climate change leading to changes in food-borne disease in the UK (Lake *et al*., 2012).

To ensure the success of these regulations, monitoring of the levels of disease causing agents in food is essential. In England this is led by the Food Standards Agency, with input as required from the Health Protection Agency and other public and private organisations. Monitoring is especially important for food sourced outside of the EU where the UK has less influence over production methods. However, monitoring can only test a small quantity of food due to logistical and budgetary constraints. This emphasises the need for HACCP (Hazard Analysis and Critical Control Point) type risk assessment along the food chain to identify areas that are undergoing significant environmental change or rapid agricultural adaptations. In these areas changes to the concentrations of disease causing agents are most likely.

In addition, the monitoring of human illnesses that may result from food consumption is important. The German outbreak of VTEC O104 in 2011 has highlighted the importance of good primary diagnosis (Chattaway *et al*., 2011). In England, this is undertaken by the HPA who use disease surveillance to detect food related outbreaks or epidemics, so that action can be taken to identify and control the source. The HPA is also involved in monitoring longer term trends of food-borne disease. All these should result in measures to protect public health. Examples include the report into the Stanley Royd outbreak of *Salmonella* Typhimurium in 1984, which resulted in 19 deaths (Hugill, 1986), and led to food safety improvements in the UK. The HPA and other Government and academic organisations also conduct epidemiological studies of data on cancer registries which may indicate the longer term effects of pesticides and veterinary medicine residues in food. If food borne outbreaks are detected or abnormalities identified through food monitoring, then food chain traceability is essential to identify the source of contamination. In the UK, this is covered by the EU General Food Law Regulation which contains requirements for food chain traceability.

Climate change may alter the status quo and render current regulations and food monitoring inadequate. This highlights the need for horizon scanning to predict threats and there are a number of such groups in the UK. Examples include the HPA Microbial Risk Assessment Group which has the remit of horizon scanning to identify and assess the threats posed by new or re-emerging infectious diseases. Given the huge uncertainties as to what the specific impacts of climate change will be, this emphasises the importance of food early warning systems (Marvin *et al*., 2009) to identify threats before they occur, or food risk detection systems (Groenevelld *et al*., 2008) to highlight longer term threats to food.

The geographical variability of the health impacts of food- and water-borne diseases are predominantly related to the breakdown of food and water supply chains and not the weather, so are unlikely to be differentially influenced by climate change. There has been a growth of infections such as L. monocytogenes and *Campylobacter* spp. in the elderly, and these could be at further risk in the future with raised temperatures as a result of the dehydration associated with both diarrhoea and hot days.

Reducing and responding to food-borne disease threats appears to be a win-win situation. The public health benefits from reduced food-borne diseases, and the benefits from reducing associated costs on the agricultural sector, manufacturers and retailers through product recalls and loss of consumer confidence. However, there are also monetary costs involved in reducing food-borne illness and it is important to ensure the cost-effectiveness of any interventions.

Food and drinking water safety are tightly controlled at the National and EU level. This provides the UK with resilience to food safety shocks and the potential to adapt to the challenges of climate change. There is a need to ensure that existing food safety measures are maintained and strengthened (Lake *et al*., 2012).

9.4.2 Evidence of the effectiveness of interventions

The response to climate change is predominantly focussed on preparing for emergency response, developing adaptation strategies or attempting mitigation. It is important to understand the likely effectiveness of various adaptations in particular, how adaptations can have co-benefits in mitigation and how adaptive responses can be used in other areas. However, some of the evidence

on the effectiveness of interventions in the water supply area for developing countries is rather poor (Clasen *et al*., 2006). The evidence linking the seasonality of enteric infections with climatic variables and other drivers is also generally poor, with the exception of *Salmonella* where the relationship to temperature seems robust. Because weather appears to be important in disease occurrence, one might expect climate change to influence the burden of disease. However, there is still a strong need for more work identifying the drivers for change with the main pathogens, norovirus, rotavirus and *Campylobacter*, although norovirus and rotavirus are mostly transmitted from person to person.

9.4.3 Measures for the food industry

There is a need for continuing vigilance with respect to the food supply, especially following the large outbreak of VTEC O104 in Germany (Frank *et al*., 2011). New pathogens will emerge and old ones can re-emerge, irrespective of changes in climate, but climate can play a role in such changes. Special care needs to go to ensure foods that are eaten raw are not contaminated by irrigation water or water used for washing. New methods of food production and emerging food types (particularly foods of animal origin) need to undergo international health impact assessments to ensure that current HACCP systems are sufficient to address potential threats.

