Article (refereed) - postprint

Heal, Mathew R.; Heaviside, Clare; Doherty, Ruth M.; Vieno, Massimo; Stevenson, David S.; Vardoulakis, Sotiris. 2013. **Health burdens of surface ozone in the UK for a range of future scenarios**.

Health burdens of surface ozone in the UK for a range of future scenarios

Mathew R. Heal[1*], Clare Heaviside[2], Ruth M. Doherty[3], Massimo Vieno[4], David S. Stevenson[3], Sotiris Vardoulakis[2]

[1]School of Chemistry, The University of Edinburgh, Joseph Black Building, West Mains Road, Edinburgh, EH9 3JJ, UK

[2]Centre for Radiation, Chemical and Environmental Hazards, Public Health England, Chilton, Oxon, OX11 0RQ, UK

[3]School of GeoSciences, The University of Edinburgh, Crew Building, West Mains Road, Edinburgh, EH9 3JN, UK

[4]NERC Centre for Ecology & Hydrology, Bush Estate, Nr. Penicuik, Midlothian, EH26 0QB, UK

*Corresponding author
Address as above.
Tel: 0131 6504764
Email: m.heal@ed.ac.uk

Highlights

Hourly surface O_3 simulated at high resolution over the UK for different scenarios

Burdens of O_3-attributable mortality and respiratory hospitalizations quantified

Largest increases under a ‘current legislation’ emissions scenario (for 2030)

For 35 ppbv O_3 threshold assumption, health burdens approx order of magnitude smaller

Spatial variation reflects interplay between background O_3 and local NO_x emissions

Abstract

Exposure to surface ozone (O_3), which is influenced by emissions of precursor chemical species, meteorology and population distribution, is associated with excess mortality and respiratory morbidity. In this study, the EMEP-WRF atmospheric chemistry transport model was used to simulate surface O_3 concentrations at 5 km horizontal resolution over the British Isles for a baseline year of 2003, for three anthropogenic emissions scenarios for 2030, and for a +5 °C increase in air temperature on the 2003 baseline. Deaths brought forward and hospitalization burdens for 12 UK regions were calculated from population-weighted daily maximum 8-hour O_3. The magnitude of changes in annual mean surface O_3 over the UK for +5 °C temperature (+1.0 to +1.5 ppbv, depending on region) were comparable to those due to inter-annual meteorological variability (−1.5 to +1.5 ppbv) but considerably less than changes due to precursor emissions changes by 2030 (−3.0 to +3.5 ppbv, depending on scenario and region). Including population changes in 2030, both the 'current legislation' and 'maximum feasible reduction' scenarios yield greater O_3-attributable health burdens than the 'high' emission scenario: +28%, +22%, +16%, respectively, above 2003 baseline deaths brought forward (11,500) and respiratory hospital admissions (30,700), using O_3 exposure over the full year and no threshold for health effects. The health burdens are greatest under the 'current legislation' scenario because O_3 concentrations increase as a result of both increases in background O_3 concentration and decreases in UK NO_x emissions. For the +5 °C scenario, and no threshold (and not including population increases), total UK health burden increases by 500 premature deaths (4%) relative to the 2003 baseline. If a 35 ppbv threshold for O_3 effects is assumed, health burdens are more sensitive to the current legislation and +5 °C scenarios, although total health burdens are roughly an order of magnitude lower. In all scenarios, the assumption of a threshold increases the proportion of health burden in the south

and east of the UK compared with the no threshold assumption. The study highlights that the total, and geographically-apportioned, O_3-attributable health burdens in the UK are highly sensitive to the future trends of hemispheric, regional and local emissions of O_3 precursors, and to the assumption of a threshold for O_3 effect.

Keywords: ozone; health impact assessment; future emissions scenarios; air pollution; climate change.

1 Introduction

Substantial epidemiological evidence exists quantifying acute effects of short-term exposure to ambient ozone (O_3), particularly on mortality and respiratory hospital admissions (Bell et al., 2005; 2006; Levy et al., 2005; Ito et al., 2005; WHO, 2006). Ozone is a secondary pollutant which is not directly emitted into the atmosphere but is created and destroyed by chemical reactions of other emitted species. The most important of these precursors are methane (CH_4) and carbon monoxide (CO), which have lifetimes of weeks to years and which, with emissions of nitrogen oxides ($NO_x = NO+NO_2$), contribute to a general hemispheric 'background' of O_3, and non-methane volatile organic compounds (NMVOC) which influence O_3 formation on a regional and local scale. When NO_x emissions are very high, such as in urban areas, production of O_3 is suppressed. Meteorology also substantially impacts on O_3 via its influences on, for example, rates of chemical reactions, deposition of O_3 to the surface, emissions of biogenic NMVOC, boundary-layer depth, stagnating air pollution episodes and long-range transport.

Ozone precursor emissions are changing, but with different individual precursor trends in different regions around the world, and consequently the relative ratios in precursor emissions are also changing in different ways in different regions (Royal Society, 2008; AQEG, 2009; Lamarque et al., 2010). Consequently, population exposure to O_3 is changing (Royal Society, 2008; Colette et al., 2012; Coleman et al., 2013). Climate change also directly and indirectly modifies surface O_3 through its influence on processes determining emissions, chemistry and dispersion (Royal Society, 2008; Jacob and Winner, 2009; Fiore et al., 2012; Langner et al., 2012; Fang et al., 2013; Doherty et al., 2013). Given these changes, it is pertinent to estimate how the health burdens associated with surface O_3 may change in the future compared with recent levels, which is the focus of this work, for the UK specifically.

Previous estimates of future surface O_3 over the UK have generally been derived either from global models whose horizontal spatial resolutions are a few degrees (~200 km), or by semi-empirical mapping methods (Stedman and Kent, 2008). In this study, a nested atmospheric chemistry transport model has been used to simulate hourly O_3 concentrations at 5 km horizontal resolution across the British Isles for 2003, for three anthropogenic emissions scenarios for 2030, and for a simulation with increased surface temperature (as one sensitivity test for climate change). Simulated O_3 changes are also set in the context of variability of surface O_3 arising from two different years of meteorology. The impacts of these simulated changes in O_3 on regional UK mortality and morbidity from short-term exposure are calculated both with and without inclusion of a threshold concentration for health effects, as recommended by the World Health Organisation (WHO, 2013). Health burdens from simultaneous changes in other air pollutant concentrations are not considered here.

2 Methods

2.1 Atmospheric chemistry transport modelling

The model used here is a grid-based, nested atmospheric chemistry transport model (ACTM) operating at 5 km by 5 km horizontal resolution over a British Isles inner domain (Vieno *et al.*, 2010) derived from the (European Monitoring and Evaluation Programme) EMEP model (Simpson *et al.*, 2012). The chemistry model is driven by the Weather Research Forecast (WRF) model at the same horizontal resolution. The WRF model is constrained by boundary conditions from the US National Center for Environmental Prediction/National Center for Atmospheric Research Global Forecast System at 1° resolution, every 6 hours. Simulations are achieved using a one-way nested domain approach in which modelling over an outer domain at 50 km resolution for Europe provides the boundary conditions for finer-scale modelling over the 5 km inner domain. The model has been extensively evaluated and used for numerous policy applications (Carslaw, 2011; Carslaw et al., 2013; Schultz et al., 2013). Emissions data, including biogenic emissions, were obtained from the UK National Atmospheric Emissions Inventory (naei.defra.gov.uk) for the inner domain covering the British Isles and from EMEP (www.emep.int) for the outer domain covering Europe.

EMEP-WRF v3 simulations were performed using the following three air quality emissions projections, notionally for 2030, derived by the International Institute of Applied Systems Analysis (Dentener *et al.*, 2005):

(1) A2: a scenario based on the IPCC SRES A2 socioeconomic scenario (Nakicenovic *et al.*, 2000), which is generally regarded as 'high' for O_3 precursor emissions, and assuming no additional implementation of air quality legislation;

(2) B2+CLE: a ‘current legislation’ scenario based on the IPCC SRES B2 socioeconomic scenario (Nakicenovic et al., 2000), which is one of the central SRES scenarios, often used as a baseline for global air quality studies (Stevenson et al., 2006), plus adherence to emissions reduction air quality legislation in force in year 2000;

(3) B2+MFR: a ‘maximum feasible reduction’ scenario also based on the IPCC SRES B2 scenario, but including reductions in emissions achievable through implementation of all abatement measures available in 2000, regardless of legislation or cost.

Output from global multi-model simulations set the corresponding global CH_4 abundance (Dentener *et al.*, 2005), and the model outer domain O_3 boundary conditions (Stevenson *et al.*, 2006), appropriate for each scenario. This ensured that the concentrations of the longer-lived CH_4 and O_3 species entering the UK domain were compatible with the emissions projections. The three scenarios span a useful range of potential emissions futures: the A2 scenario sets a likely upper bound on emissions, whilst B2+MFR sets a likely lower bound. These scenarios do not include consideration of climate change. The emissions changes between 2000 and 2030 over the British Isles for the key O_3 precursor species under each scenario are given in Table 1. No changes in the spatial distribution of emissions were applied.

For the simulation to examine the O_3 response to increased temperature, the 2003 base model run was repeated with surface and potential temperatures uniformly increased by 5 °C in the inner domain. Boundary conditions were not changed. The UKCP09 climate projections (ukclimateprojections.defra.gov.uk) indicate that under medium-to-high future greenhouse gas emission scenarios there is a medium-to-high probability of average summer temperature increases of 5 °C over most of the UK in the 2080s. Temperature increase is the only aspect of climate change investigated here but temperature increase has important direct influence on rates of biogenic VOC emissions, gas-phase chemical reaction rates, and O_3 dry deposition. Other effects of climate change, such as its influence on water vapour concentrations or atmospheric dispersion were not investigated.

The baseline experiment was also repeated using 2004 meteorology to provide an indicator of the impact on surface O_3 of a different year's meteorology.

