UK Health
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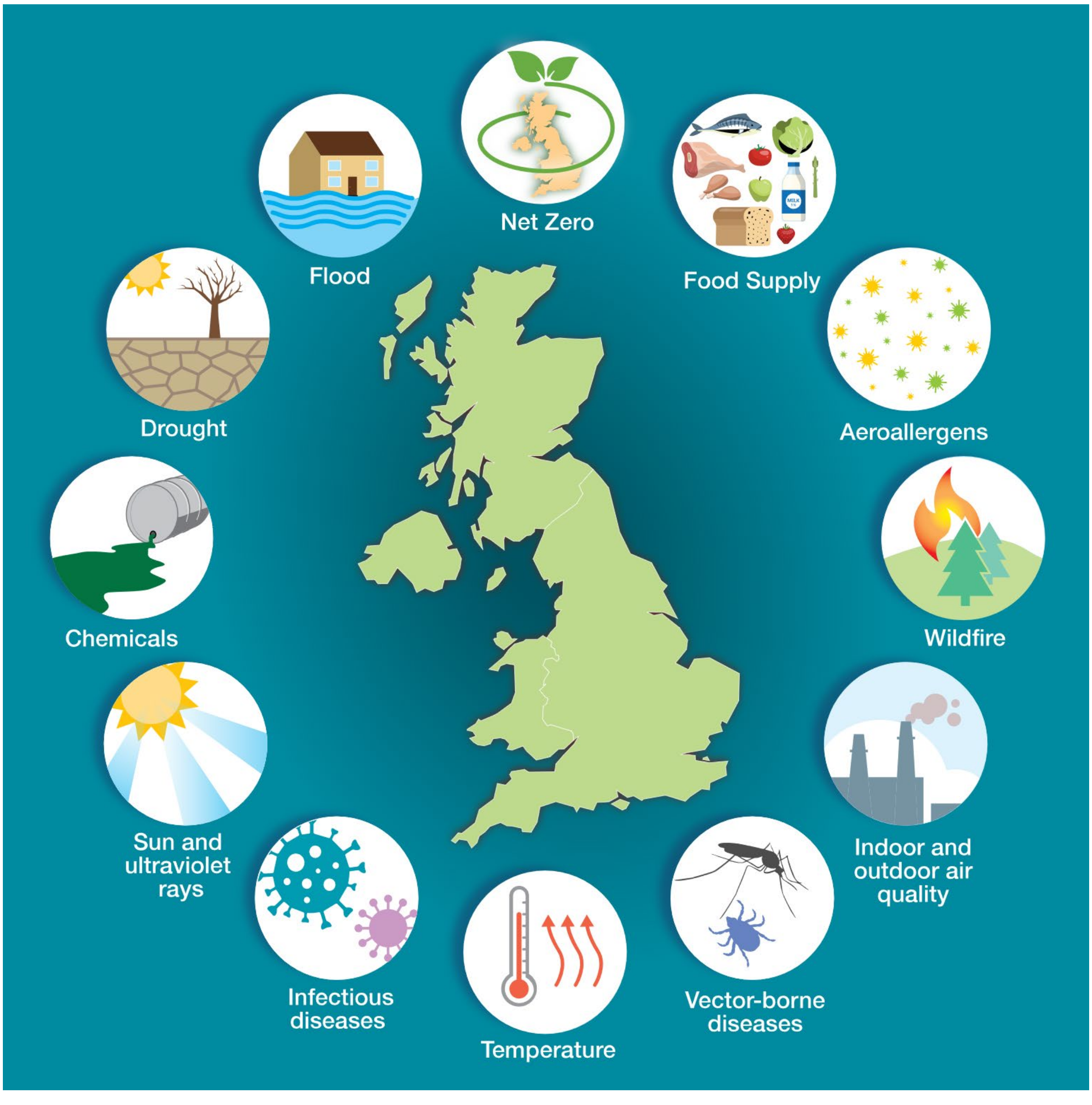
Health Effects of Climate Change (HECC) in the UK: 2023 report

Chapter 4. Impacts of climate change and policy on air pollution and human health



Summary

Air pollution is one of the greatest environmental risks to public health in the UK and is associated with an estimated 29,000 to 43,000 deaths a year. Chapter 4 considers the relationship between climate change and outdoor air pollution and includes new analyses of the health burden from long-term and short-term exposure to air pollution. The chapter was led by expert scientists in the UK Health Security Agency (UKHSA), with contributions from experts in the University of Edinburgh, UK Centre for Ecology and Hydrology and University College London.

Key outdoor air pollutants include particulate matter (PM), nitrogen dioxide (NO_2), and ozone (O_3). Exposure to these is known to reduce life expectancy and is associated with a range of negative health effects, including respiratory and cardiovascular disease. People who live near busy roads are generally exposed to higher concentrations of air pollution. Some people are more susceptible to the health effects of air pollution including those with pre-existing cardiovascular and respiratory disease, young people, pregnant women, older people and low-income communities.

Climate change will have an impact on air pollution. Changes in weather patterns, particularly temperature, rainfall and wind speed, are expected to have an effect on dispersal and concentrations of PM and O_3. However, climate change mitigation measures that reduce emissions of greenhouse gases will help reduce air pollutants and lead to improvements in health outcomes. Evidence shows that emissions of air pollutants will be the dominant driver of air pollution concentrations over the coming decades. In this context, the analyses in the chapter focus on air pollutant emissions rather than climate change projections.

Future air quality in the UK will be determined by recent policy announcements and new legislation, such as the Environment Act 2021, the Environmental Improvement Plan 2023, and the Air Quality Strategy (England), the Environment (Air Quality and Soundscapes) (Wales) Bill, Cleaner Air for Scotland 2 strategy and Clean Air strategy for Northern Ireland. In 2018, the UK government published the 25 Year Environment Plan, which set out the framework and vision for reducing emissions of key air pollutants by setting or meeting legally binding targets.

Analysis of the impacts of air quality controls over the next 2 decades indicate that by 2050, exposure to $PM_{2.5}$ will decrease by between 28% and 36%, and NO_2 exposure will decrease by between 35% and 49%, depending on the region. By 2050, annual mortality attributable to the effects of long-term exposure to $PM_{2.5}$ and NO_2 is projected to decrease roughly by between 25% and 37% compared with a 2018 baseline, depending on future demographic change in the UK. Reducing emissions, therefore, results in benefits to population health. However, due to the complex chemistry in the air, as NO_2 levels decrease, there can be local increases in O_3 in urban centres, which may increase some harms to health. The analyses in the chapter show that annual estimated emergency respiratory hospital admissions associated with short-term

effects from O_3 exposure are projected to increase by between 4% and 12% by 2050 from a 2018 baseline of 60,488, depending on demographic change.

Overall, these projections reflect significant improvements in outdoor air quality and associated reductions in the burden of long-term health impacts arising from recent and upcoming air quality controls, and the greater the efforts to mitigate emissions of air pollutants, the greater the improvement in air quality.

The results presented in the chapter have several implications for public health. Although air pollutant emission controls will reduce concentrations of some air pollutants (such as $PM_{2.5}$ and NO_2), there may be local increases in O_3, which may be exacerbated during heatwaves. Therefore, provision of localised alerting and monitoring will become particularly important. Ensuring that public health professionals and other stakeholders have accessible and high-quality information to provide health advice and raise awareness will continue to be important.

This chapter highlights several priority research gaps, including the need to:

- develop modelling techniques that consider climate-driven changes in both pollutant emissions and meteorology at spatial resolutions sufficient to quantify exposures to improve health impact assessment projections
- develop an evidence base estimating the economic benefits associated with improvements in health from air pollution reduction as a result of strategies to tackle climate change
- undertake further work to consider the potential combined effects of air pollution and other environment stressors that may be affected by climate change, such as heat and aeroallergens
- advance our understanding of how climate change-driven behavioural change could modify personal exposure to air pollution, such as increased time spent outdoors in warmer temperatures

The Department for Environment, Food and Rural Affairs (Defra), Department of Health and Social Care (DHSC) and UKHSA are undertaking a comprehensive review of how to communicate air quality information. The aim is to ensure members of the public, and vulnerable groups in particular, have what they need to protect themselves. UKHSA has also been developing an Air Pollution Exposure Surveillance (APES) vulnerability indicator which aims to indicate areas where population vulnerability to air pollution is elevated.

Contents

Chapter 4. Impacts of climate change and policy on air pollution and human health

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1. Introduction

In the UK, air pollution is the greatest environmental risk to public health. Outdoor air pollution is estimated to have an effect equivalent to 29,000 to 43,000 deaths a year in the UK (1), and exposure to ambient air pollution contributes to 4.2 million deaths annually worldwide (2). Particulate matter (PM_{10} and $PM_{2.5}$, particles with aerodynamic diameter less than 10 micrometres (μm) and 2.5μm, respectively, together referred to as 'PM'), nitrogen dioxide (NO_2), and ozone (O_3) are key pollutants that reduce life expectancy and have been associated with a range of health effects, including respiratory and cardiovascular disease, and can contribute to cognitive decline and dementia. As well as negative effects on human health, air pollution also damages crops and vegetation (O_3) and can contribute to eutrophication of sensitive habitats, leading to impacts on ecosystems (NO_2).

PM has a range of anthropogenic and natural sources including fuel combustion in vehicles and power plants, chemical reactions in the air and wind-blown dust, among others; finer particles have a larger impact on health as they can penetrate deeper into the lungs. The main sources of NO_2 are from combustion in vehicles, power stations, and heating, though there are some minor sources from soil processes and lightning. In addition, O_3 is not directly emitted but formed through complex chemical reactions of precursors (such as volatile organic compounds (VOCs), methane (CH_4) and NO_2) in the presence of sunlight.

Climate change can affect concentrations of air pollutants through influencing the emission, transformation, distribution and deposition processes related to air pollution. Weather patterns are also linked to the frequency of air pollution episodes; for example, more frequent and intense heatwaves may lead to more air pollution episodes, particularly O_3 episodes in summer. Such episodes are driven by low wind speeds and stagnation of air masses (leading to a lack of dispersal of pollution), as well as potential increases in temperature-sensitive emissions of precursors from vegetation and soils, moorland fires, and inflow of pollution from mainland Europe (transboundary pollution). Winter pollution episodes are projected to reduce as cold stagnation is expected to decrease in winter, though the consensus on the exact nature of the impact of climate change on atmospheric 'blocking' events (that lead to stagnation) is still unclear (3).

Atmospheric processes are expected to be affected directly and indirectly by climate change and this may affect the distribution and concentrations of air pollutants (Figures 1a and 1b, (4 to 6)). However, in the UK, ambient air pollution concentrations are mainly driven by emissions (anthropogenic and natural), and research has shown that changes in annual air pollution concentrations in the next few decades will be primarily driven by changes in anthropogenic emissions as opposed to changes in climate and meteorology (7, 8).

In light of this, the chapter here aims to highlight the impacts that climate change may have on air pollution in the UK over the coming decades and the implications for health, including considerations for population exposure as well as epidemiology and toxicology. As emissions are the main determinant of air pollution concentrations in the UK, environmental policies designed to reduce emissions of air pollutants and greenhouse gases (GHGs) will be highlighted, as well as how this relates to climate change. This includes how the air pollution mixture may change and what the implications of this may be for public health. Finally, key gaps and priorities for further research and public health practice are identified.

1.1 Summary of the past 3 reports

Over the last 20 years, chapters reviewing the available evidence on air pollution, health and the impacts of climate change have been included in all 3 editions of the ‘Health Effects of Climate Change in the UK (HECC)’ report.

In the 2002 HECC report, the air pollution chapter focused on short-term effects and quantified mortality and respiratory hospital admissions associated with exposure to O_3 (9). It reported that winter pollution episodes were expected to decrease with reductions in air pollutant emissions and consequent reduction in harms to health. However, there was an expected small increase in the number of O_3 episodes in the summer periods (9).

The 2008 HECC report focused on the health effects of chronic exposure to ambient air pollution, shifting the focus from the impacts of short-term episodes, and highlighted the increase of NO_2 in urban centres related to the use of diesel vehicles (10).

