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Mortality and emergency hospitalizations associated with atmospheric particulate matter episodes across the UK in spring 2014

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ABSTRACT

Exposure to particulate air pollution is known to have negative impacts on human health. Long-term exposure to anthropogenic particulate matter is associated with the equivalent of around 29,000 deaths a year in the UK. However, short-lived air pollution episodes on the order of a few days are also associated with increased daily mortality and emergency hospital admissions for respiratory and cardiovascular conditions. The UK experienced widespread high levels of particulate air pollution in March–April 2014; observations of hourly mean $PM_{2.5}$ concentrations reached up to 83 μg m^{-3} at urban background sites. We performed an exposure and health impact assessment of the spring air pollution, focusing on two episodes with the highest concentrations of $PM_{2.5}$ (12–14 March and 28 March–3 April 2014). Across these two episodes of elevated air pollution, totalling 10 days, around 600 deaths were brought forward from short-term exposure to $PM_{2.5}$, representing 3.9% of total all-cause (excluding external) mortality during these days. Using observed levels of $PM_{2.5}$ from other years, we estimate that this is 2.0 to 2.7 times the mortality burden associated with typical urban background levels of $PM_{2.5}$ at this time of year. Our results highlight the potential public health impacts and may aid planning for health care resources when such an episode is forecast.

1. Introduction

In the UK, long-term exposure to particulate air pollution from anthropogenic sources has an effect on mortality equivalent to approximately 29,000 deaths per year (COMEAP, 2010; Gowers et al., 2014). Chronic effects include respiratory and cardiovascular health conditions and lung cancer. Although long-term exposure to particulate matter (PM) is responsible for most of the mortality burden associated with particulate air pollution in the UK, exposure to PM over shorter time periods (days or weeks) has been associated with increases in respiratory and cardiovascular disease events, potentially leading to increased risk of mortality and hospitalization, and exacerbation of conditions such as asthma (Brunekreef and Holgate, 2002; COMEAP, 1998, 2009, 2010; Dockery et al., 1993; McLaren and Williams, 2015; Pope et al., 2002). This means that during periods of elevated levels of PM, which often occur in the UK during spring, there may be increased pressure on hospitals and emergency services due to health effects relating to short-term exposure.

Routine air quality monitoring has largely recorded PM_{10} concentrations (particles with an aerodynamic diameter less than 10 μm), although monitoring of $PM_{2.5}$ (particles with an aerodynamic diameter less than 2.5 μm) has become routine in the UK since 2008/9, in response to the 2008 ambient air quality directive (2008/50/EC of 21st May 2008, European Parliament (2008)).

There is little conclusive evidence as to which constituents of PM represent more of a risk to health than others (Atkinson et al., 2015; Stanek et al., 2011), although some recent work suggests black carbon is a better indicator than total PM mass for short-term studies (Janssen et al., 2011; World Health Organization, 2012). $PM_{2.5}$ is thought to be more closely associated with adverse health impacts than PM_{10} due to evidence which suggests that smaller particles such as $PM_{2.5}$ could have a greater effect on health than the coarser fraction of PM. This is due to the greater penetration of smaller particles deep in to the lungs (Raaschou-Nielsen et al., 2013) and to the greater number of particles per total mass of finer particles (Seaton et al., 1995). There is little evidence to suggest there is a safe level of PM concentration or a threshold for health effects (COMEAP, 2009).

Certain population groups (those with pre-existing heart or lung conditions, the very young and the elderly) are particularly at risk from short-term exposure to $PM_{2.5}$ which can lead to increased mortality, and emergency respiratory or cardiovascular hospital admissions (Atkinson et al., 2014; COMEAP, 2015; Pope and Dockery, 2006). Exposure to $PM_{2.5}$ is therefore likely to be a contributing factor to mortality and morbidity for vulnerable groups.

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Several studies have examined the impacts of short-term exposure to air pollutants during air pollution episodes, for example, a winter time air pollution episode in the Netherlands was associated with significant negative impacts on respiratory function in children (Hoek and Brunekreef, 1993). A study across the UK during the August 2003 heatwave looked at the effects of elevated levels of air pollution at that time. Assuming a 0.75% increase in deaths brought forward for a 10 μg m^{-3} increase in PM_{10}, they suggest that 417 additional deaths were brought forward across the UK during the first two weeks of August, compared with 239 the previous year (which experienced more typical levels of air pollution at this time; Stedman, 2004). Additionally, a number of studies in Madrid have examined the health effects of exposure to PM, in particular the influence of Saharan dust. A longitudinal epidemiological time series study looking at the effect of short-term exposure to PM on mortality from circulatory diseases found $PM_{2.5}$ to be an important risk-factor, finding a relative risk (RR) of mortality (due to circulatory diseases) of 1.022 (95% confidence interval (CI) 1.005, 1.039) for a 10 μg m^{-3} increase in $PM_{2.5}$ (Maté et al., 2010). Another Madrid based study found significant association between daily mortality and $PM_{2.5}$ concentrations (RR: 1.023 (95% CI 1.010, 1.036)), also finding the effects on mortality due to short-term exposure to PM_{10} were enhanced during dust outbreaks, although the effect was not seen for $PM_{2.5}$ (Jiménez et al., 2010; Tobías et al., 2011). A study on 12 cities across the European Mediterranean countries found a 10 μg m^{-3} increase in $PM_{2.5}$ was associated with a 0.55% (95% CI: 0.27%, 0.84%) increase in all-cause mortality (Samoli et al., 2013). One study in the US found little increase in mortality risk with short term exposure to coarse dust particles only (Schwartz et al., 1999), and other studies found no significant relationship between fine particulates and mortality during Saharan dust intrusions in Europe (Karanasiou et al., 2012; Perez et al., 2008).