2.2 Health burden assessment methodology

Population health burdens attributable to short-term exposure to O_3 were calculated as follows for the 12 UK administrative regions listed in Table 2:

Daily mortality (or morbidity) = daily O_3 × concentration-response coefficient × baseline mortality (or morbidity) rate × population

In this work, 'daily O_3' refers to the daily maximum running 8-hour mean, as widely used in O_3 health effect studies. Residential population for 2003 at 100 m × 100 m resolution for England, Wales and Scotland were taken from the UK National Population Database 2 (NPD2) (Smith et al., 2005) and aggregated to each EMEP-WRF 5 km × 5 km grid cell. Health burdens were calculated by multiplying the exposed population by the O_3 concentration in each model cell, then summing all cells within each administrative region, and dividing by the total regional population to give a population-weighted mean O_3 exposure per region. The NPD2 did not cover Northern Ireland, so geographical mean O_3 rather than population-weighted O_3 was used. Population estimates for 2030 were derived by linear interpolation between projections by the ONS (www.statisics.gov.uk) for 2026 and 2031 (English regions) and 2028 and 2033 (Wales, Scotland and Northern Ireland).

To quantify premature mortality, an all-cause mortality concentration-response coefficient of 0.3% (95% confidence interval 0.1%–0.4%) per 10 μg m^{-3} increase in daily maximum running 8-hour mean O_3 was used (0.6%, CI: 0.2%–0.8%) increase per 10 ppbv O_3), as recommended by the World Health Organisation (WHO, 2004) and used in previous UK studies (Stedman and Kent, 2008; Hames and Vardoulakis, 2012). To quantify morbidity, a concentration-response coefficient of 1.4% (CI: 0.8%–2%) increase in respiratory hospital admissions per 10 ppbv increase in daily maximum running 8-hour mean O_3 was used (COMEAP, 1998). (The latter CI is based on those for the European APHEA studies from which the COMEAP central estimate is derived.) The uncertainty in a health response coefficient, as characterised by its confidence interval, propagates linearly through the health burden calculation. Thus the confidence interval on the central estimate of any mortality health burden ranges from 33%−133% of the central estimate; the confidence interval of any respiratory hospital admission health burden ranges from 57%−143% of the given central estimate. Relative patterns of health burden across regions, scenarios and threshold assumptions are unaffected.

Daily baseline mortality rates for all causes, excluding external, were calculated based on a mean of values for each day of the year between 1993 and 2006 and for each of the 12 regions using data obtained from the ONS. Daily baseline morbidity data were not available, so an annual baseline morbidity rate (divided by 365) was used, derived from emergency respiratory hospital admissions between 2005 and 2008 obtained from NHS Hospital Episode

Statistics (www.hesonline.nhs.uk). The same mortality and morbidity rates were assumed for 2030.

Current evidence of a threshold for health effects associated with short-term exposure to O_3 is not consistent (WHO, 2013). Therefore, daily O_3-attributable premature mortality and hospitalizations, for each UK region, were calculated assuming both no threshold, and a threshold of 35 ppbv (70 μg m^{-3}) for O_3 health effects, as is currently recommended (UNECE/WHO, 2004; WHO, 2013). Health burdens were summed for the whole year of exposure.

3 Results

3.1 Surface ozone concentrations

3.1.1 Anthropogenic emissions scenarios

Figure 1 illustrates the changes in annual mean surface O_3 across the UK between 2003 and 2030 for the three different emissions scenarios. The regional annual population-weighted means of the daily maximum 8-hour O_3 for the baseline and three future scenarios are given in Table 2. In 2003 the highest annual O_3 concentrations were predominately in the northern and western regions of the UK (Scotland, Northern Ireland, Wales and South West England) and the lowest concentrations were in the eastern regions associated with greatest urbanisation and higher NO_x emissions (London, East Midlands, and Yorkshire and Humberside).

For the future emissions scenarios, the key features from Figure 1 and Table 2 are: for the B2+CLE scenario, increases in annual O_3 of 1.5-3 ppbv everywhere over the UK (up to 3.5

ppbv in London); for the A2 scenario, decreases over most of England (except the far north), reaching −2 ppbv in urban areas and −3 ppbv in the London area (Table 2), and increases of 0-3 ppbv everywhere else; and, for the B2+MFR scenario, largely the reverse of the pattern under A2 (increases of 0-3 ppbv over most of England, plus south Wales, Edinburgh-Glasgow and Belfast, and decreases up to −1.5 ppbv elsewhere).

These changes in UK surface O_3 reflect differences in the amount of background O_3 (approximately set by the boundary conditions in Table 1), in conjunction with differences due to changes in UK NO_x emissions that influence the extent of O_3 removal through reaction with NO in high NO_x (i.e. urban) regions. Thus in the A2 scenario background O_3 increases because of hemispheric increases in O_3 precursors, including CH_4 and CO, but the increased NO_x emissions (primarily related to traffic density and power generation) lead to increased loss of O_3 by reaction with NO. This effect is prominent over most major UK cities and areas of greatest population density (Figure 1). The greater annual mean surface O_3 concentration over most of England for the B2+MFR scenario is due to the substantial reductions in NO_x emissions causing a decrease in the loss of O_3 by this chemical reaction; again a prominent feature over UK cities (Figure 1). These localised O_3 increases are superimposed on the general decrease in background O_3 in this scenario. The O_3 changes are greatest under the B2+CLE scenario (Scotland excepted), since O_3 concentrations increase because of both increases in background O_3 concentration (as in the A2 scenario) and decreases in UK NO_x emissions (as in the B2+MFR scenario) (Table 1).

3.1.2 Temperature sensitivity

The change in surface O_3 for a +5 °C uniform increase in temperature for the whole year (compared with the 2003 baseline) is also shown in Figure 1. The +5 °C perturbation increases annual mean surface O_3 everywhere, with the largest increases (1.0-1.5 ppbv) in south and east England. Population-weighted annual mean daily maximum 8-hour O_3 increases in the south-east are up to 1.8 ppbv (Table 2). These changes in UK annual surface O_3 due to a higher temperature are generally lower than potential changes due to 2030 emissions changes although the higher temperature consistently yields increased surface O_3.

In these simulations it was not possible to quantify the key processes producing the O_3 increases; however simulations by Vieno et al. (2010) showed the main influence of elevated temperature on O_3 in southern UK in August 2003 was via enhanced biogenic isoprene emission, although other factors such as dry deposition rate and transboundary import also contributed to the elevated O_3 in this region at this time. Likewise, Doherty et al. (2013), in simulations for 2095 which included aspects of climate change, also showed the largest effect of temperature on surface O_3 in mid-latitude polluted areas was through elevated isoprene emissions; but they also noted O_3 increases resulting from enhanced decomposition of peroxyacetylnitrate (a temporary atmospheric reservoir species for NO_x). In these polluted mid-latitude regions, the above effects continue to outweigh O_3 decreases due to higher water vapour concentrations under simulated future climate to 2095.

3.1.3 Inter-annual variability

Figure 2 shows that annual mean surface O_3 was greater over much of southern England in 2003, which included elevated O_3 in August (Lee *et al.*, 2006; Vieno *et al.*, 2010), but was greater in 2004 over much of the northern UK. This illustration of the impact on surface O_3 from changes due to regional meteorology alone (−1.5 to +1.5 ppbv) can be compared with the general magnitude of impacts on surface O_3 from potential changes in emissions to 2030 (−3.0 to +3.5 ppbv, depending on scenario) shown in Figure 1. Whilst the O_3 changes due to inter-annual variability in meteorology are smaller they are nonetheless considerable, being up to ~50% (depending on scenario) of the changes projected to 2030 from anthropogenic emissions changes. They are also of comparable magnitude to those simulated for the +5 °C increase in temperature. Although only two meteorological years were investigated in this work, the range in inter-annual variability of surface O_3 shown here (~8%) is comparable with a study of inter-annual variability of O_3 over Europe for the period 1958-2003 which reported typical year-to-year variability over the UK of ~10% (Andersson and Langner, 2007).

3.2 Health burdens

3.2.1 2003 baseline

Premature mortality and morbidity health burdens in the UK attributable to O_3 are given in Supplementary Information Tables S1 and S2, respectively. Regional health burden rates expressed per 100,000 population are also included. The regional mortality burdens are illustrated in Figure 3. When no threshold is assumed, a total of 11,500 deaths brought forward and 30,700 hospitalizations in 2003 are attributable to O_3. Attributable health burdens are highest in the South East and North West regions (Figure 3a and Tables S1 & S2), where population is high (Table 2), but the underlying O_3-attributable mortality and morbidity rates (Tables S1 & S2) are greatest in Scotland, Wales and the South West, where annual mean O_3 concentrations are greatest (Table 2).

If a threshold for O_3 effects of 35 ppbv is assumed then total UK annual premature mortality attributable to O_3 in 2003 drops dramatically from 11,500 (no threshold) to 1,160 (Figure 3b and Table S1). Similarly, O_3-attributable hospitalizations in 2003 decrease from 30,700 to 3,210 if a 35 ppbv threshold is assumed (Table S2). There is an important shift in the geographical distribution of the health burdens if a threshold for O_3 effect is assumed. Supplementary Information Figure S1 shows that more of the attributable health burden is distributed in the north of the UK relative to the south if no threshold is assumed, but more is distributed in the south if a 35 ppbv threshold is assumed, albeit that absolute burdens are about 10 times lower in the latter case.

3.2.2 2030 projections

The annual health burdens for premature mortality and morbidity attributable to O_3 under the three different emissions scenarios are also given in Tables S1 and S2, and the mortality data are presented graphically in Figure 3.