Finally, the 2012 HECC report found that emissions are generally a stronger driver of ground-level O_3 concentrations in the UK than changes in temperature, following model simulations of projected air pollutant concentrations up to 2030 by assuming different climate-based emission scenarios and a +5°C temperature change (11). It was noted that there is a need to investigate the health effects related to exposure to O_3 considering temperature as potential effect modifier (11).

1.2 Advances since the last HECC report: state of the policy landscape and the current science

Recent policy announcements and new legislation, such as the Environment Act 2021 (applies in England), the Environmental Improvement Plan 2023 and the Air Quality Strategy (England), are expected to lead to changes in air quality.

In 2018, the UK government published the 25 Year Environment Plan (25YEP) (12), which set out the framework and vision for reducing emissions of 5 key air pollutants ($PM_{2.5}$, NOx, non-methane VOCs, SO_2, and ammonia (NH_3)) by setting or meeting legally binding targets. The Environment Act 2021 requires 2 air quality targets to be set for $PM_{2.5}$ in England (13). These targets are set out in the Environmental Improvement Plan (first revision of the 25YEP) 2023, including a legal target to reduce population exposure to $PM_{2.5}$ by 35% in 2040 compared to

2018 levels, with a new interim target to reduce population exposure by 22% by the end of January 2028 (14). There are also legal targets to reduce ambient pollutant concentrations, including a new interim target of 12μg/m^3 for $PM_{2.5}$ by the end of January 2028, and legal emission reduction targets by 2030 relative to 2005 levels for $PM_{2.5}$, NO_x, SO_2, non-methane VOCs and NH_3 (13 to 15). The updated Air Quality Strategy (applies in England) will provide a strategic framework for local authorities and other partners, setting out their powers, responsibilities, and further actions needed. The Environment (Air Quality and Soundscapes) (Wales) Bill is a key step in bringing forward measures that will contribute to improvements in air quality in Wales, including a framework for setting air quality targets in Wales (16). The Cleaner Air for Scotland 2 (CAFS2) strategy 2021 sets out how the Scottish Government and its partner organisations propose to further reduce air pollution over the period 2021 to 2026 (17). Section 9.5 of the Clean Air Strategy 2019 focuses on actions under way to tackle air pollution in Northern Ireland, and a separate Clean Air Strategy for Northern Ireland is being prepared by the Department of Agriculture Environment and Rural Affairs (DAERA) (18).

A Net Zero Strategy to decarbonise our economy (19) will also influence our future exposure to air pollutants (see Chapter 14). As air pollutants and GHGs often have common sources (for example combustion processes related to power generation, transport, and heating), measures to reduce GHG emissions (for example switching to cleaner energy sources, through renewable technologies such as wind and solar power, and electric vehicles) can mitigate climate change and benefit health through improving air quality. However, some measures such as biomass burning may increase exposure to air pollution depending on the proximity of emissions to areas of population. Therefore, to achieve substantial gains and maximise the health benefits, the challenges of air pollution and climate change need to be considered together.

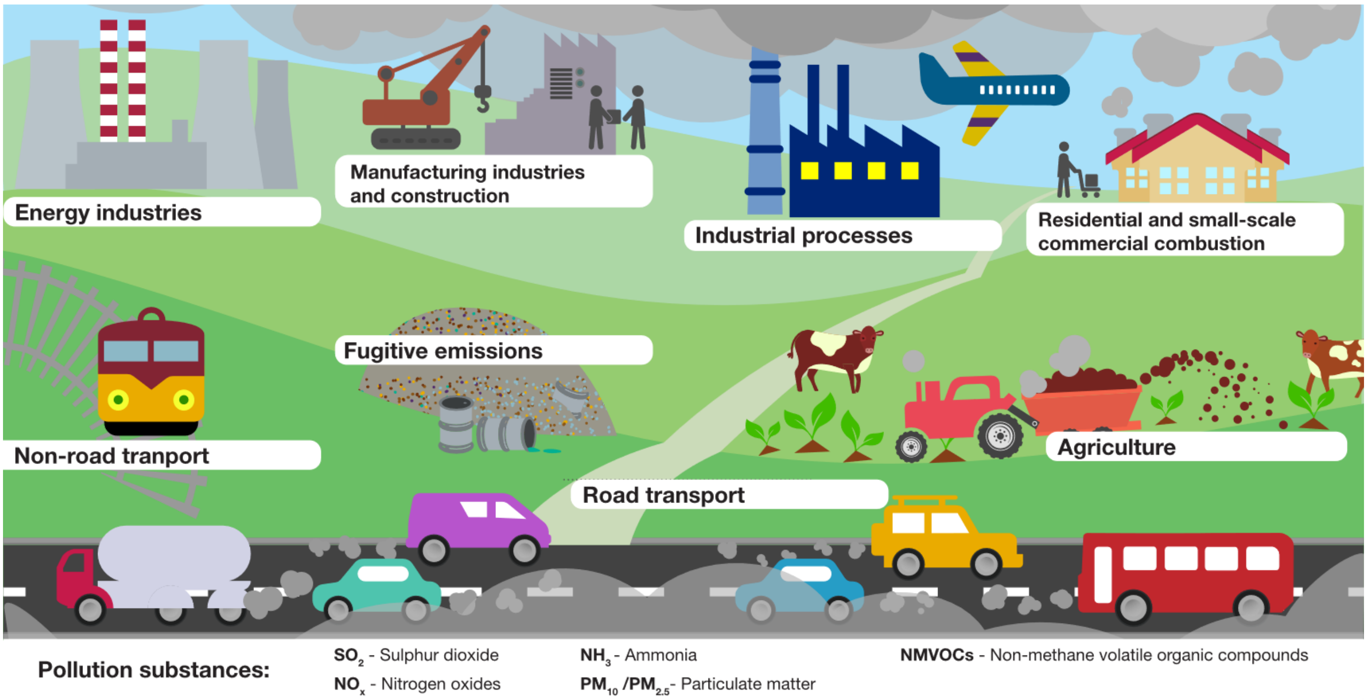
There have been several advancements in the scientific understanding of the impacts of climate change on air quality and of the links between air pollution and human health since the last HECC report was published (11). We summarise the findings of key reports and work on this topic in the following section.

1.2.1 Impacts of climate change on air pollution concentrations

Climate change can affect air pollution through changes in meteorology, which impacts emission, transformation, and deposition of air pollutants. This may be through changes in temperature, which affect emissions of some precursors, and photochemical processing. Air pollution is removed by precipitation (wet removal), and by direct contact with surfaces (dry deposition), but it is uncertain how changes in precipitation patterns might impact air pollution levels in the future. Weather patterns, and particularly the low wind speeds associated with high-pressure systems over the UK (often related to heatwaves in summer and cold snaps in winter), are also commonly linked to slow dispersal of pollution, leading to episodes of air pollution. The impacts of climate change on air quality in the UK, as well as the impact of environmental and net zero policies on air quality (and both in combination) have been recently authoritatively reviewed in detail (20) so will not be repeated here, but some of the key findings of this review are highlighted in the following paragraphs.

Regarding the impacts of climate change on air pollution in the UK, the ‘Royal Society 2021’ report (hereafter termed ‘RS2021’) reports that more frequent and intense heatwaves may lead to more air pollution episodes, particularly O_3 episodes in summer, as well as potential increases in temperature-sensitive emissions of O_3 precursors from vegetation and soils, moorland fires, and transboundary pollution. It is likely that O_3 will remain an important pollutant at global and regional scales out to 2050 and beyond, with likely increases in stratosphere-troposphere exchange of O_3, and in emissions of CH_4 – the predominant precursor for O_3 formation – from wetlands and from wildfires. These increases may be partially offset by more destruction of O_3 over the Atlantic (driven by higher humidity), and studies looking at the impact of climate change on meteorology alone (that is, excluding effects of meteorology on emissions) show a small decrease in background O_3 (20). However, O_3 may remain at similar concentrations due to these competing effects on concentrations.

Figure 1a. Sources of air pollution



Text version of Figure 1a.

Figure 1a shows sources of air pollution, which include energy industries, manufacturing and construction industries, industrial processes, road and non-road transport, fugitive emissions, residential and small-scale combustion, and agriculture. Air pollutants emitted include sulphur dioxide (SO_2), ammonia (NH_3), non-methane volatile organic compounds (NMVOCs), nitrogen oxides (NO_x), and particulate matter (PM_{10} and $PM_{2.5}$).

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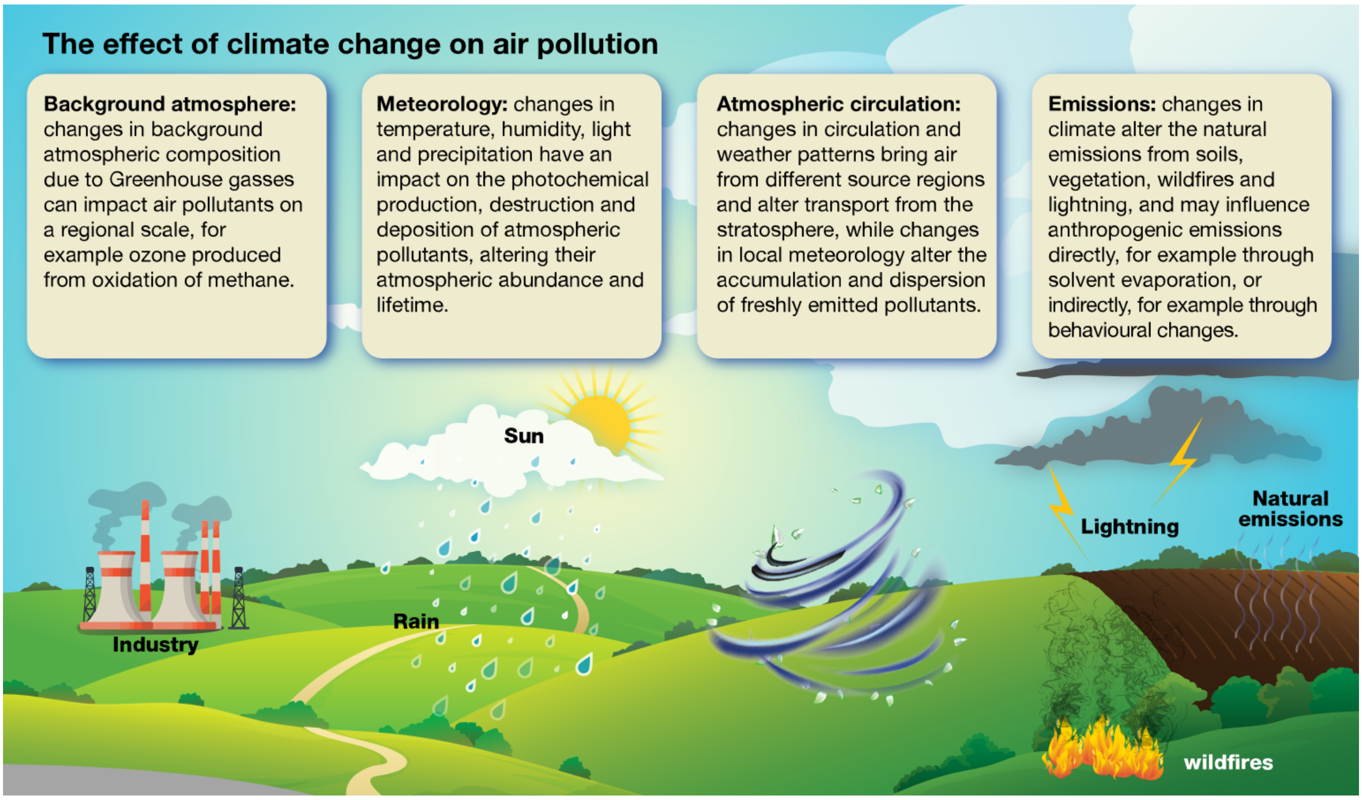
Figure 1b. The effects of climate change on ambient air pollution



The effect of climate change on air pollution

Background atmosphere: changes in background atmospheric composition due to Greenhouse gasses can impact air pollutants on a regional scale, for example ozone produced from oxidation of methane.