Recommendations from the 2008 report on the health effects of climate change in the UK (HPA, 2008) suggested educating food producers to highlight the value of continuing efforts to improve the microbiological standards of food at all stages in the food chain, and the importance of temperature regulation.

9.4.4 Measures for the water industry

The water industry in England and Wales has done much to improve the quality of drinking water over the last decade, firstly through tackling Cryptosporidium contamination and secondly through the adoption of Water Safety Plans. These measures should ensure the resilience of water supply to changes in climate. While the changes projected in UKCP09 estimates suggest overall rainfall will not change dramatically, individual water companies need to plan for local shortfalls through adjusting reservoir capacities, leakage, facilitating water movement and examining the targeted use of desalination, grey water and black water reclamation. Emergency response plans need to be regularly reviewed.

The previous report on the health effects of climate change in the UK (HPA, 2008) had emphasised the impact or expected changes on raw water quality, with increased likelihood of cyanobacterial blooms. However, there seem to be few likely health impacts from these. The potential impacts of climate change were thought to be dealt with by well managed water treatment plants ensuring the continuity of safe drinking water. However, private water supplies may pose a problem.

9.4.5 The importance of surveillance and public health

There is a growing list of emerging water-borne and food-borne pathogens, together with a range of more recognised ones. As understanding of sources, vehicles, transmission routes and the overall epidemiology of these pathogens improves, there may be additional evidence that suggests climate change may influence disease occurrence. The German outbreak of VTEC O104 in 2011 has highlighted the importance of good primary diagnosis (Chattaway *et al*., 2011). There is also the need to improve the under-diagnosis of many pathogens identified in infectious intestinal disease

studies (Tam *et al*., 2011). Changes in disease can be followed up rapidly with good local and national responses, such as outbreak investigation, epidemiological analysis, microbiological surveys and risk assessment, and these should facilitate effective controls on changing pathogen numbers.

9.5 Conclusions

Many factors affecting water and food-borne diseases can change in the timescales examined in the UKCP09 climate projections. If we look 50 years ago, the food supply chains were very different, with much more local supply, less imported foods and less developed supply chains. The food-borne pathogen *Campylobacter* was not associated with human disease, the sources of *Listeria monocytogenes* were not understood and VTEC O157 infection had yet to emerge. Water utilities did not know about *Cryptosporidium* or *Legionella*, the problems associated with them and how to prevent these. To predict changes in food-poisoning for 50 years in the future means estimating further changes in the supply chain, in the technologies of agriculture, and the legislation and other interventions that will affect disease occurrence. The UK is a trading nation with a changing population and there is likely to be an increasing percentage of diarrhoeal cases linked to travel abroad in the future. Conflict abroad can cause population movement which can bring a range of infectious diseases into this country, and climate change may contribute to some conflict and population movement. The *E. coli* O104 outbreak in Germany in 2011 has highlighted that with an increasing world population and international movement of food there is the prospect of further emergence of new pathogenic strains that might cause widespread disease. While this is not necessarily induced by climate change, there is a possibility that climate might play a role in emergence, while the timing and spread of novel pathogens is difficult to predict. From the perspective of disease prevention, we need to know more about the drivers for change that influence the main enteric pathogens, including weather related seasonal drivers.

The prevalence of diarrhoeal diseases over the next 50 years will occur as they have in the past 50 years with increases and decreases in the occurrence of individual pathogens. Changes in climate will have an impact on some of the pathogens, but these are likely to be smaller changes than those resulting from other causes including interventions. Climate change is unlikely to drastically alter the rates of water and food-borne diarrhoeal disease in the UK, provided the public health infrastructure is maintained or strengthened. While the most vulnerable drinking water provision is in rural areas with a high percentage of small private supplies, the extent to which climate change will increase risk remains to be determined.