In the UK, the annual mean urban background PM_{10} concentration is approximately 18 μg m^{-3} (measured in 2013) ranging from 10 to 28 μg m^{-3} at urban background monitoring sites across the country in recent years (Defra, 2014). Annual mean urban background $PM_{2.5}$ concentrations are 12 μg m^{-3} (measured in 2013), ranging from 12 to 14 μg m^{-3}, and exceed 20 μg m^{-3} at a few roadside sites. Though direct emissions of $PM_{2.5}$ have been declining recently in the UK (since 2009), there is as yet no significant decrease in ambient concentrations partly due to the large contribution of secondary particles, while PM_{10} has been steadily declining in the UK from an annual average of around 36 μg m^{-3} in the early 1990s (Defra, 2014).

PM in the UK comes from anthropogenic sources such as combustion for power generation and transport, as well as natural sources such as wind-blown dust and sea salt (Borge et al., 2007; Kassomenos et al., 2014; Vardoulakis and Kassomenos, 2008). Another potential source of PM is from the European continent, particularly when the wind blows from the South East, and in springtime, when agricultural and industrial emissions are high.

The Daily Air Quality Index (DAQI) is an indicator of air pollution levels in the UK, based on the highest concentration of any of five pollutants (PM_{10}, $PM_{2.5}$, ozone (O_3), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2)), and provides information which may be of use to at-risk groups as well as the general population for different levels of air pollution (Defra uk-air.defra.gov.uk). The index is numbered from 1 to 10, and divided into four bands; 'low' (1–3), 'moderate' (4–6), 'high' (7–9) and 'very high' (10). During high air pollution episodes, PM_{10} concentrations regularly exceed the EU limit value of 50 μg m^{-3}(daily mean), and can even exceed 80 μg m^{-3}, considered the 'alert level' (European Environment Agency, 2014). While no short-term limit value is given for $PM_{2.5}$, the World Health Organization recommends 25 μg m^{-3} as a guideline 24-hour mean (World Health Organization, 2006). Elevated PM_{10} is typically associated with increases in $PM_{2.5}$, though there may be occasions where dynamically generated (e.g. wind-blown) coarse particles are a dominant contributor to high PM_{10} concentrations.

An air pollution episode is generally considered to be a period of a few days up to 2–3 weeks with elevated levels of air pollution, characterised by daily exceedances of thresholds set to protect human health. Particulate air pollution episodes lasting a few days typically occur as a result of increased emissions (for example in the winter when energy demand is greater), limited dispersion of pollution during anti-cyclonic atmospheric conditions, transport of air from areas of high emissions (for example from the European continent), or during cooler months when the colder ground can lead to temperature inversions which trap pollution near ground level (AQEG, 2012). Short-lived episodes of elevated concentrations of $PM_{2.5}$ typically occur several times throughout the year, most often in spring and winter. Pollution episodes may also occur in springtime when anthropogenic pollution from agricultural and industrial activities in the continent, and/or dust from the Sahara, is advected across to the UK (Borge et al., 2007). Dust transported from the Sahara may occasionally reach the UK, when synoptic weather conditions are favourable, typically in spring and autumn. Saharan dust emission tends to be higher in spring and summer and lower in autumn and winter (Cowie et al., 2014; Prospero et al., 2002).

March–April 2014 saw increased air pollution, with two distinct 'episodes' (12–14 March and 28 March–3 April) across the UK, exacerbated by a dominant blocking anticyclonic weather system, leading to stagnant air, fog, and high air pollution levels, including pollution transported from the European continent. Blocking anticyclones are associated with the position of the Jet Stream, and some research suggests that the occurrence and persistence of future atmospheric stagnation events in mid-latitudes may increase due to climate change (Coumou et al., 2014, 2015; Dawson, 2014; Horton et al., 2014).

The DAQI reached levels of 'high' or 'very high' for several days in many regions across the country in March–April 2014 due to increased concentrations of $PM_{2.5}$ (greater than 54 μg m^{-3} classed as 'high'). Observed daily mean $PM_{2.5}$ levels reached 66 μg m^{-3} at rural background sites (Rochester Stoke, 2 April 2014), and up to 83 μg m^{-3} at urban background sites (Sheffield Devonshire Green, 31 March 2014) during the air pollution episode (AURN www.uk-air.defra.gov.uk).

Anticyclonic atmospheric conditions over parts of the UK persisted for several days, and light winds led to reduced dispersion of locally-emitted pollutants over the same period. In addition, elevated levels of secondary inorganic aerosol from continental Europe, and Saharan dust were advected to the UK (Vieno et al., 2016).

Partly because of the reduced visibility, the pollution episode in 2014 received much media attention, and was noticeable in parts of the UK (particularly the south and east of England), with numerous reports of dust deposits observed on vehicles and windows. Analysis of syndromic surveillance data (i.e. emergency departments (A&Es), general practitioners and other types of first line patient care services, such as the NHS 111 telephone service) and ambulance data for this period, shows increases in demands on health care services (mainly relating to respiratory conditions such as asthma) (Elliot et al., 2016; Smith et al., 2015).

Here we present the results of an exposure and health impact assessment of the particulate air pollution episodes that occurred in the UK during March–April 2014, at a national level and broken down into UK regions. We assess the impact on all-cause (excluding external) mortality, and emergency respiratory and cardiovascular hospital admissions.

2. Methods

2.1. Air quality data

The Automatic Urban and Rural Network (AURN) is the UK air quality monitoring network which has been operational for several decades. Sites are maintained by Defra (the Department for Environment, Food and Rural Affairs), and the data are freely available. Sites are classified into rural, urban (roadside or background) or industrial, depending on location. As their purpose is to monitor population exposure to air pollution, the majority are located near to population centres.