Meteorology: changes in temperature, humidity, light and precipitation have an impact on the photochemical production, destruction and deposition of atmospheric pollutants, altering their atmospheric abundance and lifetime.

Atmospheric circulation: changes in circulation and weather patterns bring air from different source regions and alter transport from the stratosphere, while changes in local meteorology alter the accumulation and dispersion of freshly emitted pollutants.

Emissions: changes in climate alter the natural emissions from soils, vegetation, wildfires and lightning, and may influence anthropogenic emissions directly, for example through solvent evaporation, or indirectly, for example through behavioural changes.

Text version of Figure 1b.

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Background atmosphere – changes in background atmospheric composition due to greenhouse gases can impact air pollutants on a regional scale, for example ozone produced from oxidation of methane.

Meteorology – changes in temperature, humidity, light and precipitation have an impact on the photochemical production, destruction and deposition of atmospheric pollutants, altering their atmospheric abundance and lifetime.

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End of text version of Figure 1b.

Meteorological changes may lead to more wet removal of air pollution (if precipitation increases in a warmer world), which could reduce pollution levels, but increases in secondary PM from higher VOC emissions in a warmer world (particularly biogenic emissions) and NH_3 is a concern. Non-methane VOCs (NMVOCs) comprise a wide variety of organic compounds that can harm health, with sources including industrial processes, household products and agriculture. While CH_4 and NMVOCs can contribute to ambient O_3 concentrations, human exposure to NMVOCs has been increasingly associated with indoor environments rather than outdoor air, due to their sources (such as solvents, air fresheners and cleaning products) and because people spend the majority of their time indoors (15, 21). Thus, the health impacts associated with the exposure to NMVOCs are discussed in Chapter 5. NH_3 emissions associated with agriculture (such as fertiliser application) are expected to increase due to warming soils (which retain less NH_3 when warmed), with potential negative impacts on ecosystems, and on human health by contributing to PM concentrations (20). Interventions in the agricultural sector aiming to improve air quality by reducing NH_3 emissions were discussed in Public Health England's (PHE) 'Review of Air Quality Interventions', and England's 'Chief Medical Officer's Annual Report on Air Pollution' (22, 23). The health effects linked to NH_3 are mostly indirect through the formation of particles, hence NH_3 emissions are not a focus here, but the impacts from exposure to PM are considered.

In summary, the RS2021 report concludes that ambient concentrations of PM will likely decline in future due to policy controls on air pollution, but health risks from exposure to PM will remain in 2050, with indoor exposure becoming more important (see Chapter 5). NO_2 is expected to decline, primarily due to controls on vehicle exhaust emissions and electrification of the vehicle fleet. This will lead to locally increased O_3, at least in the short-term, and most prominently in urban areas close to emission sources. The report also notes that further improvements to air quality are projected to occur as a result of net zero policies (see Chapter 14) with significant air quality co-benefits expected from actions taken to reach net zero, through switching to renewable and low-emission power sources and reducing energy use through efficiency and demand reduction (20).

1.2.2 Health effects of air pollution

Since the last HECC report in 2012 (11), the evidence on the health effects associated with air pollution has continued to grow. A recent summary of the health evidence associated with exposure to air pollution is available in England's 'Chief Medical Officer's Annual Report on Air Pollution' (23). Exposure to air pollution is not just associated with cardiovascular and respiratory disease but can contribute to the development of a wide range of health outcomes, from early life effects to increased evidence of associations with dementia and cognitive decline (23 to 25).

Methodological advancements such as enhanced statistical methods have improved our ability to estimate mortality burdens associated with low levels of air pollution (26, 27), and epidemiological cohort studies have identified negative health effects at concentrations as low as $3\mu g/m^3$ for $PM_{2.5}$ (28). Some people are more susceptible to the effects of air pollution, such as those with pre-existing cardiovascular and respiratory disease, young people, pregnant women and older people. Members of the population who live or work near busy roads will be exposed to higher concentrations of air pollution, and low-income communities are often particularly susceptible to the effects of air pollution (23, 29). Interventions to improve air quality should consider the vulnerabilities of the exposed population to prevent increases in health or social inequalities (30). UKHSA has been developing an Air Pollution Exposure Surveillance (APES) vulnerability indicator, which aims to indicate areas where population vulnerability to air pollution may be high (31, 32).

Considering the expected changes in atmospheric processes and land use (for instance, desertification and soil erosion) associated with climate change, impacts on the occurrence, frequency, and duration of locally-generated pollution episodes, but also of events linked to transboundary air pollution, may be expected in the coming years. Transboundary pollution contributes to O_3 concentrations in the UK, through transport of O_3 and precursors, and hemispheric background levels linked to CH_4 concentrations. Transboundary contributions to PM in the UK may include emissions from transport from the Benelux region (Belgium, Netherlands and Luxembourg) when weather patterns are favourable for this to occur, as well as from large dust events (such as from the Sahara), wildfires, and even volcanic eruptions.

Changes in climate may affect the transport and other physicochemical processes of naturally-produced pollutants arriving in the UK, and as emission controls act to reduce anthropogenic pollution, natural sources will become more important. As sources of pollutants change, a better understanding of the sources or constituents of PM pollutants that are most toxic will continue to be an area of interest to help understand health effects and target interventions. A number of different sources and constituents of PM are associated with adverse health outcomes across short- or long-term exposure periods with PM components associated with combustion and road traffic having received the most attention (24, 28). The Committee on the Medical Effects of Air Pollutants (COMEAP) recently concluded that different constituents are likely to have different toxicological actions and be of varying toxicity. However, the evidence does not consistently indicate specific PM components that are more toxic than others so a focus on the metric of $PM_{2.5}$ is considered most appropriate for evaluating health impacts and regulating PM concentrations (28). This is an area that needs to be kept under review as sources of air pollution change.

Modelling studies of climate change emission scenarios that include air pollutant information across the UK and Europe suggest there will be benefits to health from reduced air pollution levels associated with legislation and technological improvements (for instance, (7, 33, 34). Air pollutant emissions associated with the Representative Concentration Pathways (RCP) emission scenarios have been investigated. A previous review found that as a result of emission controls, O_3- and PM-related health burdens generally decreased, but for polluted regions, higher temperatures can increase O_3-related health burdens (especially in southern Europe) and also saw some greater $PM_{2.5}$ health burdens in these emission regions (8). Under RCP8.5 (high emission scenario), the large increase in CH_4 is expected to lead to increases in global and European excess O_3-respiratory-related mortalities in 2100.

Climate models are generally large-scale and lower resolution due to computational demands related to their complexity, large (usually global) domains, and simulations often covering extended timeframes. Consequently, climate models are typically run at spatial resolutions of approximately 100km or greater (with some downscaled to approximately 50km), with implications for how well population exposures can be represented. A small number of studies have used air quality models to investigate health impacts from air pollution under different RCP scenarios at finer resolution. A UK-focused study investigated mortality burdens attributable to air pollution in 2050 under different RCP air pollutant emission scenarios by simulating future concentrations using the Air Quality in the Unified Model (AQUM) at 12km horizontal resolution (including changes in air pollutant emissions, and biogenic emissions responding to climate change, with constant meteorology) (35). Regional annual means of maximum daily mean 8-hour O_3 were 62 micrograms per cubic metre ($\mu g/m^3$) to $80\mu g/m^3$ for present day (2000), and increased by $4\mu g/m^3$ to $9\mu g/m^3$ in all scenarios, with some increases more than $12\mu g/m^3$ (approximately 40%) and up to $18\mu g/m^3$ (approximately 50%) higher across much of the central and southern regions of England, in turn leading to increases in associated O_3-related health impacts (35). Impacts on hospital admissions have also been studied with the same AQUM model (12km), with respiratory hospitalisations in England associated with changes in $PM_{2.5}$, O_3 and NO_2 under RCPs 2.6, 6.0, and 8.5 projected to be lower in the 2050s by 10,478, 8,659, and 14,661, respectively (36). However, since concentrations of air pollutants can vary on very fine scales, detailed characterisation of population exposures to air pollutants for Health Impact Assessment (HIA) requires more spatially granular estimates of air pollution associated with climate change. Since the above analyses using AQUM, there have been updated recommendations for air pollution concentration response coefficients for various adverse health outcomes and advice to use higher resolution data not coarser than 10km for quantitative health impact assessments (28).

1.3 Topics covered in the chapter

As the impacts of climate change on air pollution have been recently extensively and authoritatively reviewed (20), we do not repeat this analysis here. In this context and that described above, the remainder of the chapter focuses on investigating:

- potential health effects of transboundary pollution, specifically from natural sources (section 2)
- quantification of likely future impacts on human health in the UK from changes in air quality driven by emission changes associated with current policy, using a quantitative HIA (applying new concentration response coefficients and using high-resolution air pollutant concentration data) (section 3)
- the combined health effects from temperature and air pollution, in particular the influence of temperature on the health effects from exposures to O_3 (section 4)

2. Transboundary pollution (natural sources) and health effects

Transboundary pollutants may have noticeable effects on future levels of air pollution in the UK. The physical state of the atmosphere and the Earth's surface can strongly affect air quality, by affecting emissions, transport, mixing, transformation and deposition processes. These effects are most evident in short-term changes in air quality related to changes in weather conditions, for example air pollution episodes that can affect the UK, such as the spring 2014 episode that led to elevated PM levels, with negative effects on health (37, 38). However, changes in air quality over longer time scales may become more significant in the future following possible changes in weather patterns due to climate change (39).

The Working Group on Effects under the United Nations Economic Commission for Europe (UNECE) Air Convention was set up following discussions on the Convention on Long-Range Transboundary Air Pollution (CLRTAP) and provides information on the degree and geographical extent of the impacts of major air pollutants, such as NO_2 and PM, on health and the environment (40). A recent study found that most ground level O_3 in the UK derives from background hemispheric sources and transboundary transport from Europe, which may influence how actions are targeted to control pollution (41). In fact, the UK is a net sink for surface O_3 due to chemical loss through reaction with NO and this sink will likely reduce in future as NO_x emissions continue to fall (42).

For naturally-produced particles in particular, climate change may influence the meteorological conditions that determine their emissions, as well as their fate after leaving the source areas. A report by the UK Air Quality Expert Group (AQEG) found that in future years, contributions to PM concentrations from natural sources, such as ash from wildfires, dust resuspended from arid areas, and occasionally volcanic eruptions, will be an increasing proportion of transboundary PM as anthropogenic sources decrease (43).

Sand and dust storms are strongly associated with meteorological conditions, as their primary driver is wind together with dry conditions that are associated with a series of other linked climatic factors, such as global warming, deforestation, and climate anomalies (6). These warmer, dryer conditions with the addition of deforestation are extending arid lands, which are the largest source of dust, resulting in an increase in dust pollution (39, 44).

It has been recognised that climate change affects the routes and paths taken by desert dust around the globe (44, 45). Also, studies have shown that climate change will affect the volcanic sulphate aerosol life cycle and radiative forcing (46), and the effects of climate change on radiative forcing may vary depending on the types of gases released from a volcanic eruption, and the type and size of the eruption (46). Extreme weather events and deglaciation may increase the number of eruptions, and heavy rainfall has been linked to several previous volcanic eruptions (46). There is a link between ice decline and increased volcanic activity in

Iceland at the end of the last glacial period, which is related to a reduction of pressure on the surface due to the receding ice (47). It is suggested that this reduction in pressure increases the production of mantle melt and changes the storage capacity within the crust. There is the potential for even smaller changes in surface loading altering the likelihood of eruptions in this region (48).

In the following paragraphs, the expected health impacts in the UK of transported desert dust particles and ash from volcanic eruptions are discussed, whilst the climate and health impacts of wildfires are discussed in Chapter 10.