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10 The health co-benefits of policies to reduce greenhouse gas emissions

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Summary

- Policies to reduce greenhouse gas emissions may have collateral effects on public health, in many cases beneficial (health co-benefits). Examples include health co-benefits arising from reduced particulate air pollution as a result of reduced coal combustion, reduced dietary saturated fat consumption from animal products or increased physical activity as result of reduced private car use in urban centres.
- Taking into account these health co-benefits suggests that such policies could offset part, and in some cases all, of the increased costs of mitigating action. In some cases they may achieve health, greenhouse gas and economic benefits simultaneously ('the triple bottom line'). This could make political decisions in favour of climate change mitigation policies particularly attractive in a time of economic difficulty.
- Some policies however may have adverse health effects, for example sealing buildings to increase their energy efficiency could lead to increased exposure to indoor air pollution unless ventilation control is simultaneously improved (Chapter 5). Because of the potential for unintended harms, climate change mitigation policies should be subject to health impact assessment.
- Sustainability of and greenhouse gas emissions from health services should also be assessed as part of the assessment of the performance of health systems.

Public Health Recommendations

- Climate change poses profound threats to health and development at a global scale. There is much that can be done via the mitigation of climate change to reduce those future risks; those actions can also improve health in the near term.
- Policymakers should capitalise on the potential to reduce greenhouse gas emissions and improve health in sectors such as urban transport, food and agriculture, housing and electricity generation. They should also promote 'low carbon' policies within the health sector.
- Public health professionals should work with their counterparts in different sectors at the national and local levels to promote the implementation of such policies.
- The education and training of public health professionals should encompass the health impacts of, and vulnerability and adaptation to climate change, as well as the health co-benefits of strategies to reduce greenhouse gas emissions.

Research needs

- Evaluation of the health effects (both positive and negative) of emerging 'low carbon' technologies and biofuel policies.
- Modelling of macroeconomic effects of greenhouse gas mitigation policies, taking health co-benefits into account.

- Epidemiological studies, including linkage to longer-term modelling of health effects, to evaluate the health effects of large scale implementation of ‘low carbon’ policies in a range of sectors including energy, housing, food and agriculture and transport in high and low income settings.

10.1 Introduction

It has become imperative to move decisively towards an economy based on technologies, policies and lifestyles that greatly reduce greenhouse gas (GHG) emissions in order to reduce the risks of dangerous climate change. Many scientists consider that these risks will greatly increase at global mean temperature rises above 2°C and it will be difficult if not impossible to keep temperature rises below this level, given current trajectories of greenhouse gas emissions (Anderson and Bows, 2011).

The perceived cost of 'low carbon' technologies and policies often constitute barriers to change, but there is also a range of benefits to society that will result from their implementation. For example, there is a growing body of evidence about the potential range of policies which could both address climate change goals and improve health. The term ' health co-benefits' is becoming widely used to describe the ancillary or collateral benefits to health arising from technologies, policies and lifestyles to reduce greenhouse gas emissions in a number of sectors (Haines *et al.,* 2009). These benefits are additional to those which would result from a reduction in projected climate change with its wide spectrum of adverse consequences for humanity and for ecosystems. They could offset part, and in some cases all, of the increased costs of action and make political decisions in favour of low carbon policies more palatable, particularly in a time of economic difficulty.

10.2 Methods

10.2.1 Assessing the potential health benefits from moving towards a more sustainable and less carbon intensive society.

The potential health co-benefits from policies that result in deep cuts in GHG emissions have been modelled in four sectors urban transport, household energy, electricity generation and food and agriculture in both high and low income country settings (Wilkinson *et al.,* 2009,Woodstock *et al.,* 2009, Markandya *et al.,* 2009, Friel *et al.,* 2009). This programme of work focused on a number of case studies to exemplify the magnitude of benefits that might be achieved in both greenhouse gas emission reductions and health outcomes using a number of different assumptions depending on the sector concerned. Health impacts were estimated using WHO Comparative Risk Assessment Methods (WHO, 2004). The objective was to reduce greenhouse gas emissions to a level consistent with the recommendations of the UK Committee on Climate Change (2008), which argued that global emissions should be reduced by at least 50% by 2050 (from a 1990 baseline). They proposed that UK emission reductions of 80% by 2050 would be a minimum contribution to this global target in view of its relatively high per capita emissions and the historical benefits it has enjoyed from fossil fuel combustion. This 2050 target would require around 50% reductions by 2030. Recently the Committee has updated its estimates for the future cuts required and suggested that between 2030 and 2050 the UK will need to make a cut of 62% in GHG emission compared with 46% between now and 2030 (Committee on Climate Change, 2010). This back-loading of emission cuts is necessary in their view because of constraints on early emission reductions.