While observational networks such as the AURN provide constant monitoring of air pollutants at sites across the UK, their spatial (and sometimes temporal) coverage is limited. A more complete spatial and temporal coverage is desirable for calculating population exposure to air pollution, and can be achieved by using modelling results.

In this study, modelled concentrations of $PM_{2.5}$ were provided by the Met Office regional air quality model AQUM (Air Quality in the Unified Model). This is a limited-area forecast and modelling system, which combines meteorological modelling with aerosol and chemistry modelling (using the UKCA sub-model) in an 'on-line' framework (i.e. the meteorological and chemistry modelling is carried out together in the same modelling system). AQUM provides the operational UK air quality forecast to the public on behalf of Defra. A detailed description and evaluation of the model is presented in Savage et al. (2013).

Although the AQUM model currently has no data assimilation for aerosol or chemical species, a bias correction is applied to forecasts of pollutant concentration, based on a comparison of model predictions and recent observations from the AURN (Neal et al., 2014). Hourly AURN observations are also used to evaluate the forecast model predictions in near-real-time.

For the work described in the present paper, the model was run in hindcast mode (for a historical period rather than a future period) for the period of the spring 2014 air pollution episodes in March and April 2014. The bias-correction post-processing step was modified to derive a correction using modelled and observed values of pollutant air concentration at the same time. This procedure results in significantly improved estimates of pollution concentrations compared to the unadjusted model. Fig. 1 (right) shows mean modelled vs observed $PM_{2.5}$ concentrations for the period covering the air pollution episodes (time series comparisons for a selection of sites are shown in the Supplementary Fig. S1). Data were provided on a 12 km grid across a domain covering the whole of the UK and part of northern Europe (Fig. 1 (left)). Regional boundaries were then applied to enable population weighed $PM_{2.5}$ concentrations to be calculated in each of the nine Government regions of England, as well as in Northern Ireland, Scotland and Wales (Fig. 2). Hourly pollutant concentrations were then used to calculate daily average (24 hour mean) $PM_{2.5}$ concentrations at 12 km × 12 km resolution across the entire UK.

2.2. Demographic and health data

The exposure metric we use is 'population weighted $PM_{2.5}$', which is calculated from the AQUM gridded $PM_{2.5}$ output, and gridded population. Population-weighted $PM_{2.5}$ was calculated for each country in the UK, and also the nine Government regions in England (Fig. 2) using residential population information gridded at 100 m resolution (National Population Database, 2015). Population weighting could not be carried out for Northern Ireland due to a lack of gridded population information, so $PM_{2.5}$ there was based on the geographical mean across Northern Ireland.

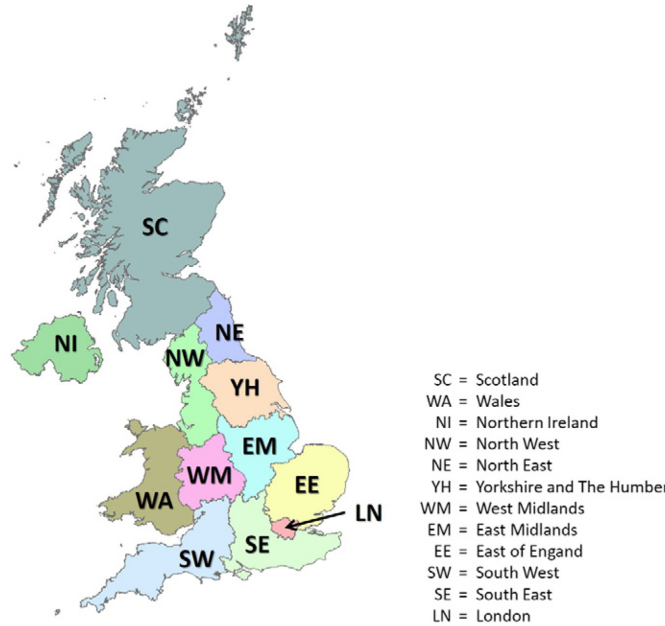

Fig. 2. Regions across the UK used for the analysis.

2.2.1. Mortality data

Daily all-cause (excluding external) mortality was obtained from the Office for National Statistics for England and Wales, National Records of Scotland (www.nrscotland.gov.uk), and Northern Ireland Statistics and Research Agency (NISRA). Daily mortality for each region is based on the date the death occurred, with the exception of Northern Ireland for which deaths are based on the date registered. To overcome null data at weekends, the deaths registered on Monday in Northern Ireland were evenly distributed across Saturday, Sunday and Monday.