2.1 Natural particles: desert dust

De Sario and colleagues reviewed the scientific evidence on the effects of climate-related hazards on respiratory health from epidemiological studies, including climate events that are interlinked with air quality, such as desert dust storms (49). The study focused mostly on the methodological challenges in the analyses of the effect of desert dust storms. Some of these challenges include:

- the different definitions of the dust events used in different areas; due to their nature the occurrence and intensity of the desert dust intrusions are strongly linked to the specific local context
- the fact that since back-trajectory analysis is considered to be a marker of desert dust transport from the source regions; in urban areas dust events may be underestimated due the presence of other, mainly anthropogenic, sources of dust

Reviews of studies linking desert dust exposure to health effects have been published in the last decade. European studies reporting on the health effects, including all-cause and cause-specific (cardiovascular, respiratory, cerebrovascular) mortality and asthma exacerbation associated with the exposure to Sahara Desert dust particles were reviewed (50). The review concluded that there was no significant association of fine particles and no clear association of the coarser particles with mortality during dust intrusions (50). In the systematic review of global studies, both positive and negative associations for respiratory and cardiovascular mortality have been reported for PM_{10} of desert dust, with the inconsistency attributed to the diversity in the geographical distribution of study areas, dust source areas, and dust trajectories (51). A review of approaches used to estimate the short-term effects of desert dust on human health reported differences in: effect estimates between studies that might be related to differences in the distances of the locations studied from the dust sources (that is, the location of the desert); exposure assessment strategies and epidemiological study designs and chemical composition of dust and carried species in the various regions (for example, as a result of mixing with anthropogenic emissions) (52).

A more recent review appraised a number of experimental studies that had identified mechanisms and endpoints underlying epidemiological evidence of an impact of desert dust on cardiovascular and respiratory health (53). The toxicological studies reviewed provided support for biological plausibility of epidemiological associations between desert dust particles and events including exacerbation of asthma, hospitalization for respiratory infections, and seasonal allergic rhinitis. In vitro studies showed that the suspended desert dust particles may provide a platform to intermix with chemicals on its surfaces, thereby increasing the bioreactivity of fine particles during dust storm episodes (53). Therefore, the toxicity of aerosols in urban environments could be enhanced through mineral dust surface reactions.

Dust storms can transport PM air pollutants, and potential allergens over thousands of kilometres from their source. The main sources of global desert dust include the Sahara, central and eastern Asia, the Middle East, Australia and parts of the western United States (54). Long-range transport of mineral dust to the UK is relatively common (occurring several times a year) and can affect levels of air pollution (55, 56). A study of the outflow of Saharan dust in the period from 1980 to 2020 concluded that the increase in Saharan surface heating conditions in the most recent years favours dust transport to the Mediterranean Sea and Europe at higher altitudes and in shorter timescales than decades ago (45). However, air masses originating over North Africa can also transfer natural and anthropogenic particles from Europe, as occurred during the European heatwave in 2003 with the arrival of fine particles from forest fires in south-western Europe (57).

During spring 2014, there was a period of increased PM concentrations in the UK, which was widely linked to being caused by a Saharan dust plume. Vieno and colleagues investigated the sources of PM causing the elevated levels and revealed that during the early stages of the episode, the Saharan dust plume was restricted to higher elevations (37). Significant ground-level Saharan desert dust mostly occurred towards the end of the pollution episode, whereas early PM increases were driven mainly by anthropogenic emissions from sources external to the UK (37). There were 2 periods of poor air quality, one from 12 to 14 March and the second from 29 March to 3 April 2014. A real-time syndromic surveillance study was conducted during this period of increased PM concentrations, finding that both periods saw a statistically significant increase in the rate of NHS 111 calls regarding breathing difficulty, as well as increases in GP consultations and sentinel emergency department attendances for asthma, breathlessness and wheezing (58). It is important to note, however, that during the second period of elevated PM, there was greater media attention, which may have possibly led to additional consultations from patients who may not usually seek medical help. Mortality and emergency hospitalisations associated with $PM_{2.5}$ pollution during this period were estimated (using a HIA) to be around 600 deaths brought forward (3.9% of the total mortality for these days), and an estimated 1,500 emergency respiratory hospitalisations; this is thought to be double that which would have occurred in the absence of the air pollution episode (38).

2.2 Natural particles: volcanic ash

Most studies have identified short-term and reversible respiratory health effects of the exposure to volcanic ash (59). The acute (short-term) effects of heavy ash fall include asthma attacks and bronchitis, increased breathlessness and coughing, tightness in the chest and wheezing, which is caused by irritation of the airways lining, due to the inhalation of fine particles (60). It is strongly suspected that the subgroups with the highest risk of experiencing adverse effects from volcanic ash inhalation are those with pre-existing conditions, in particular respiratory conditions (59). Studies have also described the potential harms of volcanic emissions (including ash and gases) on the human cardiovascular system, birth outcomes, acute injury and gastroenteritis, dental fluorosis, the increased use of healthcare medications and services and acute eye irritation (61, 62).

Although the UK does not contain any active volcanoes, volcanic ash can travel thousands of kilometres from its source (63), and the resuspension of volcanic ash by wind during and after volcanic eruptions is considered a significant hazard for longer-term and population-scale impacts (62). The UK has seen the impact of this long-range transport in recent years; in 2010 the eruption of Eyjafjallajökull in Iceland caused major disruption to air travel throughout Europe (64). On April 16, the ash cloud was situated over the UK but stayed at high altitudes due to weather conditions, though there were some reports in Scotland and other areas of the UK of light ash fall (65). Although the volcanic eruption was of medium size, due to its explosive nature and the prevailing north-westerly winds, the ash cloud was pushed south-easterly from Iceland into the UK and European air space (66). Following the eruption of Eyjafjallajökull, syndromic surveillance data was analysed to determine the health impacts within the UK (65). The study concluded that this eruption had no significant impact on public health in the UK, finding no significant increase in practitioner-based diagnosis of allergic rhinitis, respiratory conditions, and asthma during the period the ash cloud was above the UK compared with expected numbers (65). Although the 2010 eruption is not thought to have impacted on health within the UK, a study estimating the potential number of deaths and emergency hospital admissions in the UK associated with emissions from a hypothetical large fissure volcanic eruption in Iceland, assuming a 6-week and a 5-month exposure period, found that up to 3,350 deaths, 4,030 emergency cardiovascular hospital admissions and 6,493 respiratory hospital admissions could be associated with the exposure to volcanic emissions from this type of eruption (67).

In summary, the contribution of naturally-produced transboundary pollutants to the UK ambient air pollution mixture may potentially increase due to the effects of climate change. Whilst there is evidence for the effect of climate change on an increase in dust events, the exact links between climate change and the potential for changes to volcanic eruption frequency, and the mechanics of the aerosol life cycle and volcanic plumes, still requires further research. Studies have reported some associations of health impacts with desert dust events and volcanic eruptions, however further investigation is needed to assess the future health impacts in the UK.

3. Health impact assessment for future air pollution

As outlined earlier (section 1.2), many studies have been conducted on the impact of climate change alone and the impacts of emissions changes alone on air pollution, concluding that while climate change can have an impact on air quality (reviewed in detail in (20), see also Figures 1a and 1b), changes in emissions are by far the greatest driver of air pollution concentrations in the UK in the next few decades and thus on the associated future health impacts. The focus here is therefore on future health burdens associated with emissions changes expected corresponding to current environmental policies.

An up-to-date quantitative HIA was performed, using detailed atmospheric modelling at a spatial scale appropriate for HIA (sub-10km resolution, as recommended by COMEAP). A prognostic chemistry transport model was used with the latest official UK and European emissions data sets, and the most recent recommendations on exposure-response relationships from COMEAP were incorporated. Full details of the study have been reported previously (68, 69), and so only key details are reported here.

3.1 Methods

3.1.1 Air pollution modelling and emissions

The EMEP4UK atmospheric chemistry transport model is a nested version (focused on the UK (37)) of the CLRTAP EMEP MSC-W model described previously (70), with updates as specified in annual reports. This model has been widely used to simulate air quality over the UK for different time periods and for provision of evidence to the UK government (11, 42, 71, 72). The model was driven by hourly meteorology from the Weather Research and Forecasting (WRF) model (73), including data assimilation of numerical weather prediction model reanalysis (74). Air quality simulations were performed at 3km x 3km horizontal resolution for 2018, and then using anthropogenic emissions based on the years 2030, 2040 and 2050, retaining 2018 meteorology.

Anthropogenic emissions were taken from the National Atmospheric Emissions Inventory (75) for the UK (76), and official EMEP emissions fields (77) were applied for the rest of the European domain. Emissions of isoprene and other biogenic VOCs from vegetation, NO_x from lightning and soil, wind-derived dust and sea salt were linked to the meteorological year and modelled following a previous study (70), and CH_4 concentrations were set at the 2018 level. For future years, UK emissions use the ‘baseline’ scenarios developed for the Department for Environment, Food and Rural Affairs (Defra), reflecting assumed trends for anthropogenic emissions under existing interventions and policies relating to air quality. This includes real-world emissions testing of Euro 6 standards, changes associated with waste incinerator technology, and regulations related to domestic wood burning detailed in (78 to 80). For long-term impacts to health, annual mean $PM_{2.5}$ and NO_2 concentrations were used, and for short-term effects the daily maximum of the 8-hour running mean O_3 concentration were used. Population-weighted metrics were calculated for the 9 regions (formerly government office regions) in England (London, South East, South West, North East, North West, East of England, East Midlands, West Midlands, Yorkshire and The Humber), and Scotland, Wales and Northern Ireland, using 100m gridded residential population information for England, Scotland and Wales (81), and at 1km for Northern Ireland (82).

3.1.2 Health impact calculations

Health burdens were estimated for long-term exposure to air pollution (annual mortality attributable to $PM_{2.5}$ and NO_2), and also separately for short-term effects associated with O_3 (daily emergency hospital admissions for respiratory causes) for the regions described. Health burdens associated with exposure to each air pollutant (M_{aq}) were calculated for each region as follows: $M_{aq} = M_T \times AF$, where M_T is the total mortality or hospital admissions in the region, and *AF* is attributable fraction of the health outcome in that region associated with exposure to the air pollutant. The attributable fraction (*AF)* for long-term effects is based on the change in relative risk (RR) per 10µg/m^3, and for short-term effects (here respiratory hospital admissions), *AF* is calculated based on the percent increase per 10µg/m^3 reported from meta-analyses of time-series studies.

Methods recommended by COMEAP were followed; for long-term effects on all-cause mortality, the higher of estimated burdens from either $PM_{2.5}$ or NO_2 as the primary indicator of air pollution were used, by using 'unadjusted' exposure-response coefficients to capture the effect of air pollution as a whole using single-pollutant analyses. In addition, 4 pairs of mutually adjusted coefficients were used ($PM_{2.5}$ adjusted for effects associated with NO_2, and vice versa), and the range of these values together with the unadjusted coefficients gives the overall estimated range in effects (28, 83 to 86). Annual all-cause mortality data was obtained for the UK from the relevant statistical agencies[1], with extraction limited to external causes only (ICD10 codes A00-R99) for those 30 years and older. For short-term effects associated with O_3, an exposure-response coefficient of 0.75% (95% confidence intervals (CI): 0.30%,1.2%) increase in emergency respiratory hospital admissions per 10µg/m^3 daily maximum of 8-hour running mean O_3 was applied with no threshold for effects. Daily emergency hospital admissions for respiratory causes (all-ages) were obtained from ONS for the 9 regions in England and provided by Northern Ireland Statistical and Research Agency (NISRA) for Northern Ireland for 2018. For Wales, daily data was not available so annual totals for respiratory causes and emergency admission method were obtained from Patient Episode Database for Wales (PEDW, year 2018 to 2019), and distributed across days in the year using the daily cycle of the data for England.

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[1] Office for National Statistics (ONS) for the 9 regions in England and Wales, from National Records for Scotland (NRS) for Scotland, and Northern Ireland Statistical and Research Agency (NISRA) for Northern Ireland.

It should be noted that studies on the effects of long-term exposure to O_3 are inconsistent and quantification is not currently recommended (87, 88). Population size changes in future were also incorporated (as a sensitivity study). HIA results were normalised to the 2018 mid-year population estimates and then scaled according to population projections for future years following ONS ‘principal’ population projections[2] (89).

3.2 Results of health impact assessments

3.2.1 Long-term effects: $PM_{2.5}$ and NO_2

There are clear reductions in $PM_{2.5}$ and NO_2 between 2018 and 2050 (Figure 2), with greatest absolute reductions occurring close to population centres and emission sources (cities and shipping lanes), particularly for NO_2 in London. Regional reductions in exposure to $PM_{2.5}$ between 2018 and 2050 range from 28% to 36%, and for NO_2 from 35% to 49% depending on region.