This chapter focuses on the potential health co-benefits arising from GHG mitigation strategies for the UK population but additional case studies in low and middle income countries were undertaken.

10.3 Results

10.3.1 Household energy

In the case of household energy, the effects of a hypothetical programme to improve energy efficiency in UK housing stock, which is currently responsible for around 26% of the UK's total carbon dioxide emissions, were modelled (Wilkinson *et al.,* 2009). The proposed programme would encompass improvements in insulation by changes to the materials used in the walls, windows, floor and roof, ventilation control, fuel use (substitution of domestic fossil fuel use by electricity) and occupant behaviour. Such a programme would cost between around £3,000-30,000 or more per dwelling depending on factors such as size, age and design but these costs may be partly offset by reduced fuel bills. It would result in 36% reduction in greenhouse gas emissions compared with the 1990 baseline. This would be accompanied by around 5,400 fewer premature deaths annually, particularly as a result of reduced exposure to fine particles ($PM_{2.5}$) which would in turn be largely due to improvements in ventilation control systems. It was assumed that mechanical ventilation with heat recovery was installed in the 20% of houses that were most tightly sealed. The estimate of health benefits is probably conservative because it does not take into account the potential for reduction in cold related deaths. The 50% greenhouse gas reduction target could be attained by switching to less carbon intensive energy sources for electricity generation and as a result of increased efficiency of domestic devices.

10.3.2 Urban Transport

Major public health benefits could also be achieved by policies to reduce private car use and increase active travel (walking and cycling) in urban centres. Three quarters of transport-related emissions of greenhouse gas emissions are from road traffic in the UK. Transport in urban areas accounts for 20% of the distance travelled by vehicles but contributes a disproportionate share of carbon dioxide emissions and air pollution as a result of driving conditions and frequent cold starts (Favez *et al*., 2009). Transport accounts for around 25% of carbon dioxide emissions worldwide and they are rising faster than those from other energy-using sectors. This study compared business-as-usual 2030 projections (without policies for reduction of greenhouse gases) with two alternative scenarios: lower-carbon-emission motor vehicles and increased active travel in London and Delhi (Woodcock *et al.,* 2009). The models took into account changes in physical activity, air pollution and risk of road traffic injury. The health benefits were based on estimates of the association of moderate-intensity physical exercise and reductions in the incidence of pre-specified conditions (including ischemic heart disease, cerebrovascular disease, hypertensive heart disease, dementia, diabetes, breast cancer, colon cancer and depression) from the latest available systematic reviews for every condition except depression. In the case of depression no systematic review was available and therefore a broad search was undertaken and the main studies assessed. For air pollution effects only reductions in fine particles ($PM_{2.5}$) were taken into account although motor vehicles do produce other pollutants.

Greater health benefits were achieved from increased physically active travel than from the resulting reductions in air pollution from lower-carbon-emission motor vehicles however the combination of the two approaches gave the largest effect (Figure 10.1, DALYS =Disability Adjusted Life Years).

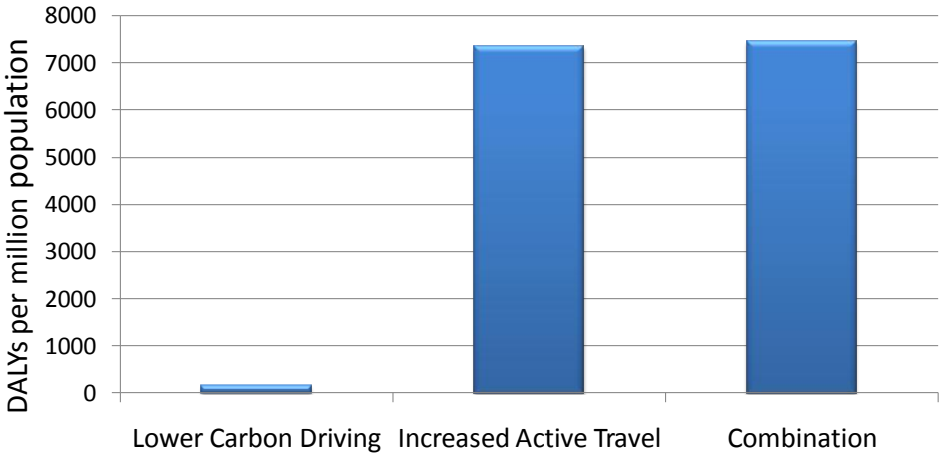

Figure 10.1. Health benefits in London – alternative scenarios. Haines (2012).