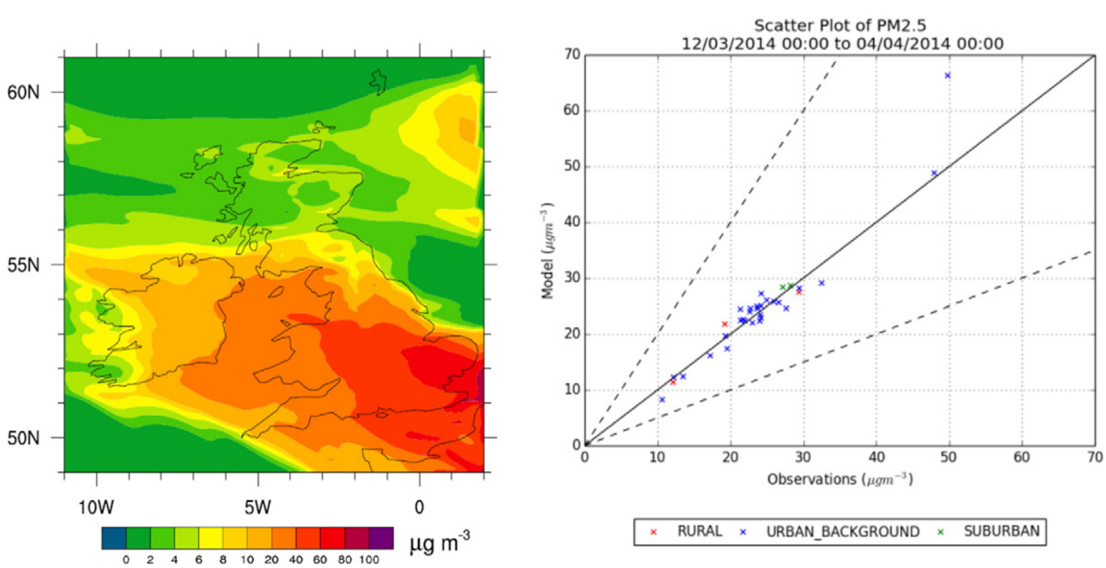

Fig. 1. (left) Daily average $PM_{2.5}$ concentrations for 2 April 2014 from the AQUM model; (right) scatter plot of mean modelled vs observed $PM_{2.5}$ at all individual observation sites for the period 12 March–4 April 2014.

2.2.2. Emergency hospital admissions data

Daily emergency hospital admissions for England are estimated from an average of daily emergency hospital admissions for each day of the year from 1997 to 2012 (Hospital Episode Statistics, www.hscic.gov.uk/hes), with rates per 100,000 estimated by dividing this by the average of the mid-year population estimates for those years (population data for all countries from Office for National Statistics, accessed via Population Analysis Tool at www.ons.gov.uk). As data are not yet available for absolute daily hospital admissions, these were estimated for 2014 from the daily rates over the period 1997 to 2012, multiplied by the mid-year estimate of population for 2014.

Daily hospital admission data for Wales were provided for 2014 by NHS Wales Informatics Service (www.wales.nhs.uk/nwis), and for Scotland by the Information Services Division (www.isdscotland.org).

Hospital admission data for Northern Ireland were available annually for 2012/13 and 2013/14 (www/dhsspsni.gov.uk). Average annual figures for emergency admissions by disease group were divided by 365, and then by mid-year population figures, to obtain an estimate of the daily rates. These are then multiplied by the mid-year estimate of population for Northern Ireland for 2014, and scaled to the annual cycle of the England data.

3. Health impact assessment

Estimates of the health effects associated with an air pollution episode can be calculated as follows:

$$M = \sum_{i=1}^{N} D_i \times AF$$

where

$$AF = \frac{RR-1}{RR}$$

and

$$RR = \exp(R_e E_i)$$

where M is the total mortality (or morbidity) associated with $PM_{2.5}$, summed over each day of the air pollution episode, i is the day within each episode, N is the total number of days in the episode, D_i is an estimate of the total regional daily mortality (or morbidity) and AF is the attributable fraction of mortality (or morbidity) associated with short-term exposure to $PM_{2.5}$. RR is the relative risk of mortality (or morbidity) related to short-term exposure $PM_{2.5}$, where R_e is the slope of the concentration-response relationship and E_i is the daily mean population-weighted $PM_{2.5}$.

A health impact assessment (HIA) was carried out for $PM_{2.5}$, to estimate all-cause mortality and morbidity (emergency cardiovascular and emergency respiratory hospital admissions) burdens related to short-term exposure to $PM_{2.5}$ over a timescale covering the whole of March and April 2014, and then separately for the most polluted days, when the DAQI reached 'high' or 'very high' during the episodes (12–14 March, and 28 March–3 April inclusive). The concentration-response coefficient R_e used here was derived from a detailed meta-analysis of published time series epidemiological studies (Atkinson et al., 2014). For mortality effects, the concentration-response relationship suggests a 1.04% (95% CI: 0.52%, 1.56%) increase in mortality for a 10 μg m^{-3} increase in $PM_{2.5}$. For hospital admissions, the relationship used was a 0.96% (95% CI: −0.63%, 2.58%) increase in respiratory emergency admissions, and a 0.90% (95% CI: 0.26%, 1.53%) increase in cardiovascular emergency admissions, both for a 10 μg m^{-3} increase in $PM_{2.5}$ (Atkinson et al., 2014). There is little evidence for a threshold below which no adverse effects from short-term exposure to particulate matter occur (COMEAP, 1998), so the full range of $PM_{2.5}$ exposure was used to calculate health impacts.

4. Results

Fig. 3 shows daily observed levels of $PM_{2.5}$ for the first six months of the year, from 2011 to 2015 inclusive, at two AURN urban background monitoring stations in London and Birmingham. Although 2014 had notable increased $PM_{2.5}$ concentrations, similar events occur each year, and $PM_{2.5}$ levels are often elevated episodically in springtime in the UK. Studying air pollution episodes such as those that occurred in 2014 can help quantify the health impacts of such annually occurring events, and may aid planning for health care resources when such an episode is forecast.

4.1. Mortality from short-term exposure to $PM_{2.5}$

In terms of daily mean $PM_{2.5}$ concentration, the days with the highest air pollution were 12–14 March, and 28 March–3 April 2014. These two episodes, totalling 10 days, are analysed in more detail for the health effects of short-term exposure to $PM_{2.5}$. Table 1 shows analysis by region for the whole of March–April, and also the two pollution episodes covering 12–14 March, and 28 March–3 April.

For these two episodes the mean percentage of deaths brought forward from short-term exposure to $PM_{2.5}$ was up to 5% of all-cause (excluding external) deaths in London and the East of England, which saw the highest levels of air pollution. This peaked at 6.6% on 3 April in the East of England. Over these two episodes (12–14 March and 28 March–3 April), the total burden due to $PM_{2.5}$ was around 600 deaths brought forward (with a range of 305–896 based on the 95% confidence interval of the concentration response coefficient, see supplementary tables) summed across the UK over the 10 days.