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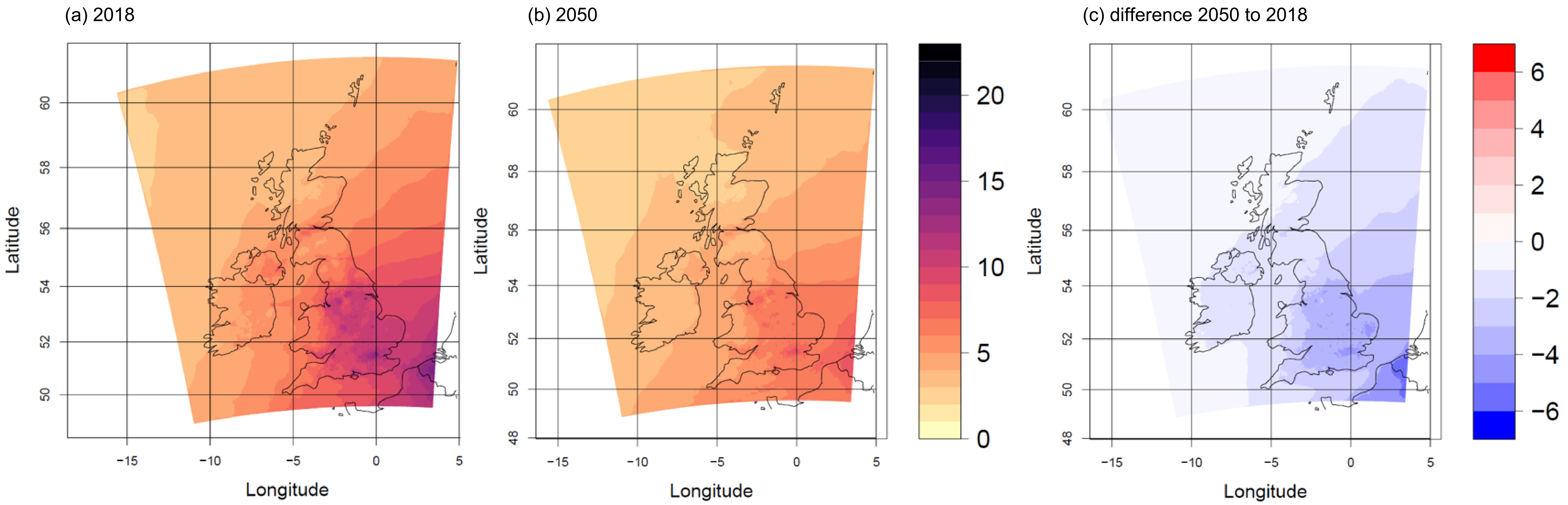
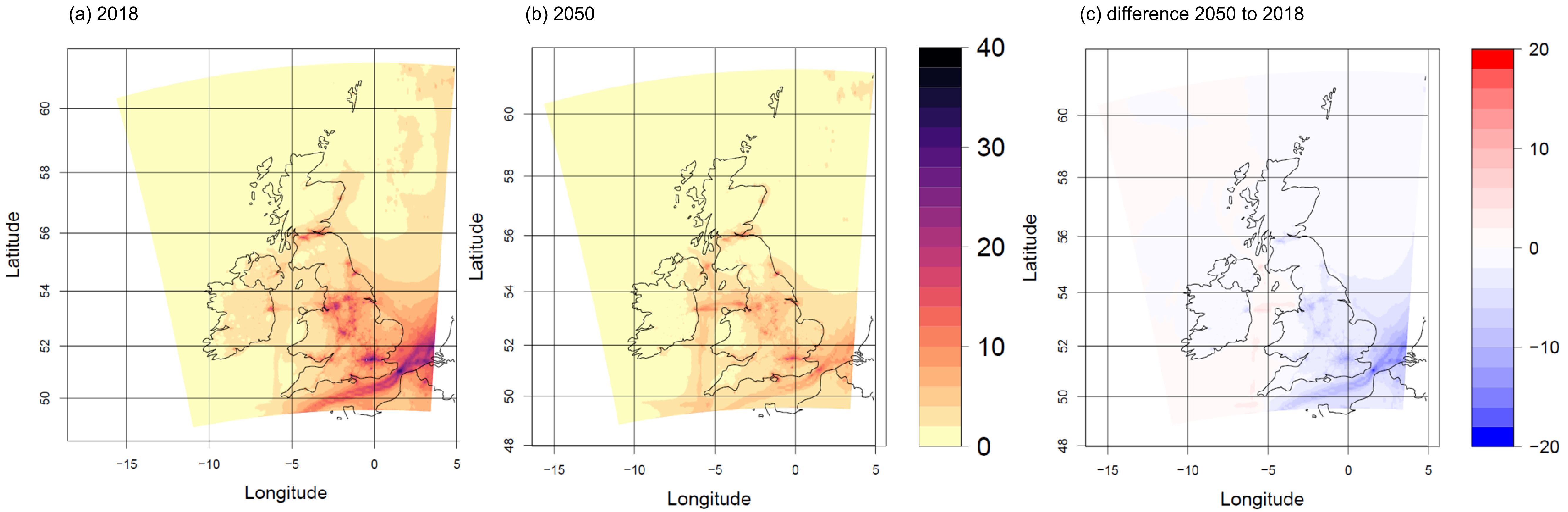
[2] ONS produce a range of population projections for the UK based on assumptions about future fertility, mortality, and migration trends (based on long-term demographic trends), with different scenarios (‘variant’ projections) produced based on high or low fertility, migration, and mortality. The use of the term ‘interim’ in the 2020 release reflects the interval between the 2020-based principal projection and subsequent projections, which will incorporate Census 2021 data. It also recognises uncertainties in the mid-2020 base year and in setting long-term demographic assumptions following the onset of the COVID-19 pandemic.

Figure 2. Annual mean $PM_{2.5}$ (top row) and NO_2 (bottom row) concentrations (µg/m³) for (a) 2018 emissions, (b) 2050 emissions, and (c) the difference

$PM_{2.5}$



NO_2



Annual estimated mortality burdens due to long-term effects of air pollution ($PM_{2.5}$ and NO_2) are shown in Table 1. Results suggest that annual mortality attributable to the effects of long-term exposure to $PM_{2.5}$ and NO_2 is between 26,287 and 42,442 for 2018 and this will be lower by 31%, 35% and 37% in 2030, 2040 and 2050 respectively, assuming no population changes. The total estimated mortality burden in each region is affected by *AF* (determined by air pollution concentrations), baseline mortality rates, and population in each region. Mortality *AF* is greatest where air pollution levels are highest; for $PM_{2.5}$ this is London and the South East, for NO_2 it is London and the North West (68). Baseline mortality rates and population will also vary in each region, with the North West, London and the South East having larger current populations. For example, the North West has the sixth highest *AF* but the second highest mortality burden. Projected population increases of approximately 15% across the UK in the over 30 years age group by 2050 are expected (90), which when accounted for in the estimates will moderate the anticipated reductions in future health impacts. Using a scenario including population growth (assuming no change in the future mortality rates) results in reductions in mortality burdens of 25%, 27%, and 26% by 2030, 2040 and 2050 respectively, compared with reductions of 31%, 35%, and 37% in 2030, 2040 and 2050 respectively assuming no population change.

Table 1. Estimated annual mortality burden associated with long-term effects of exposure to both $PM_{2.5}$ and NO_2
The range represents the spread of results from unadjusted single-pollutant calculations for PM2.5 and NO2 separately, and the range of the values from estimates using paired coefficients, following COMEAP recommended methods.

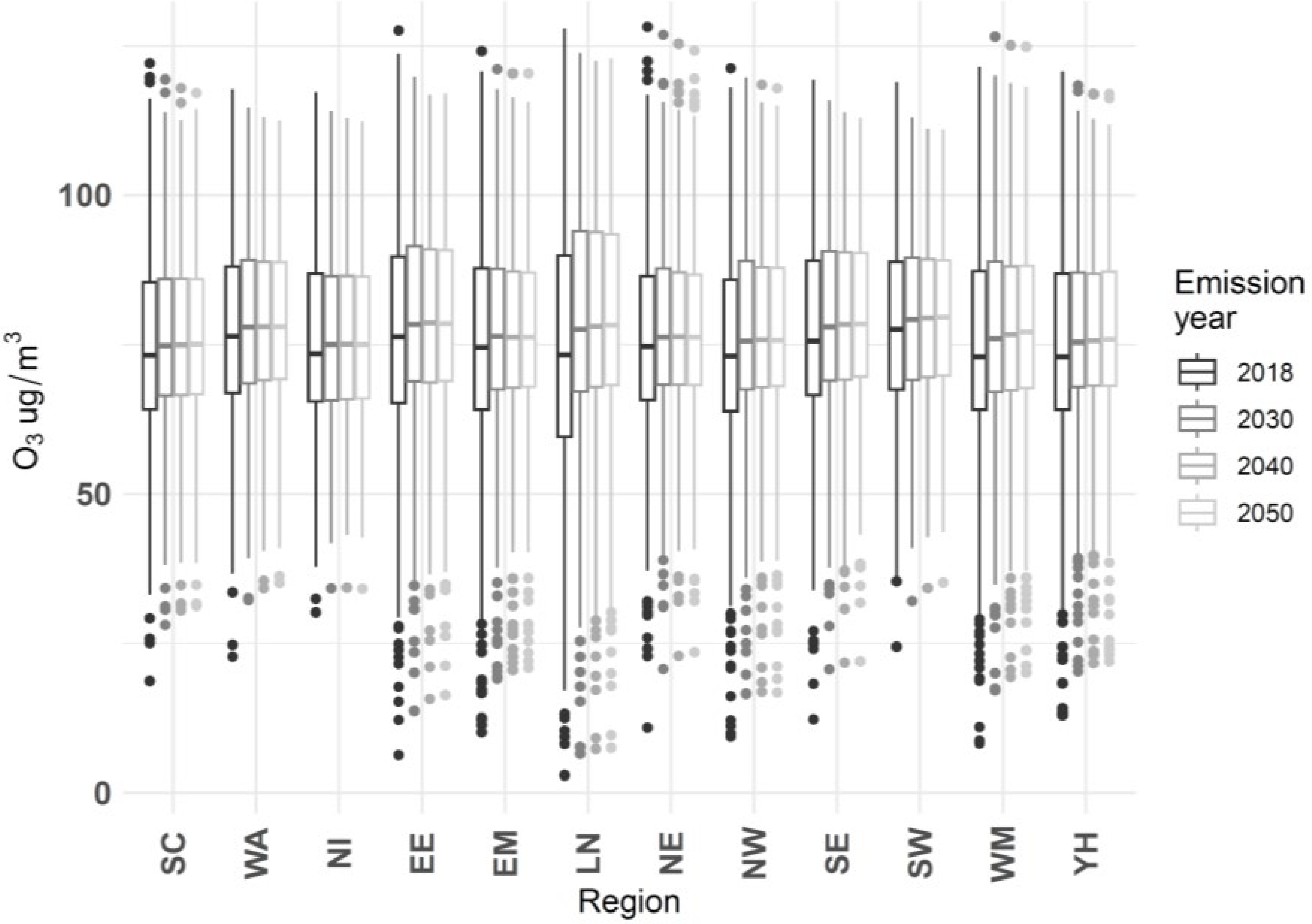
Emission year	Annual mortality long-term, UK total: no population change	Annual mortality long-term, UK total: with population change	Mid value of the range: no population change	Mid value of the range: with population change	% change from 2018: no population change	% change from 2018: with population change
2018	26,287 to 42,442	—	34,365	—	—	—
2030	17,449 to 29,879	18,887 to 32,342	23,664	25,615	−31.1%	−25.5%
2040	16,321 to 28,104	18,384 to 31,657	22,213	25,021	−35.4%	−27.2%
2050	16,010 to 27,539	18,732 to 32,220	21,775	25,476	−36.6%	−25.9%

3.2.2 Short-term effects: O_3

For O_3, population-weighted concentrations of daily maximum running 8-hour means are generally highest in the spring and early summer, and lower in winter; some very low values are seen for short periods (in some cases individual days). The impact of future emission changes on the distribution of daily exposures is a small increase in mean O_3, mainly due to the reduction of NO_x emissions (which titrate O_3 close to emission sources, for example, roadsides). Future extreme (high or low) concentrations of O_3 are brought more towards the mean value in future emission years, narrowing the overall exposure range, together with a small increase in the overall mean exposure of 5.6% by 2050 (Figure 3).