The largest health benefits were from reductions in years of life lost from ischaemic heart disease and cerebrovascular disease. A subsequent study of increased active travel in England and Wales suggested that reductions in the burden of disease from diabetes made the largest contribution to NHS costs averted (Jarrett *et al.,* 2012). In addition to the specific health outcomes it is likely that there would be substantial reductions in the prevalence of overweight and obesity. The estimated health benefits greatly exceeded the potential increases in deaths and injuries from road traffic crashes and these could be reduced further by policies to enhance the safety of cyclists and pedestrians.

10.3.3 Electricity generation

This study modelled the effects of a strategy to reduce greenhouse gas emissions in the electricity generation sector in the EU, India and China with the aim of reducing emissions by around 50% in the EU by 2030 and less in India and China in view of their lower baseline emissions (Markandya *et al.,* 2009) (Figure 10.2). These reductions were accomplished by shifting to low carbon technologies and fuels, notably by reducing coal combustion. The effect of these strategies on fine particulate matter ($PM_{2.5}$) concentrations was estimated and the consequent reductions in mortality were assessed. Health benefits of reducing particulate pollution are greatest in India (because of the high baseline level of particulate air pollution) and least in the EU but they still produce worthwhile reductions in mortality. In principle any low carbon technology that does not emit fine particulates or other pollutants has the potential to cut deaths and reduce GHG emissions in this way. Larger benefits could obviously be attained by progressive decarbonisation of the energy supply and a number of renewable technologies show considerable promise, such as solar concentrating power in deserts. To provide everyone in the world with an average European's power consumption would require the equivalent of two 1000km by 1000km squares of solar concentrating power in desert regions, and 1% of the world's deserts could meet the world's current electricity requirements using this technology (MacKay, 2009).

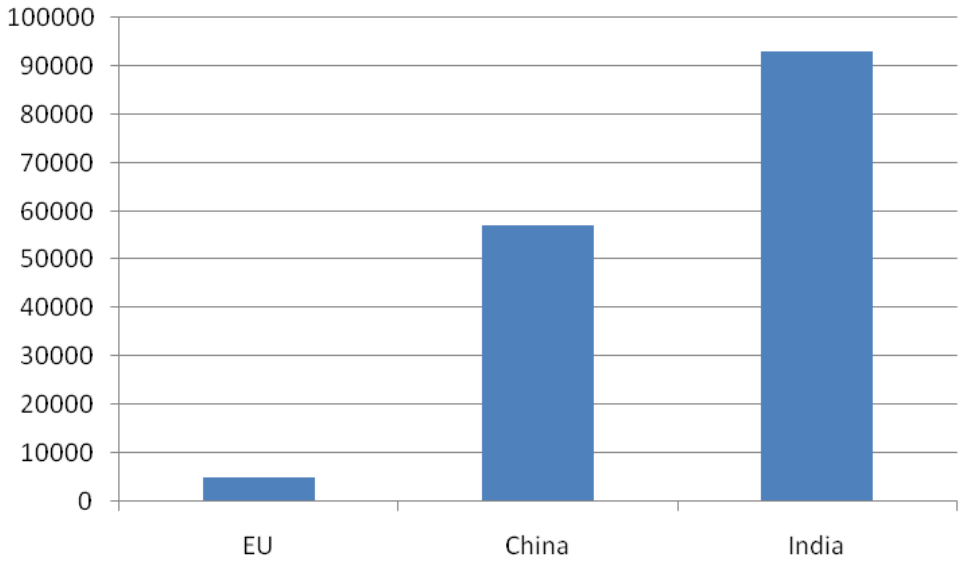

Figure 10.2. Premature Deaths Avoided in 2030 as a result of reduced particulate emissions from low carbon electricity generation. Haines (2012).