When no threshold for O_3 health effect is assumed, all three 2030 scenarios project increased mortality and hospitalization in all regions compared with 2003, but the % changes varies markedly between regions. The greatest health burdens are associated with the B2+CLE scenario. This scenario gives increases in total UK premature mortality and hospitalizations of 3,200 and 8,400 respectively, which is a 28% increase on their 2003 values of 11,500 and 30,700, respectively. These health burden increases are not only driven by the increase in UK population, which is 18% greater in 2030 than in 2003 (Table 2), but reflect the increase in surface O_3 over most of the UK under this scenario (Figure 1). Regional health burden increases under the B2+CLE scenario vary between 16% for Scotland and 38% for East England. The A2 scenario projects a 16% increase in UK premature mortality and hospitalizations in 2030, with regional increases ranging between 8% for the North West and 25% for Northern Ireland. The B2+MFR scenario projects a 22% increase in total UK health burden, with regional increases ranging between 9% for Scotland and 33% for East England and London. Thus, over the whole of the UK, both the 'current legislation' and 'maximum feasible reduction' scenarios lead to greater total health burden from O_3 in 2030 than the 'high' emission A2 scenario.

As well as giving the largest increase in total UK health burden attributable to O_3, the B2+CLE scenario also leads to the largest health burden in every region except for Northern Ireland, whose health burden is slightly larger under the A2 scenario (Tables S1 & S2). In this western location the increase in background hemispheric O_3 under the A2 scenario is slightly greater than the increase arising from declining regional NO_x emissions (Figure 1). In contrast, the increase in mortality and hospitalization is larger for the B2+MFR scenario than for the A2 scenario in the more densely populated predominately eastern regions (London, the South East, East England and the East and West Midlands), whereas the increase in health burdens is smaller for the B2+MFR scenario than the A2 scenario for the less populated regions of Scotland, Northern Ireland and Wales. In fact, for these latter regions it is the increase in population that drives the increase in absolute health burdens under the B2+MFR scenario since mean surface O_3 decreases in these regions under this scenario (Figure 1, and as discussed in Section 3.1).

The impact of increased population is removed by examination of the annual O_3-attributable mortality and morbidity rates per 100,000 population (Tables S1 & S2). The changes in these mortality rates between 2003 and 2030 for the different scenarios are illustrated in Figure 4. (Patterns in changes in hospitalizations are the same.) The B2+CLE scenario gives increases in mortality rate everywhere, and the largest increases in mortality rates of all scenarios investigated for all regions except Northern Ireland (Figure 4a). For the A2 scenario there is significant regional variation in changes in mortality rate, with substantial increases in Scotland and Northern Ireland, but substantial decreases in London, the South East and East

England (Figure 4a). Changes in mortality rate are generally smaller under the B2+MFR scenario, with small increases in the south and east of the UK, small decreases in Northern Ireland and almost no change in Scotland, Wales and the South West.

When a 35 ppbv threshold is assumed, the total UK health burdens in 2030 for the three different scenarios are very roughly an order of magnitude lower compared with no threshold, but there are marked differences in the relative changes from the 2003 burdens (Figure 3 and Tables S1 & S2). With a 35 ppbv threshold assumption, there is a 52% increase in attributable mortality and morbidity on 2003 totals for the B2+CLE scenario compared with the 28% increase on 2003 totals for this scenario when no threshold is assumed. On the other hand, the A2 and B2+MFR scenarios both project smaller mortality and morbidity increases of, respectively, 8% and 13% for 2030 compared with 2003 than the 16% and 22% increases in 2030 for these two scenarios when no threshold is assumed. This reflects that the B2+CLE scenario increases surface O_3 everywhere thereby increasing the number of days with daily maximum 8-hour O_3 above 35 ppbv, whereas the A2 and B2+MFR scenarios have relatively more impact on the background O_3 which is lower than 35 ppbv.

As with the no threshold assumption, all regions show an increase in health burden rate for the B2+CLE scenario with a 35 ppbv threshold (Figure 4b), and this increase is again greatest out of the three scenarios in all regions except Northern Ireland where greatest increase in health burden rate is for the A2 scenario. For the A2 scenario and a 35 ppbv threshold, the less densely populated regions of Scotland, Northern Ireland and Wales (and, to less extent, North East and South West England) have increased health burden rate (Figure 4b), whilst all other regions have decreased health burden rate. Taking into account population changes, most regions have increased mortality and morbidity in 2030 under this scenario (Figure 3 and Tables S1 and S2) although London shows a significant decrease (−25%) because of the strong O_3 decrease through reaction with NO in this densely urbanised region. For the B2+MFR scenario and a 35 ppbv threshold, everywhere except London and East England shows a decrease in O_3 health burden rate in 2030 (Figure 4b); but after taking into account health burden changes due to projected population changes, only the more rural regions in the north and west of the UK such as Scotland, Northern Ireland, North East England and Wales have no change (or small decreases) in mortality and morbidity, whilst the other regions show an increase (Tables S1 and S2).

In summary, if a threshold is assumed, health burden distributions under the B2+MFR scenario enhance the contrast between the more urbanised eastern and southern UK and the less densely populated Scotland, Northern Ireland and Wales. On the other hand, health burdens (with threshold) under the A2 scenario are more evenly distributed geographically.

3.2.3 Temperature sensitivity

The mortality burdens for the +5 °C perturbation (c.f. 2003 baseline) are presented in Figure 3 and Table S3. Morbidity results (not shown) have similar trends. Since no changes in population are included in these data the changes in absolute numbers of health burden shown in Figure 3 and Table S3 directly reflect the changes in exposure to O_3. Mortality rates per 100,000 population are included to enable direct comparison with data in Table S1 for the three 2030 emissions scenarios. The changes in mortality rates from baseline are shown in Figure 4.

Regardless of O_3 threshold assumption, the health burden increases in the +5 °C temperature simulation for all regions of the UK, since surface O_3 increases in all regions, although the magnitude of increase varies by region (Figure 1 and Table 2). Under the assumption of no threshold for O_3 health effect, total UK mortality increases by 500 premature deaths, or by 4% on the baseline mortality of 11,500 (Figure 3a and Tables S1 & S2). The largest increases in health burden occur in the south eastern parts of the UK (Figure 1d) coincident with the highly populated regions of London, South East and East England and the smallest increases occur in the North and West and less densely populated regions of the UK (Scotland, Northern Ireland and Wales). When a threshold for O_3 health effect is assumed, the +5 °C scenario shows a proportionally much greater increase in total UK mortality of 30% above the 2003 baseline, but the absolute mortality numbers are again considerably lower than for the no threshold assumption (350 extra deaths brought forward above the corresponding baseline of 1,160) (Figure 3b).

4 Discussion

The three 2030 scenarios used here show that, depending on anthropogenic precursor emissions trends, surface O_3 in different parts of the UK may increase or decrease. Background O_3 is particularly influenced by global levels of CH_4 and hence by CH_4 controls (Stevenson *et al.*, 2006; Wild *et al.*, 2012). The B2+CLE scenario has increased background O_3 (Table 1) but reductions in regional NO_x. It is the reductions in UK NO_x emissions which lead to localised increases in O_3 in urban locations, especially over south-east England, due to reduced reactive removal with NO. This is consistent with the findings of Collete et al. (2012) for this region. The double effect of increased background and reduced removal by NO pushes more daily maximum 8-hour O_3 concentrations over 35 ppbv for this scenario. For the B2+MFR scenario, although the lower NO_x emissions lead to increased O_3 in highly urbanised areas, the decrease in background O_3 yields lower annual mean O_3 and relatively fewer days exceeding 35 ppbv compared with the B2+CLE scenario. The potential for different changes to mean and higher quantiles of O_3 distribution caused by precursor emissions changes has been noted before (Vautard *et al.*, 2006; Wilson *et al.*, 2012; Colette *et al.*, 2012).

The range in changes of surface O_3 over the UK across the three future emission scenarios investigated are larger than the changes simulated under a 5 °C increase in air temperature. However, the latter leads to an increase in surface O_3 everywhere. Although it is not possible to make definitive statements regarding the relative influence of emissions scenarios versus climate change it is noted that the UKCP09 climate projections suggest that temperature increases of the order of 5 °C are not likely to occur until the 2080s, depending on greenhouse gas emission scenario followed (http://ukclimateprojections.defra.gov.uk). A number of recent regional modelling studies have also shown the effects of emissions changes on surface O_3 in Europe to be generally larger than those due to climate change projected to 2100 (Coleman et al., 2013; Fang et al., 2013; Hedegaard et al., 2013). Hence, in the near term, the effects of precursor emission changes and inter-annual meteorological variability on annual-mean surface O_3 are likely to outweigh the effects of changes in temperature or other effects of climate change.

The total UK mortality and hospitalisation burdens presented here for 2003 are broadly comparable with earlier studies (Stedman and Kent, 2008; Hames and Vardoulakis, 2012) but there are differences in O_3 modelling and baseline health rates used. A feature here was the use of daily O_3 and health data and application of population-weighting to the individual 5 km × 5 km grid O_3 concentrations. The use of a daily baseline mortality rate rather than a single annual rate takes account of seasonal variations in mortality. The relative extent and geographical distribution of adverse health burden of exposure to surface O_3 follows the simulated O_3 concentrations, but health burdens are also highly sensitive to whether a threshold concentration of O_3 below which no health effect is assumed. When no threshold for a health effect of O_3 is assumed, the annual total health burden from daily exposures is little affected by how the O_3 concentration varies from day to day, but if a threshold is assumed then days of highest O_3 contribute most to the estimated annual burden on health. Taking O_3 exposure over the full year as relevant the health burdens with a 35 ppbv threshold are roughly an order of magnitude lower than if no threshold is assumed, but there is a relatively greater increase in health burden in the B2+CLE and +5°C temperature scenarios. The assumption of a threshold also enhances the geographical differences in health burdens: the B2+MFR scenario emphasises a health burden differential between the more urbanised eastern and southern UK and the less densely populated north and west, whilst for the A2 scenario health burdens are more evenly distributed.