Using observations from the AURN over several years, it is possible to estimate a more typical level of $PM_{2.5}$ which would be expected at this time of year in the absence of an air pollution episode, and thus to estimate how the elevated pollution levels in 2014 increased the mortality from short-term exposure to $PM_{2.5}$. Using AURN data for the London N. Kensington site (urban background) for 2014, we calculated an average daily $PM_{2.5}$ concentration of 49.1 μg m^{-3} across the two episodes, similar to the population-weighted value calculated from the modelled AQUM concentrations for the London region (47.2 μg m^{-3}). Using mean observed $PM_{2.5}$ concentrations during springtime (March–May) in years 2011 to 2015 (but excluding 2014), we estimate a daily average $PM_{2.5}$ concentration of 18.0 μg m^{-3}. Applying this average concentration to the health and demographic data for the London region for 2014, we estimate that in the absence of an air pollution episode, there would have been 26 deaths brought forward in London from short-term exposure to ambient $PM_{2.5}$ summed across the ten days. Compared with the 69 deaths brought forward in London calculated for the 2014 pollution episodes from the AURN data for 2014, we estimate that the mortality associated with short-term exposure to $PM_{2.5}$ was around 2.7 times higher during the air pollution episodes when compared with other years (Table 2). The value calculated using the AURN observations is around 3% larger than that calculated using the AQUM modelled data (69 deaths brought forward compared with 67 from the modelled data), as we have applied the observed levels at the London N. Kensington site to the whole London region. Results are also shown for a site in the West Midlands (Birmingham Tyburn urban background site). The average $PM_{2.5}$ concentrations based on data from years 2011 to 2015 (excluding 2014) is 19.3 μg m^{-3}, which suggests there would be around 29 deaths brought forward from short-term exposure to ambient $PM_{2.5}$ in West Midlands in the absence of an episode. The 60 deaths brought forward estimated for 2014 (Table 2) is 2.1 times that estimated from urban background levels of $PM_{2.5}$ in springtime in other years. Results are also shown for Scotland (Edinburgh St Leonards urban background site), and Wales (Cardiff urban

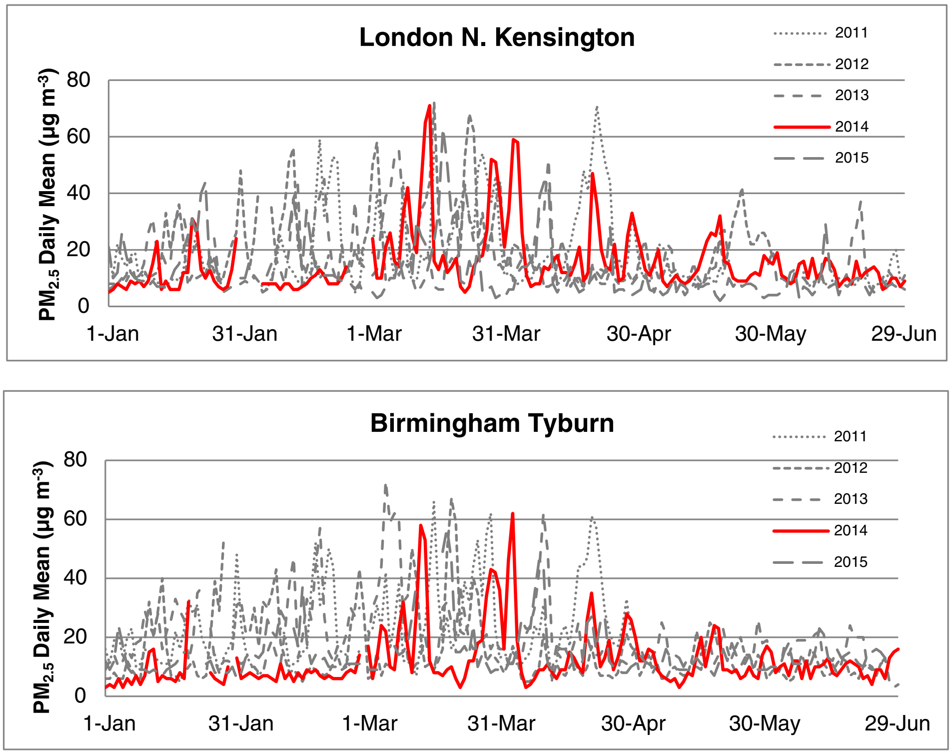

Fig. 3. Urban background $PM_{2.5}$ concentrations observed at two AURN sites during the first 6 months of 2011–2015.

background site), corresponding to an increase of 2.0 and 2.2 times the mortality associated with short-term exposure to $PM_{2.5}$ during the episodes of 2014 compared with average springtime conditions.

Although London and the East of England experienced the highest levels of $PM_{2.5}$ during the air pollution episodes in spring 2014, a comparison with previous years for the East of England cannot be performed as no urban or rural background site data for $PM_{2.5}$ from the AURN observational network are available for this period. Estimates of typical levels of particulate air pollution were based on observations where data were available, at four urban background sites for five recent years (London N. Kensington site in the London region, Birmingham Tyburn in the West Midlands, Edinburgh St Leonards in Scotland, and Cardiff in Wales). We extrapolated these results to the rest of the UK as the stations are situated in centres of high population. Although these locations may not be wholly representative of other population centres across the UK, we find only small differences in daily mean $PM_{2.5}$ concentrations calculated using the observations compared with the modelled values; for London, West Midlands and Wales, there is less than a 2 µg m^{-3} difference (less than 3%), and 3.4 µg m^{-3} difference (~15% difference on a background of 21.4 µg m^{-3}) for Scotland. While a two- to three-fold increase from typical levels was seen at the two urban background locations in London and the West Midlands, we estimate a more conservative two-fold increase when extrapolating to national figures, to allow for uncertainty based on extrapolation.