Figure 3. Boxplots of daily population-weighted O_3 exposure (based on daily maximum 8-hour running mean) across all regions and different emission years (meteorology is for 2018 in all simulations)

Whiskers extend to the largest value or no further than 1.5 × Inter Quartile Range. Outliers beyond this range are plotted individually.



Region codes: SC=Scotland, WA=Wales, NI=Northern Ireland, EE=East of England, EM=East Midlands, LN=London, NE=North East, NW=North West, SE=South East, SW=South West, WM=West Midlands, YH=Yorkshire and the Humber.* Whiskers extend to the largest value or no further than 1.5 × Inter Quartile Range. Outliers beyond this range are plotted individually.

Estimated emergency hospital admissions (respiratory causes) associated with short-term effects from O_3 exposure in 2018 are 60,488 (95% CI: 24,673 to 94,927) across the UK (out of a total of 1,147,333 emergency respiratory hospital admissions), increasing in future by 4.2%, 4.5%, 4.6% in 2030, 2040 and 2050, respectively (Table 2). The largest increases in O_3-associated hospital admissions are in London (increasing 10% by 2050), with much smaller changes in other locations (for example, 1.0% in Northern Ireland) (69). As with long-term effects, there are some regional variations, influenced by baseline admission rates, population size, and O_3 concentrations. Accounting for changes in population size in the future, annual total UK respiratory hospital admissions in 2050 are now higher, going from 63,289 to 67,566 (+4,277), meaning that the increases from the 2018 baseline of 4.2%, 4.5%, and 4.6% in 2030, 2040 and 2050 respectively (due to O_3 changes only), are now 8.3%, 10.3% and 11.7% respectively (due to both O_3 and population changes). While overall UK population increases by 2050, the population in Scotland rises in 2030, but then falls thereafter and by 2050 is −1.9% from 2018 values, resulting in a diminishing of the absolute number of admissions associated with O_3. The greatest combined (O_3 and population) changes in hospital admissions by 2050 are in London (+19.1%), the West Midlands (+14.9%), and the North West (+14.7%), from 2018 baseline (69).

Table 2. Total daily emergency respiratory hospital admissions associated with short-term exposure to O_3, including projected population growth

Confidence intervals (CI) reflect the 95% CI on the exposure-response coefficient. Future values for 2030 onwards are calculated using 2018 as the baseline.

Emissions year	Total daily hospital admissions, short-term O_3 effects: no population change (95% CI)	Total daily hospital admissions, short-term O_3 effects: with population change (95% CI)	Change from 2018 (percent change): no population change (95% CI)	Change from 2018 (percent change): with population change (95% CI)
2018	60,488 (24,673 to 94,927)	–	–	–
2030	63,024 (25,719 to 98,863)	65,495 (26,727 to 102,739)	2,535 (+4.2%)	5,006 (+8.3%)
2040	63,228 (25,802 to 99,183)	66,721 (27,227 to 104,662)	2,740 (+4.5%)	6,233 (+10.3%)
2050	63,289 (25,827 to 99,278)	67,566 (27,573 to 105,987)	2,801 (+4.6%)	7,078 (+11.7%)

3.3 Discussion of HIA analysis

The results suggest that improvements in air quality and a reduction in the burden of long-term health impacts over the coming decades is likely given current emission policies (Table 1). Annual mortality attributable to long-term effects of air pollution (related to $PM_{2.5}$ and NO_2) will likely be reduced by 28% to 39% (depending on region) in 2050 compared with 2018, though negative impacts to health will remain in future. In 2022, the World Health Organization (WHO) published updated annual average guideline values for $PM_{2.5}$ of 5µg/m^3 and for NO_2 a 10µg/m^3 (reduced from 10µg/m^3 and 40µg/m^3 respectively) (91). In terms of exposure, the analysis suggests regionally-averaged population-weighted annual mean $PM_{2.5}$ concentrations will be below 10µg/m^3 in all regions by 2030 at the latest; regionally-averaged population-weighted $PM_{2.5}$ concentrations are only likely to be below 5µg/m^3 in Scotland and Northern Ireland (by 2030), and the North East (by 2050), with values in other regions remaining above this (5.5 to 7.9µg/m^3).

For NO_2, regionally-averaged population-weighted annual mean concentrations are likely to be below 10µg/m^3 by 2050 in all regions except London. It should be emphasised that the values presented here represent regional population-weighted exposures, and individual pollution concentrations at observation sites (used for regulation) may differ from these. Due to particles generated by natural processes as well as transboundary pollution, meeting the WHO guideline for $PM_{2.5}$ of 5µg/m^3 could be challenging for some regions in the UK and could pose particular challenges on a global scale (92).

For short-term impacts related to O_3 exposure (here respiratory emergency hospitalisations), a small overall increase of about 4.6% by 2050 was suggested, corresponding to an increase of 2,801 hospital admissions annually across the UK compared with 2018. This increase in O_3 is driven by reduced NO emissions (as NO reacts with O_3 close to emission sources). Using modelling techniques that can adequately capture complex non-linear chemistry at appropriate scales is a key consideration in air quality and health studies (93). While there are likely to be significant benefits to health from reduced NO_2 exposures, there may be local increases in secondary pollutants like O_3, which may be considered a 'penalty' of reductions in NO_x emissions close to urban centres. It is important to consider these complex effects of policies relating to emission controls (for air quality or climate policy), as well as responses when air pollution episodes are forecast. This is important in the context of a changing climate as summer heatwave events are expected to become more frequent and intense and longer-lasting, and may coincide with periods of higher O_3, for example as during the 2003 European heatwave (94).

As local sources of O_3 precursors such as NMVOC and NO_x are reduced through emission controls, background concentrations will become more important contributors to overall O_3 exposure. Regional transport of O_3 and precursors from Europe as well as hemispheric background O_3 will play an increasingly important role in UK surface O_3. Some studies have suggested a 40% to 50% increase in annual mean O_3 concentrations in presently lower-O_3 parts of the UK by 2050, under RCP8.5 (35). CH_4 is a GHG that also contributes to hemispheric background O_3, and it has been suggested that efforts should be made to curb CH_4 emissions to avoid further increases in surface O_3 (42). While hemispheric CH_4 changes were not included here, a recent modelling study suggests that about 30% of monthly mean O_3 in the UK is contributed by anthropogenic NO_x emissions from the UK and Europe, while the hemispheric background contributes the majority (approximately 70%) (35, 41). Since the aim of the study was to evaluate impacts of anthropogenic emissions changes on health burdens, model simulations of future air quality use the same meteorology (2018), with emissions of biogenic VOC, soil and lightning NO_x, and wind-derived particles linked to this meteorological year, which is a study limitation. The analysis does not include estimates of changes in CH_4 concentration and outer-domain boundary conditions for O_3 and secondary inorganic aerosol (which were set at 2018 values). While this is another limitation of this study, future concentrations of CH_4 and O_3 outer-boundary concentration depend sensitively on global emissions of CH_4, which in turn depend on which socioeconomic pathway the world ultimately follows, and thus are challenging to assign with any confidence. This is discussed further in a recent report on O_3 trends in the UK (42). Imposition of these conditions has minor impacts on simulated $PM_{2.5}$ and NO_2 over the UK but may have some impact on O_3. However, as with the use of constant meteorology in this work, imposition of these conditions allows for the focus on the impact of changes in UK and other European emissions on relative and absolute changes in UK air pollutant levels and the associated health impacts.

4. Interactions between temperature and air pollutants in relation to health

4.1 Impact of temperature on air pollutant concentrations

During heatwaves, episodes of high air pollution are more common, with concentrations of O_3, PM_{10} and NO_2 found to increase with increasing temperatures in the UK (42). As heatwaves are likely to become more frequent and intense in the future, this may lead to more episodes of high O_3 and PM (20). As outlined in section 1.2.1, O_3 is formed by chemical reactions in the air involving NO_x, VOCs, and sunlight. Its formation is affected by anthropogenic and biogenic emissions and meteorological conditions, and importantly compared to other air pollutants, it is the most strongly influenced by temperature (20). NH_3 emissions may also rise with the increased temperature so agricultural emissions may become more important for PM air pollution in future (see Chapter 12).

Rises in temperature can increase O_3 concentrations in several ways. For example, higher temperatures can increase emission of precursors such as the release of biogenic volatile organic compounds (bVOCs), thought to be one of the drivers of the high O_3 concentrations seen during the 2003 heatwave (94, 95). It should be noted that bVOCs can be released during wildfires, which can also increase during heatwaves (see Chapter 10). Low soil moisture can cause an increase in release of NO_X from the soil, and warm and dry conditions can stimulate vegetation stomata to close (to help reduce water loss through evapotranspiration), resulting in less O_3 loss by dry deposition to vegetation. As temperatures rise, there is likely to be an increase in CH_4 emissions from wetlands, and as CH_4 is a GHG contributing to climate change, this may lead to further amplification of temperature-dependent drivers on O_3 formation (42).

In the 2012 HECC report (11), a detailed modelling exercise was completed, including looking at the impact of a +5°C temperature increase on O_3. Moderate increases in O_3 (+1.0 to +1.5 parts per billion per volume (ppbv) depending on UK region, comparable to changes due to interannual variability, and smaller than for changes in future precursor emissions) may arise, and model resolution played a key role in estimates due to the complex non-linear chemistry involved (93). The size and direction of correlation between O_3 and other pollutants can vary as the temperature changes, and may be part of the reason why there seem to be greater effects of O_3 on days with higher temperatures (87). Previous modelling has demonstrated a non-linear relationship between O_3 with temperature and NO_x, with greatest O_3 production at high temperatures and moderate emissions of NO_x (96). Conversely, lower NO_x levels led to a minimal increase of O_3 with temperature (96).

4.2 Impact of temperature on the short-term health effects of air pollutants

The 2003 European heatwave in early August was associated with high concentrations of O_3 (and PM) in the UK and Europe, and estimated excess mortality was reported as greater than for other recent heatwaves (97). It has been estimated that 21% to 38% of excess deaths due to the 2003 heatwave in the UK during the first 2 weeks of August were associated with PM_{10} and O_3 (98), though this study assumed no interaction between temperature and O_3 effects.

Traditionally, ambient temperature has been treated as a confounder in studies of the short-term health effects of O_3 (and other air pollutants) and has therefore been controlled in analyses. However, increased temperature could potentially worsen the health effects due to short-term exposure to ground-level O_3 and other pollutants (87). COMEAP noted that a limited number of time-series studies suggest effect modification of the O_3 and all-cause mortality association by temperature, with larger associations at higher temperatures (99 to 101, 87). For example, Atkinson and colleagues examined the associations between daily measurements of O_3 and daily mortality in 5 urban and 5 rural areas of England and Wales from 1993 to 2006 (99). Results of sensitivity analyses of data for the summer period for London suggested effect modification of the O_3–mortality relationship by temperature. Specifically, there was clear evidence of a relationship on hot days with mean temperatures above 20°C (99). Pattenden and colleagues estimated the acute effects of summer O_3 on mortality using data from 15 conurbations in England and Wales from 1993 to 2003 (101). The authors found a stronger O_3 effect on all-cause mortality, cardiovascular and respiratory mortality during hot days compared to non-hot days (101).

Several studies have also been undertaken to investigate indirect evidence by considering a potential modifying effect of temperature during warm or cold seasons instead of focusing specifically on temperature changes.