It is important to recognise that the simulated O_3 concentrations are derived from a single model, albeit a widely used and evaluated CTM (Carslaw, 2011; Carslaw et al., 2013; Schultz et al., 2013). Nevertheless, considerable inter-model variability in simulation of O_3 has been noted elsewhere (Stevenson *et al.*, 2006; Colette *et al.*, 2012). The greatest uncertainties in simulated O_3 pertinent to future scenarios relate to uncertainty in O_3 precursor emissions, particularly from climate-sensitive biogenic sources (Guenther et al., 2012; Langner et al., 2012) and in parameterisations of O_3 dry deposition especially under drought conditions (Emberson *et al.*, 2012). Many other potential meteorological influences of climate change may be relevant, including changes in humidity and in atmospheric transport and mixing processes, e.g. boundary layer depth, storm tracks and blocking highs. However, as highlighted above, future changes in anthropogenic emissions are generally found to be more important than changes in meteorology for changes in mean surface O_3 (Fiore et al., 2012; Hedegaard et al., 2013) and in O_3 exceedences (Coleman *et al.*, 2013).

Different health burden attribution methodologies may also yield different results. For example, there are uncertainties in the magnitude of concentration-response coefficients. Coefficients used here are derived from consideration of (mainly) full-year time series studies that focus on short-term population exposure to O_3, and in this work O_3 exposure over the full year was considered, a position supported by a recent review (WHO, 2013). Issues surrounding potential modification of the health effect of O_3 by temperature are unresolved (Filleul et al., 2006; Ren et al., 2008; Pattenden et al., 2010; Atkinson et al., 2012). Complications also arise due to seasonally-varying correlations between O_3 and other air pollutants with health effects, particularly particulate matter (PM). However, most studies find the effects of O_3 are relatively independent of those of PM (WHO, 2006). It has been assumed that regional daily baseline mortality and morbidity rates remain constant in the future. Coefficients and threshold values were applied equally to all UK population demography, and to future populations. Regarding the latter, it is not possible to predict with certainty changes in concentration-response coefficients and threshold effects of any autonomous or planned adaptation to future O_3 levels or to future climate change (Knowlton et al., 2004).

5 Conclusions

Under future emissions scenarios, simulated concentrations of surface O_3 in the UK are highly sensitive to the interplay between levels of hemispheric background O_3 and, especially in urban locations, the magnitude of local NO_x emissions. Potential changes in surface O_3 due to precursor emissions changes by 2030 are larger in magnitude (−3.0 to +3.5 ppbv, depending on scenario assumed) than those due to inter-annual variability from meteorological influences (−1.5 to +1.5 ppbv), and also larger than the surface O_3 increases under a +5 °C temperature scenario (1.0 to 1.5 ppbv, depending on geographic area).

Including estimated population increases, both the B2+CLR 'current legislation' and B2+MFR 'maximum feasible reduction' emissions scenarios lead to greater UK health burden attributable to O_3 in 2030 than the A2 'high' emissions scenario: increases in deaths brought forward or hospitalisations on 2003 values of 28%, 22% and 16% for the three scenarios, respectively. Geographical contrasts are particularly notable between the densely populated areas in the south east of the UK and the more rural regions in the north and west. For all scenarios, relatively more of the O_3 health burden is distributed in the north and west UK if no threshold for O_3 health effects is assumed, and relatively more in the south and east if a threshold of 35 ppbv is assumed, but total health burdens are roughly an order of magnitude lower for the latter.

Under a +5 °C temperature perturbation (and not including changes in other meteorological variables or population) total modelled UK health burden increases by 4% (corresponding to 500 additional deaths brought forward), if no O_3 threshold is assumed, or by 30% (350 additional deaths brought forward) for a 35 ppbv threshold. These data reflect that the impact of increased temperature is to increase the instances of daily O_3 above 35 ppbv.

Overall, this study highlights that total, and geographically-distributed, O_3-attributable health burdens in the UK are highly sensitive to the future trends in hemispheric, regional and local emissions of O_3 precursors, and to the assumption of a threshold for O_3 health effects. It is an important issue for policy-makers that maintaining the status quo on airshed management is in some areas unlikely to reduce surface O_3 and that a more customised analysis of the VOC/NO_x regime is required.

Acknowledgements

This paper is based on work undertaken for the Health Protection Agency report "Health Effects of Climate Change in the UK 2012 - current evidence, recommendation and research gaps" sponsored by the Department of Health (Vardoulakis and Heaviside, 2012). MRH, RMD, MV and DSS acknowledge funding from the NERC Environment & Human Health Programme under grant NE/E008593 for which Professor Paul Wilkinson of the London School of Hygiene and Tropical Medicine was Principal Investigator. The development of the UK version of the EMEP model is supported jointly by the UK Department for the Environment, Food and Rural Affairs and the NERC Centre for Ecology & Hydrology.

References

Andersson, C., Langner, J., 2007. Inter-annual variations of ozone and nitrogen dioxide over Europe during 1958–2003 simulated with a regional CTM. Water, Air, & Soil Pollution: Focus 7, 15-23.

AQEG, 2009. Ozone in the United Kingdom. Fifth report of the Air Quality Expert Group., UK Department for Environment, Food and Rural Affairs, PB13216. ISBN 978-0-85521-184-4., London.

Atkinson, R. W., Yu, D., Armstrong, B. G., Pattenden, S., Wilkinson, P., Doherty, R. M., Heal, M. R., Anderson, H. R., 2012. Concentration-response function for ozone and daily mortality: results from five urban and five rural UK populations. Environmental Health Perspectives 120, 1411-1417.

Bell, M. L., Dominici, F., Samet, J. M., 2005. A meta-analysis of time-series studies of ozone and mortality with comparison to the national morbidity, mortality, and air pollution study. Epidemiology 16, 436-445.

Bell, M. L., Peng, R. D., Dominici, F., 2006. The exposure-response curve for ozone and risk of mortality and the adequacy of current ozone regulations. Environmental Health Perspectives 114, 532-536.

Carslaw, D., 2011. Defra regional and transboundary model evaluation analysis - Phase 1, A report for Defra and the Devolved Administrations, http://uk-air.defra.gov.uk/reports/cat20/1105091514_RegionalFinal.pdf.

Carslaw, D., Agnew, P., Beevers, S., et al, 2013. Defra Phase 2 regional model evaluation analysis, A report for Defra and the Devolved Administrations, http://uk-air.defra.gov.uk/reports/.

Coleman, L., Martin, D., Varghese, S., Jennings, S. G., O'Dowd, C. D., 2013. Assessment of changing meteorology and emissions on air quality using a regional climate model: Impact on ozone. Atmospheric Environment 69, 198-210.

Colette, A., Granier, C., Hodnebrog, Ø., et al , 2012. Future air quality in Europe: a multi-model assessment of projected exposure to ozone. Atmospheric Chemistry and Physics 12, 10613-10630.

COMEAP, 1998. Quantification of the effects of air pollution on health in the United Kingdom, Committee on the Medical Effects of Air Pollution, HMSO, London.

Dentener, F., Stevenson, D., Cofala, J., Mechler, R., Amann, M., Bergamaschi, P., Raes, F., Derwent, R., 2005. The impact of air pollutant and methane emission controls on tropospheric ozone and radiative forcing: CTM calculations for the period 1990-2030. Atmospheric Chemistry and Physics 5, 1731-1755.

Doherty, R. M., Wild, O., Shindell, D. T., Zeng, G., MacKenzie, I. A., Collins, W. J., Fiore, A. M., Stevenson, D. S., Dentener, F. J., Schultz, M. G., Hess, P., Derwent, R. G., Keating, T. J., 2013. Impacts of climate change on surface ozone and intercontinental ozone pollution: A multi-model study. Journal of Geophysical Research: Atmospheres 118, doi:10.1002/jgrd.50266.

Emberson, L. D., Kitwiroon, N., Beevers, S., Büker, P., Cinderby, S., 2012. Scorched earth: how will changes in ozone deposition caused by drought affect human health and ecosystems? Atmospheric Chemistry and Physics Discussions 12, 27847-27889.

Fang, Y., Naik, V., Horowitz, L. W., Mauzerall, D. L., 2013. Air pollution and associated human mortality: the role of air pollutant emissions, climate change and methane concentration increases from the preindustrial period to present. Atmospheric Chemistry and Physics 13, 1377-1394.

Filleul, L., Cassadou, S., Medina, S., Fabres, P., Lefranc, A., Eilstein, D., Le Tertre, A., Pascal, L., Chardon, B., Blanchard, M., Declercq, C., Jusot, J. F., Prouvost, H., Ledrans, M., 2006. The relation between temperature, ozone, and mortality in nine French cities during the heat wave of 2003. Environmental Health Perspectives 114, 1344-1347.

Fiore, A. M., Naik, V., Spracklen, D. V., et al , 2012. Global air quality and climate. Chemical Society Reviews 41, 6663-6683.

Guenther, A. B., Jiang, X., Heald, C. L., Sakulyanontvittaya, T., Duhl, T., Emmons, L. K., Wang, X., 2012. The Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2.1): an extended and updated framework for modeling biogenic emissions. Geosci. Model Dev. 5, 1471-1492.

Hames, D., Vardoulakis, S., 2012. Climate Change Risk Assessment for the Health Sector. UK 2012 Climate Change Risk Assessment, Defra. http://randd.defra.gov.uk/Document.aspx?Document=10077_CCRAfortheHealthSector16July2012.pdf.

Hedegaard, G. B., Christensen, J. H., Brandt, J., 2013. The relative importance of impacts from climate change vs. emissions change on air pollution levels in the 21st century. Atmospheric Chemistry and Physics 13, 3569-3585, http://www.atmos-chem-phys.net/13/3569/2013/acp-13-3569-2013.pdf.

Ito, K., De Leon, S. F., Lippmann, M., 2005. Associations between ozone and daily mortality - Analysis and meta-analysis. Epidemiology 16, 446-457.

Jacob, D. J., Winner, D. A., 2009. Effect of climate change on air quality. Atmospheric Environment 43, 51-63.