From the above calculations we estimate that during the most polluted days in the 2014 episodes (12–14 March and 28 March–3 April), the mortality burden associated with short-term exposure to $PM_{2.5}$ was 2.0 to 2.7 times higher than expected based on average $PM_{2.5}$ concentrations at this time of year (Table 2). By extrapolating these results to the rest of the UK, we estimate that of the 600 deaths brought

Table 1
Estimated mortality burden of short-term exposure to $PM_{2.5}$ across different periods in spring 2014. Initials for region names correspond to those in Fig. 2.

Region	March and April			12–14 March			28 March–3 April		
		Deaths brought forward			Deaths brought forward			Deaths brought forward	
	Mean daily $PM_{2.5}$ (µg m^{-3})	Number	Percent of all-cause	Mean daily $PM_{2.5}$ (µg m^{-3})	Number	Percent of all-cause	Mean daily $PM_{2.5}$ (µg m^{-3})	Number	Percent of all-cause
EE	19.9	181	2.06%	38.4	17	3.93%	49.6	54	5.04%
EM	18.5	131	1.88%	36.8	12	3.72%	46.9	38	4.75%
LN	21.4	176	2.25%	49.5	21	5.01%	46.2	46	4.73%
WM	17.7	152	1.82%	39.2	17	3.94%	43.4	43	4.39%
SE	19.3	252	1.99%	44.1	28	4.47%	41.3	61	4.17%
NW	17.1	199	1.77%	33.7	20	3.45%	40.8	57	4.16%
YH	17.6	142	1.77%	38.2	15	3.89%	40.5	35	4.09%
WA	16.0	87	1.65%	39.0	11	3.94%	32.4	20	3.28%
SW	16.2	147	1.67%	41.0	18	4.16%	31.3	34	3.22%
NE	13.8	62	1.42%	35.9	8	3.68%	24.8	13	2.56%
NI	12.4	30	1.27%	31.8	5	3.23%	23.7	6	2.02%
SC	10.0	89	1.04%	24.4	11	2.51%	15.2	15	1.58%
TOTAL		1649			182			422	

Mean daily all-cause (excluding external) mortality across the regions ranged from 1.506 to 2.792 per 100,000 for March and April, and 1.612 to 2.954 per 100,000 during the days of the air pollution episodes (see Supplementary Table S1).

Table 2
Estimated deaths brought forward from short-term exposure to typical springtime levels of $PM_{2.5}$, and for $PM_{2.5}$ during the episodes (12–14 March and 28 March–3 April 2014) for N. Kensington (London), Birmingham Tyburn (West Midlands), Edinburgh St Leonards (Scotland) and Cardiff (Wales).

	Mean daily $PM_{2.5}$ [$\mu g\ m^{-3}$]		Deaths brought forward: Number	Percent of all-cause	Increase in 2014 from typical levels
LN	Typical concentration[a]	18.0	26	1.85%	
	2014 (AURN)	49.1	69	5.00%	2.70 times
WM	Typical concentration[a]	19.3	29	1.99%	
	2014 (AURN)	41.9	60	4.23%	2.13 times
SC	Typical concentration[a]	10.9	16	1.13%	
	2014 (AURN)	21.4	31	2.21%	1.96 times
WA	Typical concentration[a]	15.1	14	1.56%	
	2014 (AURN)	34.5	30	3.49%	2.23 times

Mortality numbers may not total exactly due to rounding approximations.
[a] Average of 1 March–31 May for years 2011–2015 inclusive, excluding 2014.

forward from short-term exposure to $PM_{2.5}$ over the ten most polluted days in spring 2014, around 300 of these would be expected, had there been more typical springtime levels of $PM_{2.5}$. This suggests that the episodes doubled the mortality burden associated with short-term exposure to $PM_{2.5}$. For regions more strongly affected by the air pollution episodes, an increase in mortality burdens associated with short-term exposure to $PM_{2.5}$ of more than two-fold may have occurred.

4.2. Emergency hospital admissions during the air pollution episodes

Analysis for the number of emergency respiratory and cardiovascular hospital admissions for the episodes (12–14 March and 28 March and 3 April) is shown in Table 3. Our analysis suggests a range of 2.3% (Scotland) to 4.6% (East of England) of emergency respiratory admissions were associated with short-term exposure to $PM_{2.5}$ over these ten days. This peaked at 6.0% of admissions in both the East of England and the West Midlands on 3 April 2014. It should be noted that regions with the highest pollution did not always see the highest rates of associated admissions. For example, London had the highest mean daily $PM_{2.5}$ concentrations (approximately 50 $\mu g\ m^{-3}$), whereas the North East had the highest overall mean daily rate of associated admissions (0.17 per 100,000 compared with 0.14 for London), despite having daily $PM_{2.5}$ concentrations much lower than London (approximately 36 $\mu g\ m^{-3}$; Table 3(a)). The differences are due to the underlying total hospital admission rates being higher in these regions (supplementary Table S2) and reflect that populations in regions with higher underlying morbidity rates may be more susceptible to the effects of air pollution. For the 10 days of the air pollution episodes, there were around 840 (95% CI: −568, 2174) emergency respiratory hospital admissions associated with $PM_{2.5}$, summed across the UK. The 95% confidence intervals for the concentration-response coefficient for emergency respiratory hospital admissions range from −0.63% to 2.58% resulting in negative values when estimating based on the stated confidence levels. While this may be unphysical, we have included the results here for completeness, and note that estimates of emergency respiratory hospital admissions should be treated as a sensitivity analysis (see also supplementary Table S2).