In the 'Air Pollution and Health: A European Approach (APHEA2)' project (102), the effects of short-term ambient O_3 concentrations on mortality were investigated in 23 European cities or areas for at least 3 years since 1990, with no significant effects observed during the cold season. By contrast, an increase in the 1-hour O_3 concentration was associated with an increase in the total daily number of deaths, and in the number of cardiovascular and respiratory deaths (102). A time-series study was conducted (as part of the APHEA project) to investigate the impact of several air pollutants on daily hospital admissions in London for the period between 1987 to 1988 and 1991 to 1992 (103). Short-term exposure to O_3 was significantly associated with an increase in daily admissions among all age groups (except the 0 to 14 group) and this effect was stronger in the warm season (103).

A systematic review and meta-analysis investigated effect modification of the short-term effects of several air pollutants, including O_3, on morbidity by season (104). Short-term exposure to O_3 was significantly associated with an increased risk of total morbidity and specifically, of stroke, asthma and pneumonia during the warm season (104). By contrast, no association was found for the cold season (104). Another meta-analysis found no association between short-term O_3 exposure and respiratory mortality risk or respiratory hospital admissions during the cold season (105). For the warm season, they found short-term O_3 exposure was associated with a slight, but significant, increased risk of mortality and a very small but non-significant risk of respiratory hospital admissions (105).

A scoping review on the cold climate impact on traffic-related air pollution related health outcomes (106) identified 8 papers which explored the interplay between temperature and air pollution and the impact on health, mainly cardiovascular and respiratory mortality effects. The evidence from the studies was inconsistent, with 5 studies showing an increased impact of O_3 (and other pollutants) exposure on health end points at either cold or warm temperatures or at both temperatures, and 3 papers showing that temperature did not modify the effects (106).

The health outcomes associated with PM and NO_2 and modified by temperature have also been investigated in some epidemiological studies. Short-term exposure to $PM_{2.5}$, PM_{10} and NO_2 was associated with a significant risk of morbidity on lag-0 and lag-1 day, but not on lag-2 (104). Another study reported that high temperatures increased the effect of PM_{10} and $PM_{2.5}$ on non-accidental, cardiovascular and respiratory mortality as well as increased morbidity effects such as hospital admissions for cardiovascular and respiratory effects (107).

A systematic review and meta-analysis included 29 studies focused on the modifying effect of either low or high temperature on the association between short-term PM_{10} and non-accidental, cardiovascular disease, and respiratory disease mortality (108). The authors concluded that there was moderate evidence that high temperatures enhance the effect of short-term PM_{10} on mortality, and that the modifying effect was largest at higher temperature and for respiratory deaths (108).

In another systematic review and meta-analysis, the epidemiological evidence on the modification of temperature on the effects of several air pollutants on non-accidental and cardiovascular mortality was investigated (109). The authors observed interactions between high temperature and short-term PM_{10} in the effects on nonaccidental and cardiovascular mortality (109). By contrast, cold temperature decreased the effect of PM_{10} on cardiovascular mortality. In addition, they found no substantial variation in effects of short-term NO_2 on non-accidental and cardiovascular mortality at different temperatures (109).

One study found a small number of papers that confirmed a hypothesis about the interplay between air pollution and temperature on health (110). However, the authors concluded that due to the large heterogeneity between the studies, a meta-analysis was not possible to estimate the size of effect (110). Furthermore, they also highlighted how inconclusive the evidence is, with some studies showing no statistically significant interaction between air pollution, high temperature, and respiratory health outcomes (110). The conflict between different studies has been previously highlighted: some studies show modifying effects of O_3 exposure in the warm season compared to other studies which show the same effect in the cold season, whilst other studies show no interaction between O_3 and season or temperature at all (111).

Interpreting the evidence related to the health impacts of temperature and O_3 (and other pollutants) is clearly challenging, due to the variability in study design and inconsistent results. Silmann and colleagues noted the heterogeneity of studies is due in part to the various metrics of temperature used (such as apparent temperature, daily maximum temperate, heatwaves, hourly temperature), as well as location, pollutant and health outcome studied (107). They also highlighted the need to ensure that confounders and other factors such as geography, meteorology, industrialization, demography and behaviour are considered (107).

The importance of considering susceptibility based on geographical region has been previously highlighted, due to differences in access to healthcare and socioeconomic status (104). Furthermore, meteorological conditions, which act as confounders, can differ across regions and alter health outcomes, for example humidity and rainfall, which correlate with O_3, should be included (104, 111). Behaviours which change depending on season could impact the size of the effect modification overall. For example, people tend to open windows and go outdoors more in the warm season and therefore have higher personal exposure to outdoor air pollutants. Other factors which could change exposure dependent on weather patterns include the use of air conditioning and heating-systems which vary dependent on geographical location, even down to city-to-city comparisons (104).

In summary, while some reviews have examined the interactive effect of air pollution and temperature upon different health outcomes, the evidence is not clear and further work is needed. UKHSA is currently undertaking a systematic review on the evidence for the health effects due to exposure to short-term O_3 being modified by increases in temperature. Understanding the links between O_3 and temperature effects on health is important given increasing frequency, intensity and duration of heatwaves, and potential for O_3 episodes to coincide with such events in future.

5. Discussion

5.1 Policy review: long-term effects

International initiatives such as the Gothenburg Protocol (implemented through the National Emission Ceilings (NEC) directive), the Air Quality directive of the European Parliament and Council (for example, 2008/50/EC), and Air Quality Standards Regulations 2010, have brought improvements in UK air quality over the past several decades. Such improvements since the 1970s which were primarily driven by policy interventions have led to a reduction in UK attributable mortality due to exposure to $PM_{2.5}$ and NO_2 of 56% and 44%, respectively between 1970 and 2010 (76). Despite this, there is still a large mortality and morbidity burden due to exposure to current concentrations of air pollutants. The Environmental Improvement Plan 2023 has made various commitments to reduce emissions and concentrations of pollutants including a legal target of a maximum annual mean $PM_{2.5}$ concentration of 10µg/m^3 by 2040 (14). Scotland already has an existing target for $PM_{2.5}$ of 10µg/m^3 (112), and Wales and Northern Ireland follow the air quality standards set by the EU directive (2008/50/EC). While reducing annual mean $PM_{2.5}$ to 10µg/m^3 will bring additional benefits to health, it is double the most recent guideline annual average value recommended by the WHO of 5µg/m^3 (91). There are challenges to reaching these targets in the UK and worldwide; one study has shown that even under an extreme abatement scenario, more than half the world's population would still experience annual $PM_{2.5}$ levels greater than 5µg /m^3, including over 70% of African and over 60% of Asian populations (92).

The transition to low-carbon energy and clean transport are 2 themes to support action on climate change that have air quality health benefits highlighted as a mutual benefit. There are clearly key benefits to health of co-ordinated environmental policies, with climate change, air pollution, and health being one example. Historically, energy has been produced from combustion processes (which generate GHGs, PM, and gaseous air pollutants), so switching to clean energy sources will be a win-win for climate and air pollution. The WHO 'COP26 report on climate change and health' highlighted the health benefits of co-ordinated action on mitigation through benefits from improved air quality, finding benefits outweighed costs by two to one (113). However, AQEG and the Royal Society have highlighted the potential for transitionary localised air pollution impacts associated with construction of infrastructure to expand the renewable, nuclear, transport and decarbonisation sectors in the UK (20, 114). The 'Lancet Countdown on Health and Climate Change' also provides recommendations and policy briefs for the UK, including action across 3 areas, including cleaner energy and improved air quality (115).

Currently, developers in England must demonstrate how they will minimise local air quality impacts during the construction (and demolition) phase of new developments (116). Given the potential scale of infrastructure development needed to achieve the UK's climate commitments, RS2021 recommends that additional control measures for large infrastructure projects would be beneficial (20). Globally, a rapid phase-out of fossil fuels could result in an avoided excess mortality rate of approximately 3.6 million annually from ambient air pollution (117), and in the UK, it has been estimated that $PM_{2.5}$ concentrations are predicted to decrease by around 43% by 2050 (compared to 2011) for scenarios meeting a commitment of 80% reduction in CO_2 equivalent emissions by 2050 (118). Such evidence is used to strengthen the case for ambitious policy through demonstrating mutual benefits to health and climate (113). Health effects of net zero measures more widely are covered in Chapter 14.

The ‘UN Emissions Gap Report 2022’ highlights that ambitious policies and system-wide transformation will be needed globally to meet climate targets (119). Global emissions must reduce by 45% compared with current policy in place by 2030 and decline rapidly thereafter to be on track for limiting global warming to 1.5°C (119). Such policies may in some circumstances be unpopular (for example, the removal of fuel subsidies led to civil unrest in Egypt, Indonesia and Nigeria), but there is evidence that such policies are more acceptable if the subsidy funding is redirected to actions with wide public benefit, such as public health spending (120).

In the WHO COP26 report, 10 overall recommendations for health and climate were made, with those related to air pollution including ‘harness the health benefits of climate action’, ‘create energy systems that protect and improve climate health’ and ‘reimagine urban environments, transport, and mobility’ (113). In addition, zero exhaust emission vehicles (often termed ZEVs, or electric vehicles, EVs) will need to be rolled out twice as fast to meet the 2050 emission reduction targets of the Paris Agreement (113). Benefits to health through air quality improvements from EV roll-out depend heavily on the existing energy mix in the country grid. An EU-based study suggests that countries relying on low air pollutant fuel mixes may gain significantly, with benefits extending across the EU, especially for emissions in small countries, while countries that depend on more polluting fuel mixes may not benefit at all from introducing electric vehicles (121). In terms of health impacts, adopting EVs would generally relocate emissions away from population centres and thus reduce air pollution exposure, but may not harness benefits from actions such as increasing active travel. EVs will also still be a source of local particle emissions from tyre-wear and road surface wear and resuspension (122). Furthermore, a review highlights the difficulty in disentangling the health effects associated with non-exhaust PM (for example, brake and tyre-wear) from road transport, from the health effects related to exhaust emissions and other particulate pollution (123). In addition, the review suggests areas for further research, such as the use of high-quality receptor modelling in epidemiological studies to distinguish particle sources, and toxicological studies that directly compare toxicity of non-exhaust PM to the particulates from exhaust PM (123).

Active travel such as walking and cycling is a win-win-win for air quality, climate change and health and wellbeing. A review of people’s exposure to air pollution in different transport modes and active travel identified ways to reduce risks of travelling in polluted areas and enhance health benefits (124). Recommendations included promotion of less polluting and more frequent public transport, as well as advice for maintaining or stimulating active travel while considering reducing exposure to air pollution (124). One study suggested that modes of transport such as electric cycles could cut CO_2 emissions from transport in England by up to 50%, with scope for electric bikes to help people who are most affected by rising transport costs (125).

5.2 Incidence response and alerting: short-term effects

Information on current and forecast levels of air pollution in the UK and accompanying health messages are provided to the public by Defra, the Scottish Environmental Protection Agency (SEPA), DAERA and Welsh Government. During episodes of elevated air pollution, UKHSA helps raise awareness of the actions that the public can take to protect their health, both prior to and during, episodes of elevated air pollution, as well as disseminating health messages to raise public awareness and amplifying social media messages published by Defra (31). With the potential for air pollution (O_3) episodes coinciding with heatwave events set to worsen in future, and with the interacting effects of O_3 and temperature on human health still unclear, advice and alerts may need to be adapted as the evidence develops.

Following the 2021 inquest into the death of Ella Adoo Kissi-Debrah, it was concluded that air pollution "made a material contribution" to her death, as explained in the 'Prevention of Future Deaths (PFD)' report (126). It has become even more apparent that there is a need to improve the quality and provision of information of the negative health impacts of air pollution and the actions that can be taken to better protect the public. It was also highlighted in a recent House of Commons Committee of Public Accounts publication ('Tackling local air quality breaches') that it is too difficult for the public to find local air quality information. It recommended improvements in the accessibility of information and actions to improve air quality (126). UKHSA, Defra and the Department of Health and Social Care (DHSC) have begun an Air Quality Information Systems Review. Working with a multidisciplinary expert group, the aim is to steer a review and provide clear, actionable recommendations on the changes that need to be made to the present air quality information system to better meet the needs of individuals, healthcare professionals, government bodies and other key users (31).