Knowlton, K., Rosenthal, J. E., Hogrefe, C., Lynn, B., Gaffin, S., Goldberg, R., Rosenzweig, C., Civerolo, K., Ku, J. Y., Kinney, P. L., 2004. Assessing ozone-related health impacts under a changing climate. Environmental Health Perspectives 112, 1557-1563.

Lamarque, J. F., Bond, T. C., Eyring, V., et al , 2010. Historical (1850-2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application. Atmospheric Chemistry and Physics 10, 7017-7039.

Langner, J., Engardt, M., Baklanov, A., Christensen, J. H., Gauss, M., Geels, C., Hedegaard, G. B., Nuterman, R., Simpson, D., Soares, J., Sofiev, M., Wind, P., Zakey, A., 2012. A multi-model study of impacts of climate change on surface ozone in Europe. Atmospheric Chemistry and Physics 12, 10423-10440.

Lee, J. D., Lewis, A. C., Monks, P. S., et al , 2006. Ozone photochemistry and elevated isoprene during the UK heatwave of August 2003. Atmospheric Environment 40, 7598-7613.

Levy, J. I., Chemerynski, S. M., Sarnat, J. A., 2005. Ozone exposure and mortality - An empiric Bayes metaregression analysis. Epidemiology 16, 458-468.

Nakicenovic, N., Swart, R., Alcamo, J., Davis, G., Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Gruebler, A., 2000. Special Report on Emissions Scenarios. Working Group III of the Intergovernmental Panel on Climate Change (IPCC)., Cambridge University Press, Cambridge. ISBN 0-521-80493-0.

Pattenden, S., Armstrong, B. G., Milojevic, A., Heal, M. R., Chalabi, Z., Doherty, R., Barratt, B., Kovats, R. S., Wilkinson, P., 2010. Ozone, heat and mortality: acute effects in 15 British conurbations. Occupational & Environmental Medicine 67, 699-707.

Ren, C., Williams, G. M., Mengersen, K., Morawska, L., Tong, S., 2008. Does temperature modify short-term effects of ozone on total mortality in 60 large eastern US communities? - An assessment using the NMMAPS data. Environment International 34, 451-458.

Royal Society, 2008. Ground-level ozone in the 21st century: future trends, impacts and policy implications. Science Policy Report 15/08., The Royal Society, London. ISBN: 978-0-85403-713-1. http://royalsociety.org/policy/publications/2008/ground-level-ozone/.

Schultz, M., Gauss, M., Benedictow, A., et al, 2013. Transboundary Acidification, Eutrophication and Ground Level Ozone in Europe in 2011. EMEP Status Report 2013., Norwegian Meteorological Institute, Oslo, Norway. ISSN 1504-6192. http://emep.int/publ/reports/2013/EMEP_status_report_1_2013.pdf.

Simpson, D., Benedictow, A., Berge, H., et al , 2012. The EMEP MSC-W chemical transport model - technical description. Atmospheric Chemistry and Physics 12, 7825-7865.

Smith, G., Arnot, C., Fairburn, J., Walker, G., 2005. A national population database for major accident hazard modelling, HSE Books, Sudbury. www.hse.gov.uk/research/rrpdf/rr297.pdf.

Stedman, J. R., Kent, A. J., 2008. An analysis of the spatial patterns of human health related surface ozone metrics across the UK in 1995, 2003 and 2005. Atmospheric Environment 42, 1702-1716.

Stevenson, D. S., Dentener, F. J., Schultz, M. G., et al , 2006. Multimodel ensemble simulations of present-day and near-future tropospheric ozone. Journal of Geophysical Research 111, D08301, doi:10.1029/2005JD006338.

UNECE/WHO, 2004. Modelling and assessment of the health impact of particulate matter and ozone, Joint Task Force on the Health Aspects of Air Pollution, http://www.unece.org/env/documents/2004/eb/wg1/eb.air.wg1.2004.11.e.pdf.

Vardoulakis, S., Heaviside, C., 2012. Health Effects of Climate Change in the UK 2012 - Current evidence, recommendations and research gaps, Health Protection Agency. Centre for Radiation, Chemical and Environmental Hazards, UK. www.hpa.org.uk/hecc2012.

Vautard, R., Szopa, S., Beekmann, M., Menut, L., Hauglustaine, D. A., Rouil, L., Roemer, M., 2006. Are decadal anthropogenic emission reductions in Europe consistent with surface ozone observations? Geophysical Research Letters 33.

Vieno, M., Dore, A. J., Stevenson, D. S., Doherty, R., Heal, M. R., Reis, S., Hallsworth, S., Tarrason, L., Wind, P., Fowler, D., Simpson, D., Sutton, M. A., 2010. Modelling surface ozone during the 2003 heat-wave in the UK. Atmospheric Chemistry and Physics 10, 7963-7978.

WHO, 2004. Meta-analysis of time-series studies and panel studies of particulate matter and ozone. EUR/04/5042688, World Health Organisation, Bonn. http://www.euro.who.int/document/e82792.pdf.

WHO, 2006. *Air quality guidelines. Global update 2005. Particulate matter, ozone, nitrogen dioxide and sulfur dioxide.*, World Health Organisation Regional Office for Europe, Copenhagen. ISBN 92 890 2192 6. http://www.euro.who.int/__data/assets/pdf_file/0005/78638/E90038.pdf.

WHO, 2013. Review of evidence on health aspects of air pollution – REVIHAAP Project: first results, World Health Organisation, Copenhagen, Denmark. http://www.euro.who.int/__data/assets/pdf_file/0020/182432/e96762-final.pdf.

Wild, O., Fiore, A. M., Shindell, D. T., et al , 2012. Modelling future changes in surface ozone: a parameterized approach. Atmospheric Chemistry and Physics 12, 2037-2054.

Wilson, R. C., Fleming, Z. L., Monks, P. S., Clain, G., Henne, S., Konovalov, I. B., Szopa, S., Menut, L., 2012. Have primary emission reduction measures reduced ozone across Europe? An analysis of European rural background ozone trends 1996–2005. Atmospheric Chemistry and Physics 12, 437-454.

Table 1: Percentage changes in annual anthropogenic emissions between 2000 and 2030 for the EMEP-WRF British Isles inner domain, and the changes in CH_4 and average O_3 mixing ratios at the inner domain boundary over their 2003 values given in parentheses.

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

Table 2. UK administrative regions and their populations in 2003 and 2030. Also included are the regional population-weighted annual mean daily maximum 8-hour O_3 concentrations from EMEP-WRF simulations for 2003 (baseline year), and the changes in the population-weighted O_3 concentrations for +5 °C temperature sensitivity on the baseline year, and for projections for 2030 for the A2, B2+CLE and B2+MFR emissions scenarios. Regions are ordered approximately from north and west UK to south and east UK.

	2003		**2030 emissions scenarios**				**+5 °C c.f. 2003**
Region	**Population (1000s)**	**Baseline O_3 (ppbv)**	**Population (1000s)**	**A2 ΔO_3 (ppbv)**	**B2+CLE ΔO_3 (ppbv)**	**B2+MFR ΔO_3 (ppbv)**	**+5 °C ΔO_3 (ppbv)**
Scotland – SC	5,057	33.1	5,522	1.6	2.2	-0.1	0.9
Northern Ireland – NI	1,703	34.9	1,998	2.3	1.9	-1	0.7
North West – NW	6,799	31.5	7,411	-0.4	2.8	1.2	1.2
North East – NE	2,540	32.7	2,804	0.4	2.5	0.5	1.2
Yorkshire & Humberside –YH	5,029	31.4	6,180	-0.8	2.8	1.3	1.4
Wales – WA	2,929	35.4	3,313	0.7	2.2	-0.1	1.2
West Midlands – WM	5,310	32.2	6,037	-0.8	2.7	1.1	1.5
East Midlands – EM	4,254	32.3	5,237	-1.1	2.7	1.1	1.6
South West – SW	5,003	36.4	6,197	-0.1	2.2	-0.1	1.5
East England – EE	5,468	33.1	6,963	-1.9	2.8	1.4	1.8
South East –SE	8,080	35.0	9,859	-1.8	2.4	0.7	1.8
London – LN	7,380	31.2	9,029	-3.1	3.1	2.5	1.8
Total population	59,552		70,550				

Figure 1: Changes in annual mean surface O_3 (ppbv) in 2030 for emissions scenarios A2 (top left), B2+CLE (top right) and B2+MFR (bottom left), and for a +5°C increase in temperature applied uniformly for the whole year within the British Isles inner model domain (bottom right), all relative to baseline meteorological year 2003.