10.3.4 Food and agriculture

Agriculture is responsible for around 10-12% of global greenhouse gas emissions. However, major additional contributions arise from deforestation to clear land for crops or livestock. Emissions from the sector are projected to rise substantially over coming decades with a disproportionate contribution from increased demand for animal products in low income countries (FAO, 2003). Around 80% of the sector's emissions are thought to come from livestock production, both nitrous oxide from land used to grow feed crops and methane from ruminants such as cows and sheep. However although the greenhouse gas emissions from monogastric animals such as pigs and chickens are generally lower than those from ruminants, monogastric animals are often dependent on the use of soy or cereals which could be more efficiently consumed directly by humans. Cattle and sheep can also subsist on marginal land which is unsuitable for other types of food production. The emissions of different types of livestock can depend on how animals are reared and the scale of demand. Changing technologies can help to reduce greenhouse gas emissions but not sufficiently to achieve deep cuts in emissions, and for this reason the health effects of a decline in animal product consumption were modelled.

The case study used to illustrate the potential benefits to health of reducing animal product consumption in high consumption societies involved modelling the likely reduction in the burden of disease due to ischaemic heart disease and cerebrovascular disease in the UK as a result of a pro rata reduction in saturated fat and dietary cholesterol intake following a 30% reduction in animal product consumption (Friel *et al.,* 2009). Additional potential benefits, such as reduced incidence of colon cancer as a result of reductions in red meat consumption were not modelled. In the UK it was estimated that the burden of disease from IHD would be reduced by 15% assuming that the saturated fat was replaced by polyunsaturated fat of plant origin. Although in reality complete replacement may not be feasible, additional health benefits should result from increasing fruit and vegetable consumption.

Reducing the consumption of animal products may not be an appropriate policy goal in countries that already have low per capita consumption and in countries where for example nomadic pastoralists depend on their livestock for their livelihoods. Nevertheless, in those countries with high consumption, reducing the production and intake of animal products could make important contributions to greenhouse gas emissions and benefit health.

10.4 Discussion

Although there are uncertainties in assessing both the impacts of climate change and the magnitude of co-benefits from strategies to reduce greenhouse gas emissions, a range of policies can benefit health as well as helping to prevent climate change. The health co-benefits may accrue to individuals (e.g. due to increased physical activity) or to populations (e.g. reduced exposure to air pollution) or to health systems (e.g. through reduced costs of electricity due to increased efficiency). In some cases the value of the health benefits of these policies can partly or wholly offset the costs of implementing them. Uncertainties include those relating to future trends in population health profiles and technological developments as well in our understanding of the relationships between various exposures and health outcomes. Some of these uncertainties can be reduced by additional high quality research. However this is a not a reason for inaction because in many respects a low carbon economy will be a healthier and more sustainable economy than one dependent on increasingly expensive fossil fuels with their attendant problems. Some policies may however have adverse effects on health, for example those which price clean energy beyond the reach of poor populations, or biofuels derived from crops which are grown on land that could be used for food production (Tilman *et al.,* 2009). Thus all climate change mitigation policies should be subject to health impact assessment to ensure that such adverse impacts are anticipated and prevented.

There are of course many barriers to change, including vested interests in existing patterns of development, attachment to high consumption lifestyles and lack of financial incentives to invest in research and implementation of new technologies. Policies to promote low carbon development must be accompanied by action to reduce inequities in access to clean energy for disadvantaged populations if we are to capitalise effectively on opportunities to improve health and environmental sustainability simultaneously.

Greater awareness of the health co-benefits of policies to reduce greenhouse gas emissions should make climate change mitigation more attractive to policymakers in both high and low income countries. Indeed, given the on-going rise in non-communicable disease incidence in the majority of lower-income countries, the bonus health co-benefits from climate change mitigation actions makes those actions even more attractive. This knowledge and rationale should therefore be given greater prominence in international negotiations to limit greenhouse emissions and in national policymaking. In the UK, the costs of caring for patients together with an ageing population makes it imperative to address the underlying causes of common chronic diseases that in many cases are inextricably linked to our societal dependence on a plentiful supply of energy from fossil fuels (Roberts and Edwards, 2010).

The NHS and the HPA can play leadership roles in moving towards a low-carbon economy which capitalises on the potential for improving health. The NHS Sustainable Development Unit has pioneered the assessment of the greenhouse gas emissions from health systems and has set out a number of policies which could drive down emissions through for example procurement of

pharmaceuticals and other products with a lower carbon footprint (NHS Sustainable Development Unit, 2010) or encouraging energy conservation. Providing facilities to encourage staff to work at home and encouraging the consumption of locally sourced more sustainable food can help trigger behaviour change.