Such alert systems may need to consider the changing sources of air pollution and taking action at an international scale; for example, WHO has outlined multiple ways of reducing the impact of desert dust and dust storms (91). Mitigation of effects can be implemented during dust events at international, national, regional, and local levels, and international agreements and multi-scale approaches are needed for effective desert dust control (91). National, regional and local interventions for reducing the impacts of desert dust include: alerting health authorities and vulnerable members of the population to increased levels of air pollution; raising public awareness of personal interventions that can reduce indoor and outdoor air pollution during dust episodes; and reducing dust and other pollutants from anthropogenic sources (91). It is estimated that 40% of aerosols within the troposphere are dust particles as a result of wind erosion (91), and therefore international agreements and measures are suggested to reduce wind erosion impacts, including protecting soil at the source of dust, via reforestation and the planting of shrubs (91). For volcanic hazards, the International Volcanic Health Hazard Network

(IVHHN) provides information on the health hazards and impacts of volcanic eruptions, determines the health impacts of volcanic emissions, and protects exposed communities via the publication of guidance, briefing notes and other public information. In the UK, the London Volcanic Ash Advisory Centre (VAAC), hosted and run by the Met Office, is an International Civil Aviation Organization (ICAO) designated centre, that issues advisories for volcanic eruptions occurring in Iceland and the north-eastern part of the North Atlantic. VAAC has specialist forecasters who use a combination of ground-based, aircraft and satellite observations, and weather forecast and dispersion models for producing the advisories and guidance (127).

With potential for changes in meteorologically-driven PM events, particularly with dust events reaching the UK in future, it is important to have the mechanisms that forecast and monitor these events, issue advice and guidance and also health services and effective response plans in place for managing such conditions in the future.

5.3 Considerations for adaptation and mitigation

Adaptation to air pollution is not considered a common concept; emissions (and mitigation actions) are currently the main driver of air quality across the UK. System-wide changes in activities are likely to be needed to reduce GHG emissions to mitigate climate change. Actions taken at a global scale in response to the COVID-19 pandemic led to significant changes in people's daily lives and impacted global emissions of GHGs and air pollution. The 'lockdown' periods implemented in response to the COVID-19 pandemic resulted in reductions in PM and NO_2 concentrations mostly due to the travel restrictions (NO_2 reduced on average 42%, and 48% at roadsides, (128)), with working from home decreasing daily trips. It was shown that maintaining some practices from these periods could have positive results on future environment and health. However, local increases in O_3 concentrations are linked to reduction in NO_x emissions. In addition, increases in O_3 have also been linked to hot weather and this highlights the importance of looking at the interactions between temperature and air pollutants and the associated health effects (128, 129). The 'climate penalty' is a recognised issue associating increases in O_3 concentrations and other pollutants with the increases in temperature and may need to be considered carefully in future.

Changes in energy sources may lead to unintended consequences in terms of air pollution. Biofuel is often regarded as a lower emission option for energy, as trees or crops can be re-grown. It has been reported that some are moving to log-burners in response to sharp increases in energy prices, with some retailers seeing a 60% increase in sales compared to last year (130). A recent study estimated that wood burning in the UK contributed 8% of $PM_{2.5}$ between 2009 to 2021, with concentrations greatest in the evenings, and varying with temperature and windspeeds (131). The most recent data published by Defra states that emissions of PM arising from the domestic combustion of wood as a fuel increased by 124% between 2011 and 2021 and accounted for 21% of primary emissions of $PM_{2.5}$ in 2021 (132). Wood burning may contribute to increases in other air pollutants; for example, higher ambient concentrations of arsenic are being detected (132). This suggests there is an increase in burning of waste wood that has been treated with preservatives containing arsenic (133). Furthermore, epidemiological studies have shown a positive association between solid fuel burning and respiratory problems (134).

Other fuels such as hydrogen (H_2) may help reduce carbon emissions but depending on how they are converted to energy could potentially lead to worsening air quality (114). There are concerns about transitions of energy sources to cleaner fuels including the economic costs and the associated increase in social inequalities (135, 136). To address this, it is important for policy and decision-makers to better understand how climate policies are expected to affect different economic sectors and provide them with appropriate tools to ensure that decarbonisation is fair and equitable.

As discussed earlier in this chapter, emissions are the main driver of the air pollutant concentrations across the UK, though certain weather conditions can lead to air pollution episodes. During periods of calm weather which are often driven by atmospheric ‘blocking’ events, air pollution levels can worsen as dispersion of pollutants is limited and often accompanied by transport of pollution from the continent, leading to episodes of poor air quality across the UK (often coinciding with other hazards such as heatwaves or cold weather events). An important question therefore is how the occurrence of such events might change in future with climate change. Modelling studies suggest a slight decline in the frequency of blocking events across the UK, but observations suggest a slight increase has occurred, though the observational record is too short to determine a trend. Analysis of the UKCP18 projections suggests that future changes in large-scale circulation tend towards winter decreases in blocking weather patterns, while in summer there may be a shift to increased dry settled weather types (137). There is also uncertainty around how well climate models capture the development of these phenomena, leading to overall uncertainty in how such blocking events may change in future (3), and this is an active area of research. Other uncertainties related to the impact of climate change on air pollution include temperature-driven emissions such as from bVOCs and NH_3, with implications for secondary organic aerosol (SOA) and O_3. Therefore, future research should seek to understand and reduce these sources of uncertainty.

Adaptation and mitigation policies may have important air quality considerations. Buildings are a significant contributor to GHG emissions through energy used to heat and power them and are highlighted as a target for emission reduction actions, such as energy efficient retrofit (see Chapter 14). Such measures are likely to alter the indoor environment, with potentially mixed impacts to occupant health. Greenspace or nature-based interventions for climate can include increasing urban greenspace to provide shade and cooling, improve flood management, expand opportunity for active travel and improve biodiversity. As such, they are regarded as providing multiple co-benefits related to climate adaptation and improving the environment. However, careful consideration is needed when implementing these interventions so that green infrastructure does not unintentionally restrict air flow in street canyons, which may lead to a potential build-up of pollution at pedestrian level. Negative effects on biodiversity or other adverse outcomes, such as increasing emission of bVOC (an O_3 precursor) or pollen, with potential impacts to health, should also be considered. Careful design and appropriate vegetation selection could off-set these issues, and health considerations should be included in intervention design (see Chapters 5 and 14).

6. Conclusions and priorities

The HIA, based on current and future modelled air pollution concentrations from current emission controls, suggests that improvements in air quality will lead to a reduction in air pollution-related deaths; however, absolute reductions may be moderated by expected increases in total population. Where possible, HIAs should also seek to include health economic impact assessments to help understand and provide evidence to make the case for action that can be used to prioritise different air pollution reduction measures, and that may help in implementation of interventions. In 2018, PHE produced a tool to help local authorities estimate the burden of air pollution on the health care system (138).

Hospital admissions associated with short-term effects from O_3 will be increased in some places following the reduced sink of O_3 from titration by NO. However, studies have shown that the health effects associated with short-term exposure to O_3 may be aggravated by concurrent increases in temperature exposure, and UKHSA is investigating these interactions.

With reductions in UK anthropogenic emissions of air pollutants (due to environmental policies), transboundary effects, including transport of particles from natural sources, may have more noticeable effects on future levels of PM in the UK following changes in weather patterns due to climate change that is expected to accelerate. Exposure to particles from natural sources has been associated with negative health outcomes, including respiratory, cardiovascular and mortality. Thus, appropriate mechanisms that respond to incidents of long-range pollutant transport are important for forecasting and monitoring these events, and for issuing health advice and guidance.

The impacts of poor air quality on health, even if only localised and for a short time period, can have immediate effects, such as increased hospital admissions. Whilst the implementation of policies to achieve net zero by 2050 will likely see health benefits across the population, a reduction in air pollution concentrations will see some of these health benefits realised in shorter timeframes.

Actions that can offer mutual benefits to climate change and air pollution, such as those related to energy transition and clean transport, should be considered in an integrated manner, to ensure that trade-offs are identified, and co-benefits to health maximised (20). The health benefits of climate change actions through improving air pollution are important co-benefits to health, with benefits often outweighing the costs. Actions that reduce air pollution, mitigate climate change, and improve health can be regarded as win-win-win actions, for example active travel options. Reducing CH_4 will be important for reducing O_3 exposure – action on CH_4 is a win-win for climate and air pollution (20).

6.1 Research priorities

As the sources of pollution change, establishing the importance of differential toxicity of air pollutants (PM composition) is even more necessary, particularly considering the likely changing pollutant mix. This includes non-exhaust emissions, secondary inorganic aerosol, biogenic emissions and also domestic and transboundary pollution sources.

To provide quantitative estimates of health impacts associated with air pollution, detailed spatial modelling techniques at scales appropriate for health impact assessment should be explored as spatial scales coarser than 10km are unlikely to pick up variations in concentrations that would be reflected in the exposure metrics used in the exposure-response relationships, as acknowledged in (28). The estimates of health impacts would be improved if modelling at this scale also includes changes in meteorology due to climate change (which affects natural emissions such as bVOCs), along with the expected emissions of air pollutants.

Health economic impact assessments should be included within HIAs where possible to help understand and provide evidence to inform decision-makers and that can be used to prioritise different air pollution reduction measures, and that may help in implementation of interventions and in making the case for action.

Within the UK there is limited research conducted on desert dust days and health impacts. Further research conducted into how desert dust episodes may increase levels of PM at ground level will give an indication of the potential threats to public health, or even highlight a different source of heightened PM levels. After the air pollution episode of 2014, during which Saharan desert dust was blamed for the peaks in PM, it was later found to be mainly driven by emissions from Europe. Understanding the sources of PM responsible for episodes will help advise government, local councils and the public on suitable actions to take during these events.

There is a need for an integrated approach to the consideration of both outdoor and indoor air quality resulting from climate action, such as alternative energy (for example, hydrogen gas boilers), energy retrofit and nature-based solutions such as greening (see Chapters 5 and 14).

While some reviews have examined the interactive effect of air pollution and temperature, the evidence is not clear and further work is needed to understand the evidence for the health effects due to exposure to short-term O_3 being modified by increases in temperature. UKHSA is undertaking a review in this area.

A better understanding is required of how behaviours will change due to the impacts of climate change, and influence personal exposure to air pollution, for example more time spent outdoors due to warmer temperature, as well as indoor exposures (see Chapter 5).

6.2 Implications for public health

In relation to short-term air pollution episodes (including transboundary pollution), further development of the existing alert and monitoring systems to provide data on exposure to various air pollutants (and PM components) for health studies; relevant information should be also considered for applying measures to reduce population exposure during high air pollution events, which may worsen with climate change.

Raising awareness of air pollution impacts itself will not automatically encourage a change in behaviour to reduce a person's exposure to air pollution. However, by improving the accessibility and quality of information relating to the health harms due to air pollution, ensuring that it is easy to understand and relevant to individuals, for example providing air pollution levels in the local area and how they will impact the health of the general public and those more vulnerable, it will ensure that people have the capability, opportunity and motivation to make a change to limit their exposure.

Explore whether the alerting system needs to be expanded to incorporate other environmental stressors, for example heat, pollen and noise, as our understanding of combined effects improves.

Acronyms and abbreviations

Abbreviation	Meaning
25YEP	25 Year Environment Plan
AF	attributable fraction
APHEA	Air Pollution and Health: A European Approach project
AQEG	Air Quality Expert Group
AQUM	Air Quality in the Unified Model
bVOCS	biogenic volatile organic compounds
CH_4	methane
CLRTAP	Convention on Long-Range Transboundary Air Pollution
COMEAP	Committee on the Medical Effects of Air Pollutants
DAERA	Department of Agriculture Environment and Rural Affairs
Defra	Department for Environment, Food and Rural Affairs
DHSC	Department of Health and Social Care
EVs	electric vehicles
GHG	greenhouse gas
H_2	hydrogen
HECC	Health Effects of Climate Change in the UK report
HIA	health impact assessment
NH_3	ammonia
NMVOCs	Non-methane VOCs
NO_2	nitrogen dioxide
O_3	ozone
PM	particulate matter
RCP	representative concentration pathways
RR	relative risk
RS2021	Royal Society 2021 report
VAAC	Volcanic Ash Advisory Centre
VOCs	volatile organic compounds

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