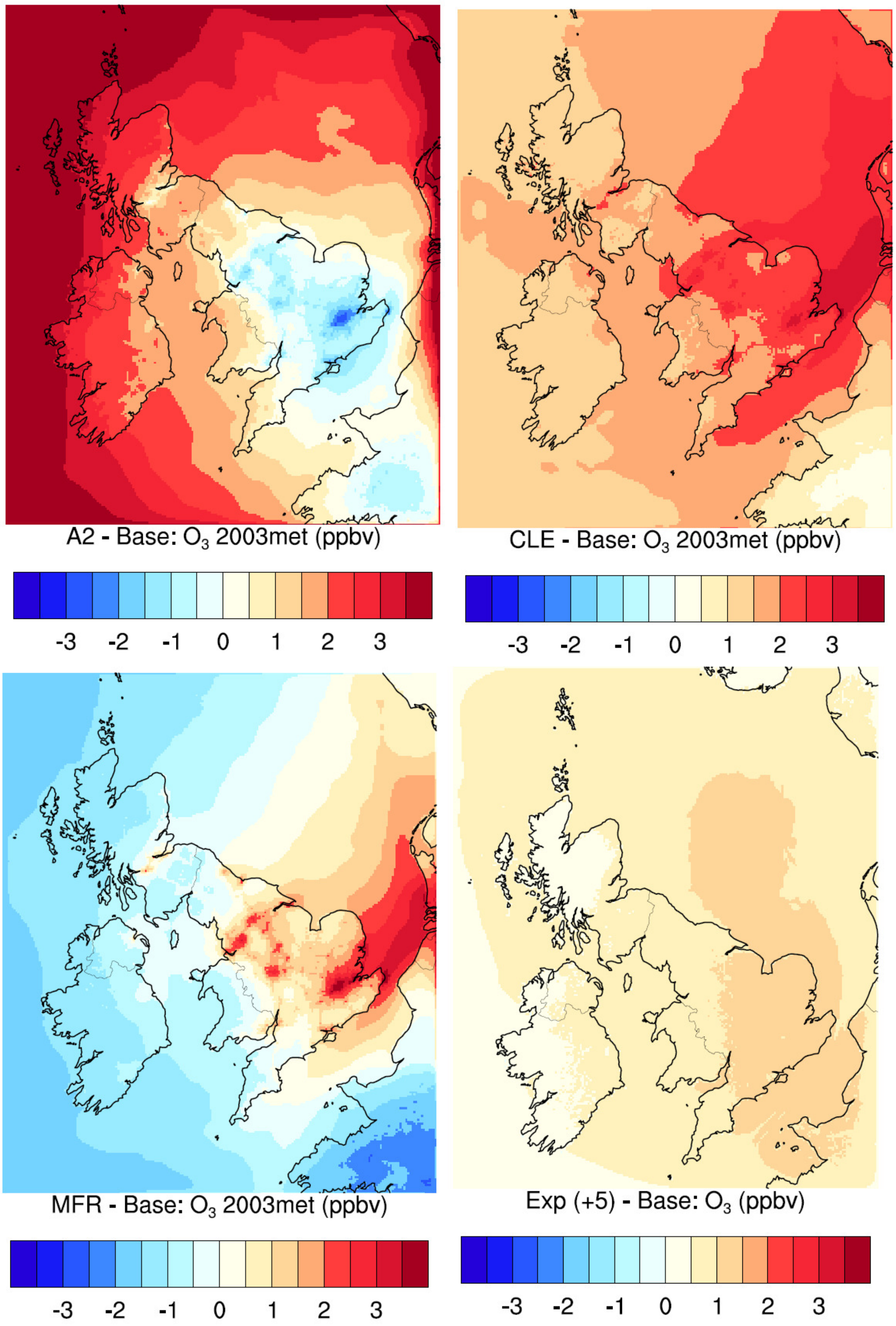


Figure 2: Example impact of meteorological variability on annual mean surface O_3 (ppbv) simulated by EMEP-WRF (year 2004 meteorology – year 2003 meteorology).

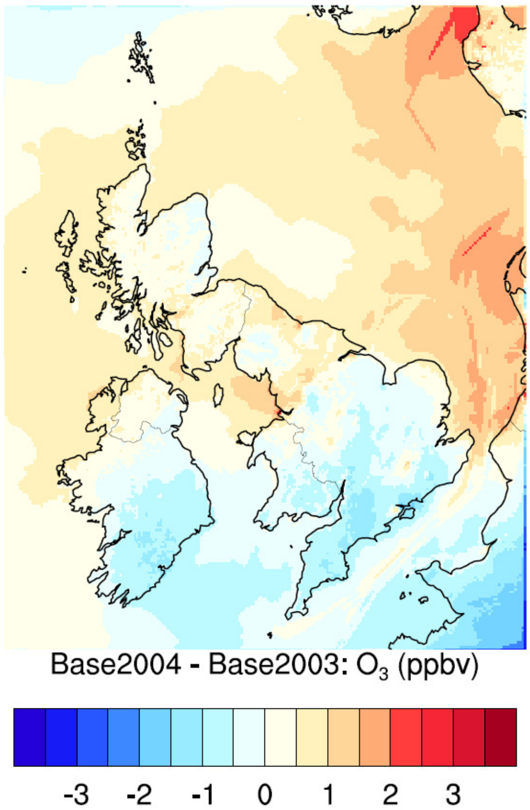
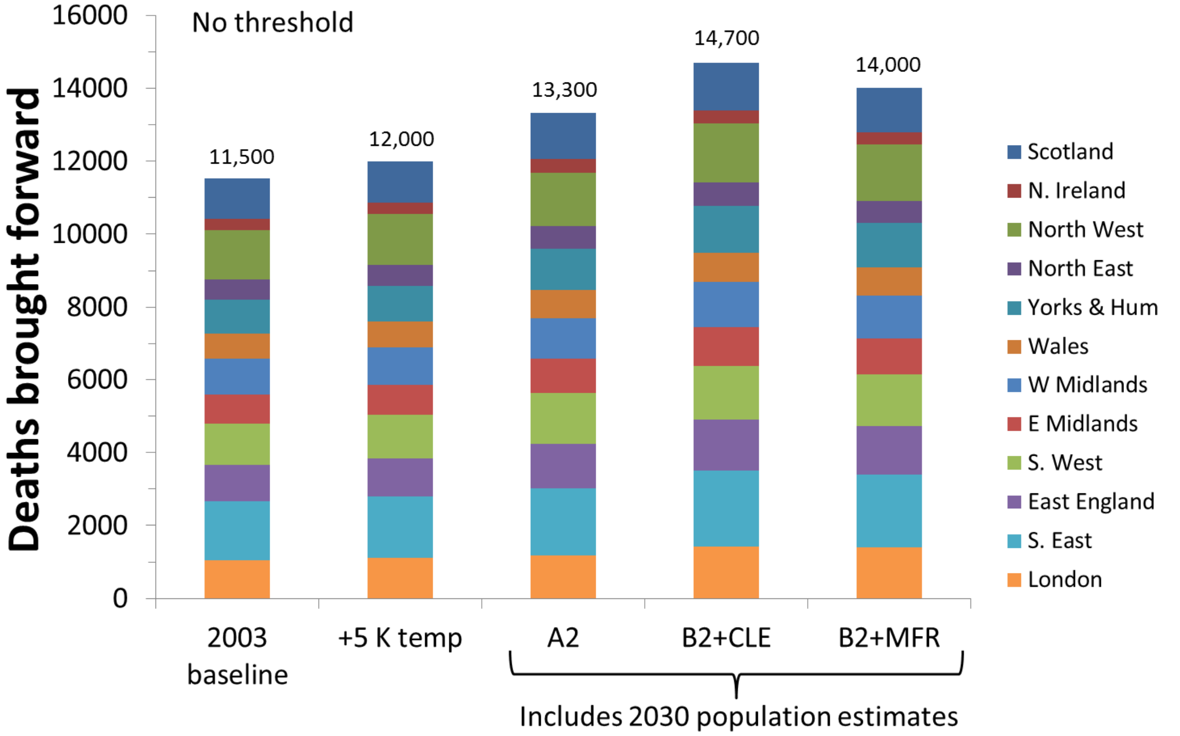


Figure 3: UK annual deaths brought forward attributable to O_3 for the 2003 baseline, a +5 °C temperature perturbation on baseline, and projections for 2030 under the A2, B2+CLE and B2+MFR emissions scenarios. The latter include estimated 2030 populations. (a, upper): assuming no threshold for O_3 effect; (b, lower): assuming a 35 ppbv threshold for O_3 effect. Note the sensitivity of absolute health burden values on uncertainty in the assumed health response coefficient, as discussed in Section 2.2; relative patterns of health burden across regions, scenarios and threshold assumptions are unaffected.