Both climate change adaptation and mitigation should be covered in undergraduate and postgraduate curricula for public health professionals so that they feel better able to address the threat of climate change.

Although climate change poses major challenges for health and development, there is much that can be done to promote healthier and low carbon technologies, policies and lifestyles in order to achieve both health and environmental goals.

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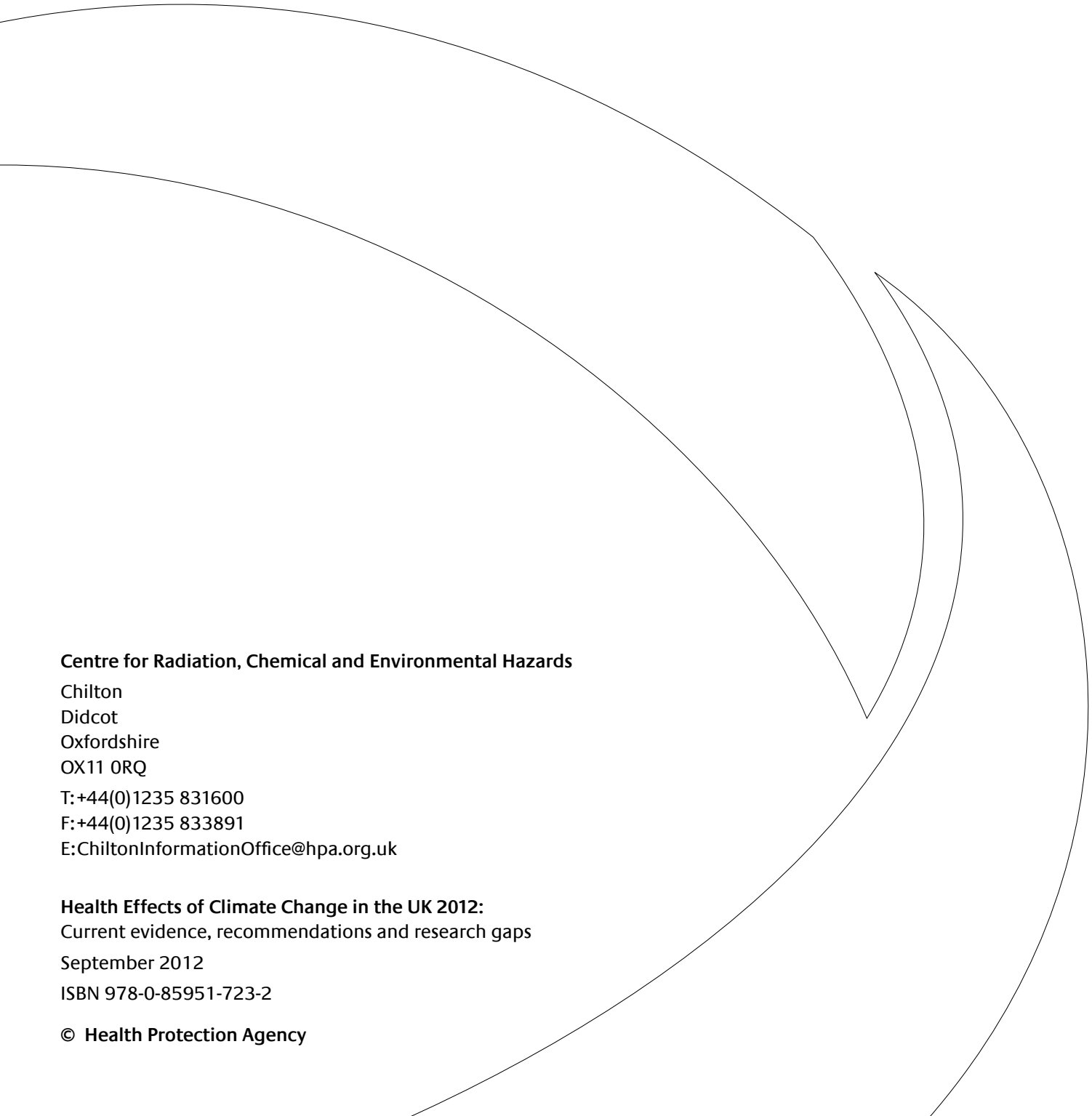

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