Our analysis suggests that between 1.3% (Scotland) and 4.4% (Eastern of England) of emergency cardiovascular hospital admissions were associated with $PM_{2.5}$ (Table 3(b)). For the 10 days of the air pollution episodes, we estimate there were around 730 (95% CI: 213–1221) emergency cardiovascular hospital admissions summed across the UK associated with short-term exposure to $PM_{2.5}$.

In total, over the two air pollution episodes (12–14 March; 28 March–3 April), the total burden of emergency hospital admissions for respiratory and cardiovascular causes associated with short-term exposure to $PM_{2.5}$ was around 1500, summed across the UK (around 3.5% of total emergency respiratory and cardiovascular hospital admissions).

Table 3
Estimated emergency hospital admissions associated with short-term exposure to $PM_{2.5}$ over the episodes from 12 to 14 March, and 28 March to 3 April 2014. (a) emergency respiratory admissions and (b) emergency cardiovascular admissions.

Panel A: Emergency respiratory hospital admissions [a]

Region	12–14 March: Mean daily $PM_{2.5}$ ($\mu g\ m^{-3}$)	Associated admissions: Number	Percent of baseline	28 March - 3 April: Mean daily $PM_{2.5}$ ($\mu g\ m^{-3}$)	Associated admissions: Number	Percent of baseline
EE	38.4	20	3.63%	49.6	58	4.65%
EM	36.8	17	3.45%	46.9	51	4.38%
LN	49.5	36	4.63%	46.2	76	4.34%
WM	39.2	25	3.69%	43.4	64	4.04%
SE	44.1	35	4.14%	41.3	73	3.88%
NW	33.7	31	3.18%	40.8	87	3.84%
YH	38.2	25	3.59%	40.5	62	3.82%
WA	39.0	12	3.67%	32.4	24	3.06%
SW	41.0	20	3.84%	31.3	36	2.96%
NE	35.9	13	3.37%	24.8	21	2.36%
NI	31.8	7	3.00%	23.7	11	2.25%
SC	24.4	14	2.30%	15.2	19	1.34%
Total		255	3.59%		582	3.57%

Panel B: Emergency cardiovascular hospital admissions [b]

Region	12–14 March: Mean daily $PM_{2.5}$ ($\mu g\ m^{-3}$)	Associated admissions: Number	Percent of baseline	28 March–3 April: Mean daily $PM_{2.5}$ ($\mu g\ m^{-3}$)	Associated admissions: Number	Percent of baseline
EE	38.4	20	3.40%	49.6	62	4.37%
EM	36.8	16	3.25%	46.9	48	4.14%
LN	49.5	29	4.34%	46.2	65	4.06%
WM	39.2	21	3.46%	43.4	53	3.82%
SE	44.1	32	3.88%	41.3	71	3.64%
NW	33.7	24	2.99%	40.8	68	3.58%
YH	38.2	20	3.38%	40.5	51	3.57%
WA	39.0	9	3.45%	32.4	18	2.86%
SW	41.0	20	3.62%	31.3	38	2.77%
NE	35.9	10	3.18%	24.8	17	2.20%
NI	31.8	4	2.82%	23.7	7	2.09%
SC	24.4	10	2.17%	15.2	13	1.31%
Total		215	3.41%		513	3.42%

[a] Mean daily rates of admission across the regions ranged from 3.017 to 5.068 per 100,000 during the days of the air pollution episodes (see supplementary Table S2).
[b] Mean daily rates of admission across the regions ranged from 2.568 to 4.264 per 100,000 during the days of the air pollution episodes (see supplementary Table S2).

Using the method described in Section 4.1 for mortality effects, we estimated the emergency hospital admissions that might be expected given typical concentrations of $PM_{2.5}$ at this time of year (i.e. in the absence of an air pollution episode). Results for the London N. Kensington site (London region), the Birmingham Tyburn (West Midlands region), Edinburgh St Leonards (Scotland), and Cardiff (Wales) are shown in Table 4. Again, there is some regional variation, but our analysis suggests that in most regions, the air pollution episodes doubled the number of expected emergency hospitalizations for respiratory and cardiovascular admissions.

We estimate that emergency respiratory hospital admissions in 2014 for the most polluted days were 1.9 to 2.7 times higher than would be expected given typical $PM_{2.5}$ concentrations in other years, and that of the 840 associated admissions in 2014, approximately 420 would be expected from more typical $PM_{2.5}$ concentrations. Furthermore, we estimate that emergency cardiovascular hospital admission rates in 2014 for the most polluted days were also around 1.9 to 2.7

Table 4
Estimated emergency hospitalisations associated with short-term exposure to typical springtime levels of $PM_{2.5}$, and for $PM_{2.5}$ during the episodes from 12 to 14 March, and 28 March–3 April 2014. Results are shown for respiratory admissions, and for cardiovascular admissions, for London, the West Midlands, Scotland and Wales.

	Mean daily $PM_{2.5}$ [μg m^{-3}]		Emergency *respiratory* hospitalisations			Emergency *cardiovascular* hospitalisations		
			Number of admissions	Percent of baseline	2014 increase above typical levels	Number of admissions	Percent of baseline	2014 increase above typical levels
LN	Typical concentrations[a]	18.0	43	1.71%		36	1.60%	
	2014 (AURN)	49.1	117	4.60%	2.69 times	97	4.27%	2.67 times
WM	Typical concentrations[a]	19.3	41	1.84%		34	1.72%	
	2014 (AURN)	41.9	88	3.91%	2.13 times	74	3.69%	2.14 times
SC	Typical concentrations[a]	10.9	21	1.04%		14	0.98%	
	2014 (AURN)	21.4	41	2.00%	1.92 times	27	1.86%	1.90 times
WA	Typical concentrations[a]	15.1	16	1.44%		12	1.35%	
	2014 (AURN)	34.5	36	3.25%	2.25 times	27	3.04%	2.25 times

Numbers of admissions may not total exactly due to rounding approximations.
[a] Average of 1 March–31 May for years 2011–2015 inclusive, excluding 2014.

times higher than would be expected for more average $PM_{2.5}$ conditions, and that of the 730 emergency cardiovascular admissions in 2014, approximately 365 would be expected from more typical pollution levels at this time of year.