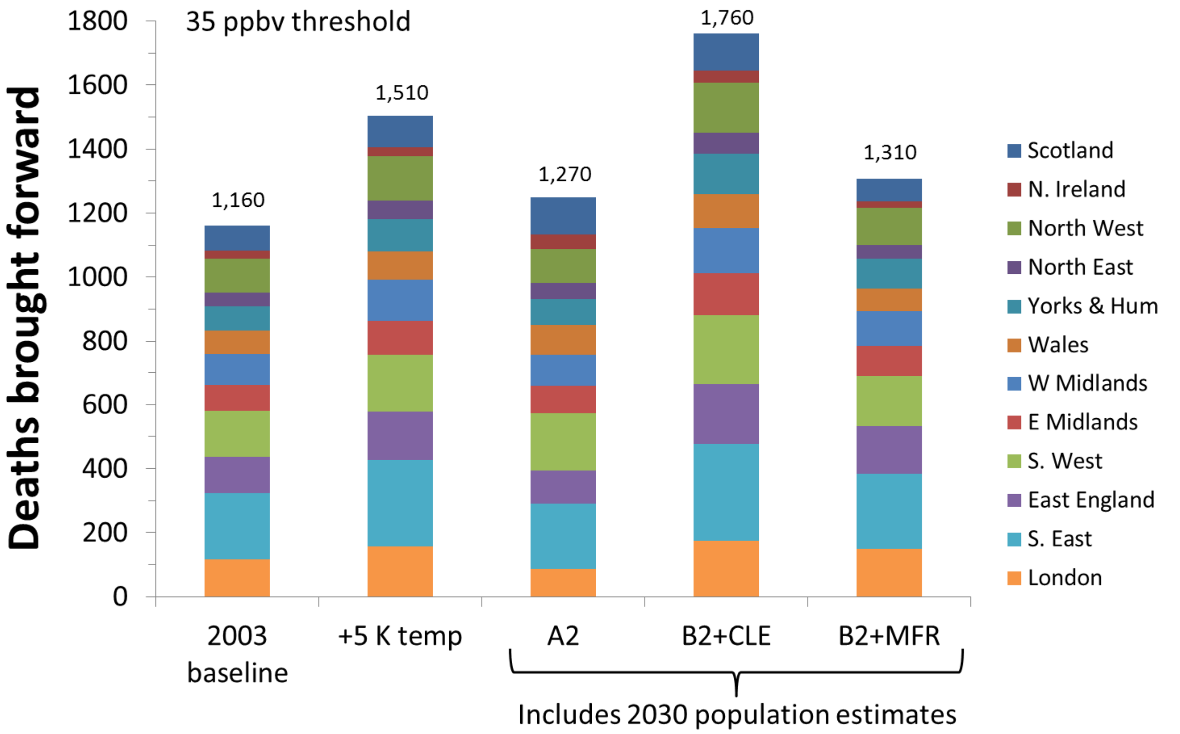
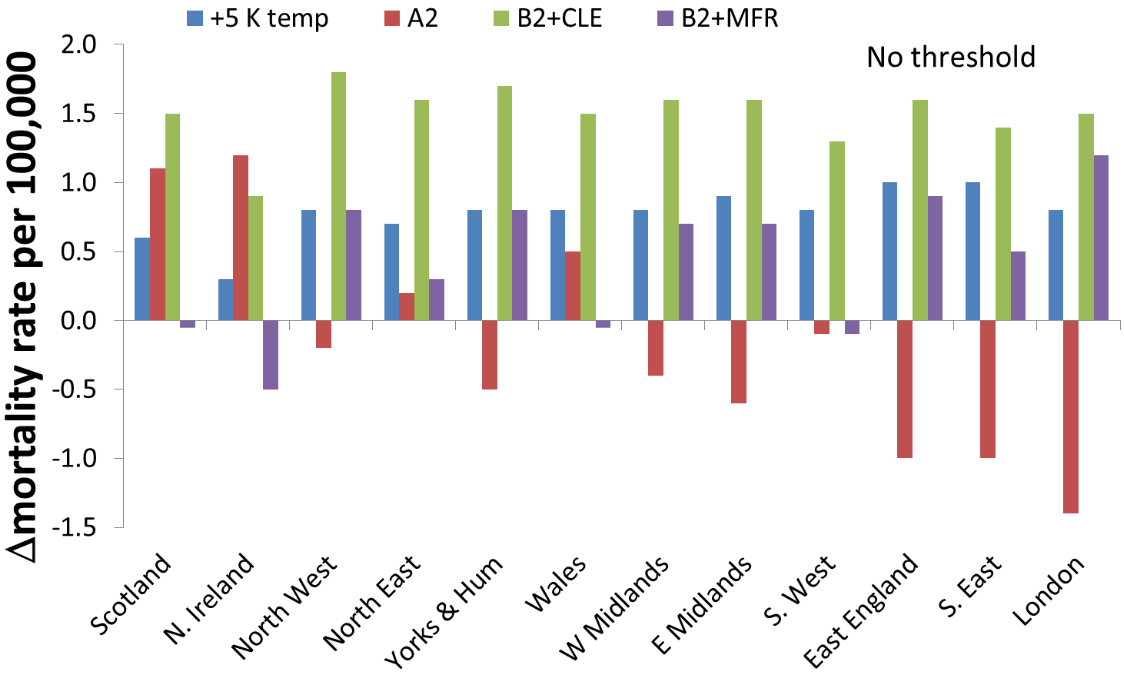
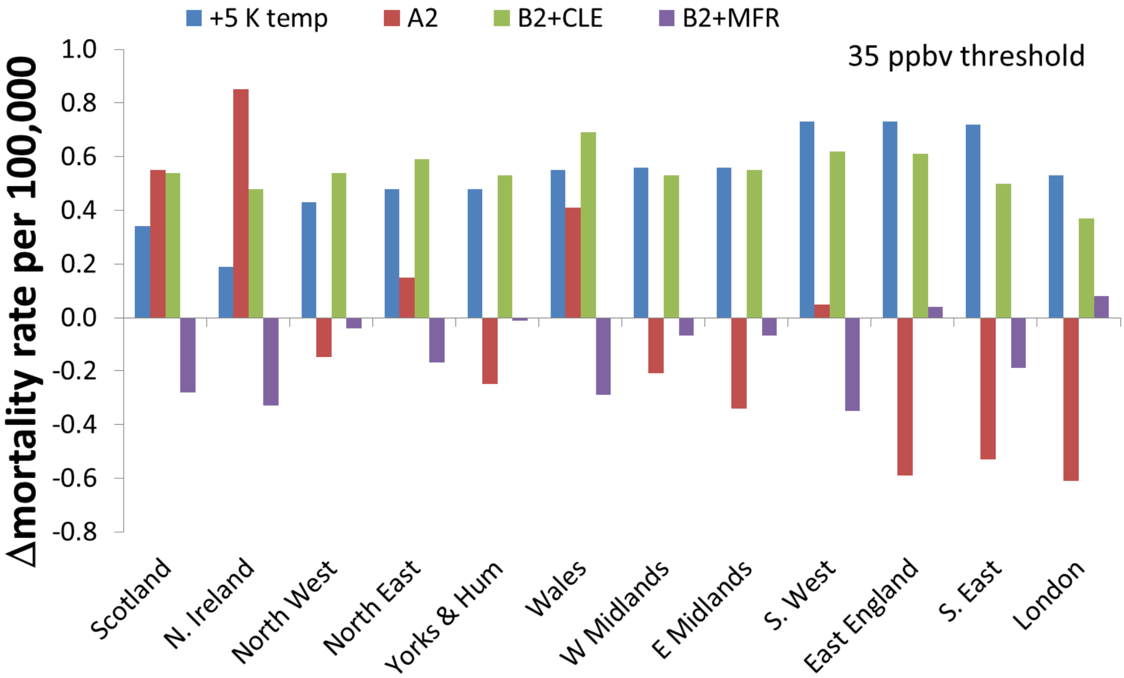


Figure 4. Changes in regional annual mortality rate per 100,000 population between 2003 and 2030 for the three emissions projection scenarios and assumptions of no threshold (a, upper) and 35 ppbv threshold (b, lower) for O_3 effects. The regions are ordered left to right approximately geographically from the north and west of the UK to the south and east. Note the sensitivity of absolute health burden rates on uncertainty in the assumed health response coefficient, as discussed in Section 2.2; relative patterns of health burden rates across regions, scenarios and threshold assumptions are unaffected.





Supplementary Information

Health burdens of surface ozone in the UK for a range of future scenarios

Mathew R. Heal[1*], Clare Heaviside[2], Ruth M. Doherty[3], Massimo Vieno[4], David S. Stevenson[3], Sotiris Vardoulakis[2]

Figure S1: Proportion by UK region of total UK deaths brought forward attributable to O_3 in 2003, for assumptions of no threshold and 35 ppbv threshold for effect of O_3. The regions are ordered left to right approximately geographically from the north and west of the UK to the south and east. Proportionally more of the health burden is distributed in the north and west (i.e. regions plotted to the left of the figure) if no threshold is assumed, but proportionally more is distributed in the south and east (to the right of the figure) if the threshold is assumed.

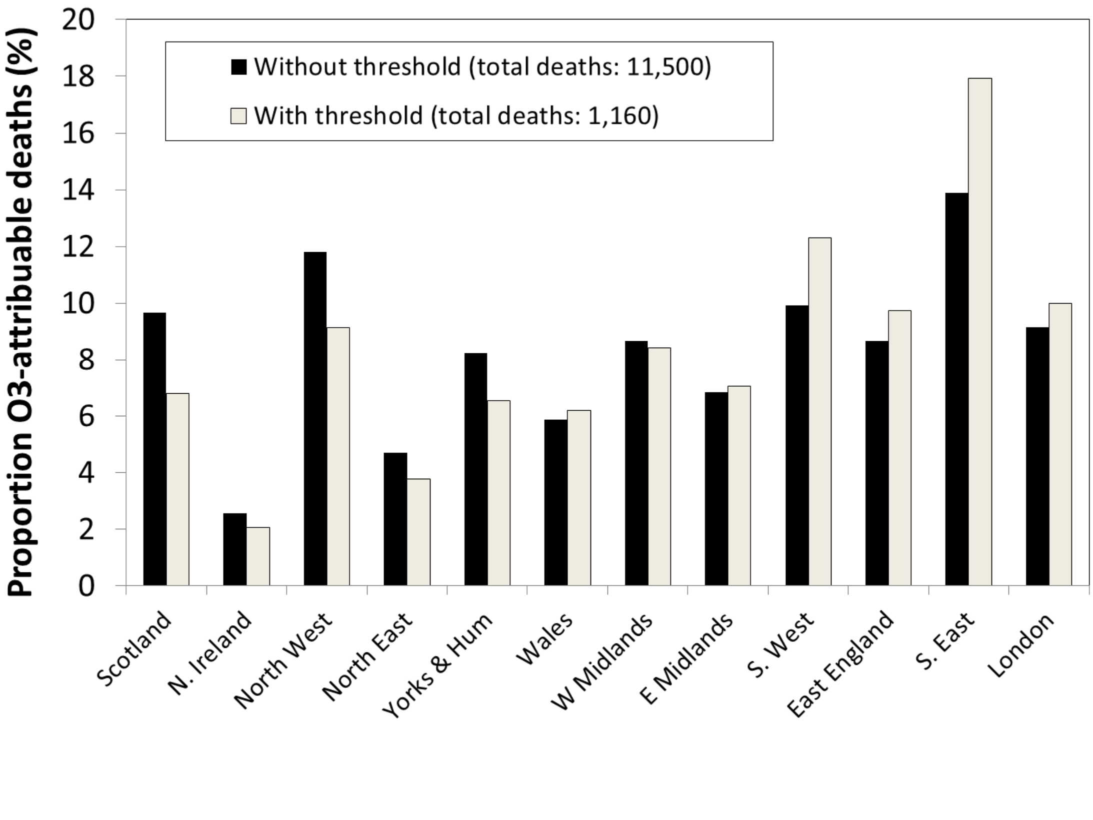


Table S1: Regional and total UK annual deaths brought forward attributable to O_3, assuming no threshold and a 35 ppbv threshold, for the 2003 baseline and for 2030 projections under the A2, B2+CLE and B2+MFR emissions scenarios (including estimated populations for 2030). The annual deaths brought forward per 100,000 population for each region and each scenario are provided in parentheses. Individual data are presented to a maximum of 3 significant figure.

