Potential health impacts from sulphur dioxide and sulphate exposure in the UK resulting from an Icelandic effusive volcanic eruption

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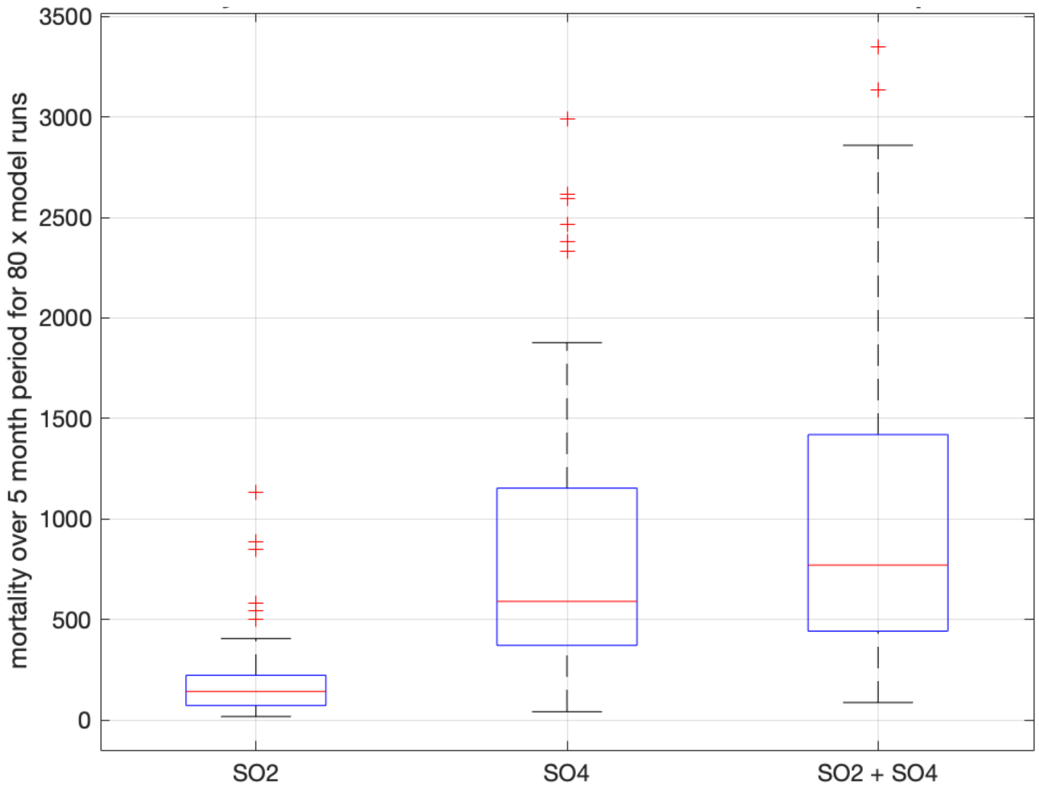
Highlights

- Sulphur dioxide (SO_2) and sulphate (SO_4) are associated with volcanic eruptions
- Exposure to these gases and particles is a risk to human health
- We used a dispersion model to estimate potential mortality from volcanic SO_2/SO_4
- Over 5 months exposure we find up to 3,350 excess deaths and 6,493 hospitalizations

Graphical abstract



Estimates of the total estimated number of deaths across each of 80 atmospheric model simulations, scaled for a 5-month volcanic eruption, for SO_2 (left), SO_4, (middle) and for SO_2 and SO_4 in each simulation combined (right).

Abstract

Ash, gases and particles emitted from volcanic eruptions cause disruption to air transport, but also have negative impacts on respiratory and cardiovascular health. Exposure to sulphur dioxide (SO_2) and sulphate (SO_4) aerosols increases the risk of mortality, and respiratory and cardiovascular hospital admissions. Ash and gases can be transported over large distances and are a potential public health risk. In 2014-15, the Bárðarbunga fissure eruption at Holuhraun, Iceland was associated with high emissions of SO_2 and SO_4, detected at UK monitoring stations.

We estimated the potential impacts on the UK population from SO_2 and SO_4 associated with a hypothetical large fissure eruption in Iceland for mortality and emergency hospital admissions. To simulate the effects of different weather conditions, we used an ensemble of 80 runs from an atmospheric dispersion model to simulate SO_2 and SO_4 concentrations on a background of varying meteorology. We weighted the simulated exposure data by population, and quantified the potential health impacts that may result in the UK over a 6-week period following the start of an eruption.

We found in the majority of cases, the expected number of deaths resulting from SO_2 over a 6-week period total fewer than ~100 for each model run, and for SO_4, in the majority of cases, the number totals fewer than ~200. However, the 6-week simulated period with the highest SO_2 was associated with 313 deaths, and the period with the highest SO_4 was associated with 826 deaths. The single 6-week period relating to the highest combined SO_2 and SO_4 was associated with 925 deaths. Over a 5-month extended exposure period, upper estimates are for 3,350 deaths, 4,030 emergency cardiovascular and 6,493 emergency respiratory hospitalisations. These figures represent a worst-case scenario and can inform health protection planning for effusive volcanic eruptions which may affect the UK in the future.