5. Discussion and conclusions

In March and early April 2014, the UK experienced elevated levels of air pollution, with two air pollution episodes (particularly $PM_{2.5}$) from 12 to 14 March, and 28 March to 3 April, covering 10 days in total. The highest concentration of $PM_{2.5}$ was over southern and eastern areas of the UK. Such air pollution events are observed to occur across the UK several times each year, and often in springtime (Fig. 3).

Over the two episodes, the estimated total mortality burden attributable to short-term exposure to $PM_{2.5}$ was around 600 deaths brought forward summed across the UK over 10 days, equivalent to 3.87% of the total recorded all-cause (excluding external) mortality on these days. By examining observed $PM_{2.5}$ concentrations in spring (March–May) in other recent years (2011, 2012, 2013 and 2015), we estimated that around half (300) of these estimated deaths were expected to occur due to typical urban background levels of $PM_{2.5}$ at this time of year. This suggests that the presence of these episodes may have doubled the mortality burden associated with short-term exposure to $PM_{2.5}$ in the UK over the 10 days (Tables 2 and 3). We estimate there were around 840 emergency respiratory and 730 emergency cardiovascular hospital admissions associated with short-term exposure to $PM_{2.5}$ over the 10 days of the air pollution episodes, corresponding to 3.59% and 3.36% of the total admissions on these days, respectively. Carrying out a quantitative health impact assessment, we estimate that these numbers of admissions is double the estimates for average $PM_{2.5}$ levels under typical springtime conditions.

The Public Health Outcomes Framework for England indicator for air pollution quantifies the mortality burden attributable to long-term exposure to anthropogenic $PM_{2.5}$ as being 5.3% of total all-cause (excluding external) adult mortality across England in 2013 (Public Health Outcomes Framework www.phoutcomes.uk). While the annual average urban background concentration of $PM_{2.5}$ is much lower than that seen during the air pollution episode of March–April 2014, the concentration-response coefficient for long-term exposure is higher (6% per 10 μg m^{-3} compared with 1.04% for short-term exposure). It is likely that chronic exposure to $PM_{2.5}$ shortens the lifetime of individuals in the general population, and as such, the mortality burden from long-term exposure is of continuing public health concern, and efforts to reduce the burden from long-term exposure are needed. Studies which investigate long-term exposure may account for the some of the effects of short-term exposure, and the aim here is not to try to separate long- and short-term effects explicitly, but to quantify the immediate health impact of an air pollution episode compared with average springtime conditions. It is thought that the associations between short-term exposure to fine particles and adverse health outcomes may lead to clinical events when experienced by individuals who are already vulnerable due to existing chronic or acute disease (Atkinson et al., 2014). The results presented here illustrate that the mortality and morbidity burden associated with short-term exposure to $PM_{2.5}$ episodes (which may take place more immediately after exposure, typically over a number of days) represents an important health impact.

Our analysis suggests that short term episodes of elevated $PM_{2.5}$ such as the one experienced in spring of 2014 may result in a 2.0 to 2.7 times increase in $PM_{2.5}$ related mortality and a 1.9 to 2.7 increase in $PM_{2.5}$ related morbidity (emergency respiratory and emergency cardiovascular admissions) compared with periods where $PM_{2.5}$ concentrations are more typical. The 10 days of the two episodes examined here are associated with around 600 deaths brought forward nationally, and around 1570 emergency respiratory and cardiovascular hospital admissions. This highlights the risk of increased pressure on emergency services and health authorities in the days immediately following an air pollution episode. Consequently, the continued use and development of forecasting and early warning systems for air pollution may provide a useful tool for preparedness in the health care and public health sector.

The mortality and morbidity estimates presented here use modelled exposure data and published concentration-response coefficients, and are based on several assumptions and simplifications. As such, they should be interpreted with caution. The concentration-response coefficients used here are from a comprehensive review and meta-analysis using over 100 peer-reviewed time-series studies that covered many regions globally, but mainly in North America and Europe. It is not known if these studies were conducted under conditions that may have included any intervention or mitigation measures. Potential harvesting effects could not be determined by this analysis.

Particulate matter comes from a variety of sources and is varied in composition. There is little clear evidence about the toxicity of particles from different sources and of different composition, though some suggest that black carbon and organic carbon content are indicators of toxicity (Atkinson et al., 2015; Harrison and Yin, 2000; Peng et al., 2009; Valavanidis et al., 2008). Since there is a lack of differential coefficients for quantification, here we use a single concentration-response coefficient which assumes that particles from all sources are equally toxic.

Observations were not available at urban background sites in all regions for the UK during spring 2014, so typical levels of particulate air pollution were based on observations at four urban background sites (in London, the West Midlands, Scotland and Wales) for five recent years. The sites represented a geographical spread for the UK and were located in centres with large population. We only found small differences (3%) in $PM_{2.5}$ concentrations calculated using the observations compared with the modelled values. However, so as to ensure we did not overestimate the burdens, we estimate a two-fold increase when extrapolating to national figures, although increases from typical levels were estimated to be between 1.96 and 2.70 times larger.

Our analysis is based on modelled $PM_{2.5}$, validated against observed concentrations, allowing complete geographical coverage of the UK, something difficult to achieve with air quality monitoring networks alone due to the limited number of sites with sufficient data coverage and their limited spatial representativeness.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.envint.2016.07.018.

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