	Annual deaths brought forward (& rate per 100,000), no threshold							**Annual deaths brought forward (& rate per 100,000), with 35 ppbv threshold**						
	2003	**2030**						**2003**	**2030**					
	Baseline	**A2**		**B2+CLE**		**B2+MFR**		**baseline**	**A2**		**B2+CLE**		**B2+MFR**	
Region	**mortality (rate)**	**mortality (rate)**	**% mortality change**	**mortality (rate)**	**% mortality change**	**mortality (rate)**	**% mortality change**	**mortality (rate)**	**mortality (rate)**	**% mortality change**	**mortality (rate)**	**% mortality change**	**mortality (rate)**	**% mortality change**
SC	**1110 (22.0)**	1270 (23.1)	14.4	1300 (23.5)	16.4	1210 (22.0)	8.8	**79 (1.56)**	117 (2.11)	48.1	116 (2.10)	46.8	70 (1.28)	-11.4
NI	**296 (17.4)**	371 (18.6)	25.3	366 (18.3)	23.6	338 (16.9)	14.2	**24 (1.41)**	45 (2.26)	87.5	38 (1.89)	58.3	22 (1.08)	-8.3
NW	**1360 (20.0)**	1470 (19.8)	7.9	1620 (21.8)	18.7	1540 (20.8)	13.2	**106 (1.57)**	105 (1.42)	-0.9	156 (2.11)	47.2	114 (1.53)	7.5
NE	**543 (21.4)**	606 (21.6)	11.6	645 (23.0)	18.8	609 (21.7)	12.2	**44 (1.72)**	52 (1.87)	18.2	65 (2.31)	47.7	43 (1.55)	-2.3
YH	**950 (18.9)**	1140 (18.4)	19.9	1270 (20.6)	34.0	1220 (19.7)	28.2	**76 (1.52)**	79 (1.27)	3.9	127 (2.05)	67.1	93 (1.51)	22.4
WA	**677 (23.1)**	782 (23.6)	15.5	815 (24.6)	20.4	765 (23.1)	13.0	**72 (2.45)**	95 (2.86)	31.9	104 (3.14)	44.4	72 (2.16)	0.0
WM	**1000 (18.8)**	1110 (18.4)	10.9	1230 (20.4)	23.2	1180 (19.5)	17.8	**98 (1.84)**	98 (1.63)	0.0	143 (2.37)	45.9	107 (1.77)	9.2
EM	**788 (18.5)**	939 (17.9)	19.2	1050 (20.1)	33.6	1010 (19.2)	27.7	**82 (1.94)**	84 (1.60)	2.4	130 (2.49)	58.5	98 (1.87)	19.5
SW	**1140 (22.9)**	1410 (22.8)	23.5	1500 (24.2)	31.1	1410 (22.8)	23.5	**143 (2.87)**	181 (2.92)	26.6	216 (3.49)	51.0	156 (2.52)	9.1
EE	**998 (18.2)**	1200 (17.2)	20.2	1380 (19.8)	38.3	1330 (19.1)	33.1	**113 (2.07)**	103 (1.48)	-8.8	187 (2.68)	65.5	147 (2.11)	30.1
SE	**1600 (19.8)**	1860 (18.8)	16.1	2090 (21.2)	30.5	1997 (20.3)	24.7	**208 (2.58)**	203 (2.05)	-2.4	303 (3.08)	45.7	236 (2.39)	13.5
LN	**1060 (14.3)**	1170 (12.9)	10.7	1430 (15.8)	35.0	1400 (15.5)	32.8	**116 (1.57)**	87 (0.96)	-25.0	175 (1.94)	50.9	149 (1.65)	28.4
TOTAL	**11,500**	**13,300**	15.6	**14,700**	27.7	**14,000**	21.5	**1,160**	**1,250**	7.5	**1,760**	51.5	**1,310**	12.5

Table S2: Regional and total UK annual respiratory hospitalizations attributable to O_3, assuming no threshold and a 35 ppbv threshold, for the 2003 baseline and for 2030 projections under the A2, B2+CLE and B2+MFR emissions scenarios (including estimated populations for 2030). The annual hospitalizations per 100,000 population for each region and each scenario are provided in parentheses. Individual data are presented to a maximum of 3 significant figure.

	Annual hospitalizations (& rate per 100,000), no threshold							**Annual hospitalizations (& rate per 100,000), with 35 ppbv threshold**						
	2003	**2030**						**2003**	**2030**					
	baseline	**A2**		**B2+CLE**		**B2+MFR**		**baseline**	**A2**		**B2+CLE**		**B2+MFR**	
Region	**morbidity (rate)**	**morbidity (rate)**	**% morbidity change**	**morbidity (rate)**	**% morbidity change**	**morbidity (rate)**	**% morbidity change**	**morbidity (rate)**	**morbidity (rate)**	**% morbidity change**	**morbidity (rate)**	**% morbidity change**	**morbidity (rate)**	**% morbidity change**
SC	**2530 (50.0)**	2900 (52.5)	14.4	2950 (53.4)	16.4	2750 (50.0)	8.8	**186 (3.7)**	272 (4.9)	48.1	272 (4.9)	46.8	166 (3.0)	-11.4
NI	**1150 (67.7)**	1440 (72.2)	25.3	1420 (71.2)	23.6	1310 (65.6)	14.2	**96 (5.6)**	178 (8.9)	87.5	149 (7.4)	58.3	86 (4.2)	-8.3
NW	**3900 (57.3)**	4190 (56.6)	7.9	4620 (62.3)	18.7	4400 (59.4)	13.2	**316 (4.7)**	308 (4.2)	-0.9	463 (6.3)	47.2	338 (4.5)	7.5
NE	**1240 (49.0)**	1390 (49.5)	11.6	1480 (52.6)	18.8	1390 (49.6)	12.2	**104 (4.1)**	123 (4.4)	18.2	153 (5.4)	47.7	103 (3.7)	-2.3
YH	**2590 (51.6)**	3100 (50.0)	19.9	3470 (56.1)	34.0	3320 (53.6)	28.2	**216 (4.3)**	220 (3.5)	3.9	358 (5.8)	67.1	265 (4.3)	22.4
WA	**1620 (55.3)**	1870 (56.4)	15.5	1950 (58.9)	20.4	1830 (55.2)	13.0	**178 (6.1)**	232 (7.0)	31.9	257 (7.8)	44.4	177 (5.3)	0.0
WM	**2740 (51.4)**	3030 (50.2)	10.9	3370 (55.7)	23.2	3210 (53.2)	17.8	**278 (5.2)**	276 (4.6)	0.0	408 (6.8)	45.9	305 (5.0)	9.2
EM	**2360 (55.4)**	2810 (53.5)	19.2	3150 (60.1)	33.6	3010 (57.4)	27.7	**256 (6.1)**	260 (5.0)	2.4	405 (7.8)	58.5	305 (5.8)	19.5
SW	**2950 (59.1)**	3640 (58.8)	23.5	3860 (62.4)	31.1	3630 (58.7)	23.5	**383 (7.7)**	479 (7.7)	26.6	577 (9.3)	51.0	417 (6.7)	9.1
EE	**2550 (46.4)**	3060 (43.8)	20.2	3520 (50.5)	38.3	3380 (48.6)	33.1	**301 (5.5)**	271 (3.9)	-8.8	496 (7.1)	65.5	391 (5.6)	30.1
SE	**3870 (47.8)**	4480 (45.3)	16.1	5040 (51.2)	30.5	4820 (48.9)	24.7	**525 (6.5)**	507 (5.1)	-2.4	765 (7.8)	45.7	596 (6.0)	13.5
LN	**3210 (43.5)**	3540 (39.1)	10.7	4320 (47.9)	35.0	4240 (46.9)	32.8	**366 (5.0)**	273 (3.0)	-25.0	552 (6.1)	50.9	472 (5.2)	28.4
TOTAL	**30,700**	**35,400**	15.6	**39,100**	27.7	**37,300**	21.5	**3,210**	**3,400**	7.5	**4,860**	51.5	**3,620**	12.5

Table S3. Regional and total UK annual deaths brought forward attributable to O_3, assuming no threshold and a threshold of 35 ppbv, for a +5 °C temperature perturbation compared with the 2003 baseline. Deaths brought forward per 100,000 population are given in parentheses. Individual data are presented to a maximum of 3 significant figure.

	Annual deaths brought forward, no threshold			**Annual deaths brought forward, with 35 ppbv threshold**		
Region	**2003 baseline**	**+5 °C temp**	**% change**	**2003 baseline**	**+5 °C temp**	**% change**
SC	1110 (22.0)	1140 (22.6)	**2.4**	79 (1.6)	98 (1.9)	**24.5**
NI	296 (17.4)	302 (17.7)	**1.9**	24 (1.4)	28 (1.6)	**16.5**
NW	1360 (20.0)	1410 (20.8)	**3.7**	106 (1.6)	139 (2.0)	**30.8**
NE	543 (21.4)	562 (22.1)	**3.6**	44 (1.7)	57 (2.2)	**29.7**
YH	950 (18.9)	988 (19.7)	**4.0**	76 (1.5)	101 (2.0)	**33.0**
WA	677 (23.1)	700 (23.9)	**3.3**	72 (2.5)	89 (3.0)	**23.9**
WM	1000 (18.8)	1040 (19.6)	**4.2**	98 (1.8)	128 (2.4)	**31.0**
EM	788 (18.5)	824 (19.4)	**4.5**	82 (1.9)	108 (2.5)	**31.2**
SW	1140 (22.9)	1190 (23.7)	**3.8**	143 (2.9)	178 (3.6)	**24.4**
SE	1600 (19.8)	1680 (20.8)	**4.9**	208 (2.6)	270 (3.3)	**29.6**
EE	998 (18.2)	1050 (19.2)	**5.2**	113 (2.1)	152 (2.8)	**34.3**
LN	1060 (14.3)	1120 (15.1)	**5.5**	116 (1.6)	156 (2.1)	**34.7**
TOTAL	**11,500**	**12,000**	**4.1**	**1,160**	**1,510**	**29.5**