Keywords

Volcano, health risk assessment, sulphate, sulphur dioxide, emergency respiratory hospitalization, emergency cardiovascular hospitalization, mortality, effusive eruption, Iceland

1. Introduction

Volcanic eruptions can cause loss of life and severe damage and disruption in affected communities. They broadly take one of two forms: explosive eruptions, which are associated with gas driven explosions propelling material into the atmosphere; and effusive eruptions where lava is erupted over weeks to months, and which can include lava fire-fountaining and some explosive activity. Both types of eruption can have widespread societal impacts and are associated with the release of fine particulate matter (PM) and gases such as sulphur dioxide (SO_2), which can affect health and agriculture as well as the weather and climate (Robock, 2000; Sigl et al., 2015; Timmreck, 2012). Volcanoes are important drivers of natural climate variability, affecting atmospheric composition and dynamics, hydrological and carbon cycles, and marine and terrestrial biogeochemistry (Timmreck, 2012). Even though effusive eruptions are less violent than explosive eruptions, they are associated with negative impacts, including disruption to aircraft flight paths and increases in respiratory illness resulting from the release and atmospheric transport of gases over long distances (Durand and Grattan, 2001).

Iceland is a particularly volcanically active country, due to its unique geological position on the mid-Atlantic ridge, and records suggest there are an average of 20-25 eruptions per century in Iceland (Thordarson and Larsen, 2007). Historical eruptions in Iceland have had significant societal impacts. Most notably, the violent eruption of the Laki volcanic fissure from June 1783 to February 1784 led to destruction of villages, large scale contamination of soil, destruction of crops and livestock, and ultimately caused depopulation and a widespread famine in Iceland (Brayshay and Grattan, 1999). The eruption led to the release of large amounts of basalt lava, and clouds of gases such as SO_2 and hydrofluoric acid, two thirds of which were confined to the troposphere (Brayshay and Grattan, 1999). Weather conditions at the time of eruption (low pressure over Iceland and high pressure over northern Europe) meant that some of the volcanic aerosols and material was transported over large distances, affecting much of Europe following the eruption (Grattan et al., 2005, 2003; Kington, 1988). There are suggestions of a rise in excess mortality in England at the time of the Laki eruptions (Witham and Oppenheimer, 2004). Schmidt et al. (2011) used a global aerosol model to estimate the potential impacts of $PM_{2.5}$ on cardiopulmonary deaths that might be expected from a Laki type eruption, and suggested there may have been around 142,000 additional deaths from cardiopulmonary causes across Europe.

In August 2014, there was an eruption of the Bárðarbunga fissure, at Holuhraun, Iceland which resulted in significant emissions of SO_2, on the order of around 4.5 times the daily anthropogenic emission of SO_2 from the entire European Union countries, Norway, Switzerland and Iceland combined (Steensen et al., 2016). The nature of the effusive eruption meant that aerosols and gases were emitted into the troposphere, and therefore were clearly detected by ground based observing stations (Ialongo et al., 2015; Pfeffer et al., 2018; Twigg et al., 2016). Elevated concentrations of SO_2 were detected at UK stations, and the sulphate aerosol (SO_4) component of $PM_{2.5}$ and PM_{10} (particles with aerodynamic diameters up to 2.5 μm and 10 μm respectively) was significantly elevated from background levels (Twigg et al., 2016).

SO_2 and particulate air pollution in the form of $PM_{2.5}$ have well-established associations with health effects such as respiratory and cardiovascular illness, hospitalizations, and premature mortality (Atkinson, R.W. et al., 2014; Department of Health, 1998; WHO, 2006). Volcanic material emitted from effusive volcanic eruptions such as the 2014-15 Icelandic eruption is therefore likely to lead to adverse health impacts from increased exposure to SO_2 and sulphate aerosols (SO_4), which are a constituent of $PM_{2.5}$ (Gudmundsson, 2011; Hansell and Oppenheimer, 2004; Longo et al., 2008). Links between volcanic atmospheric emissions and health impacts have been made in the past; for example, surveys carried out on the Caribbean island of Montserrat showed that volcanic ash emissions adversely affected the respiratory health of children (Forbes et al., 2003). Similarly, the number of medically diagnosed acute respiratory illnesses was assessed for two 14-week periods, one before the eruption of the Kilauea Volcano (Hawaii) in 2008, and the second period immediately following the eruption. There was a six fold increase in visits for acute respiratory problems, primarily from younger people, following the eruption (Longo et al., 2010). A further study found long-term exposure to SO_2 as a result of the eruption was associated with increased cough in school children (Tam et al., 2016). In the Azores (Portugal), studies between two groups of people, one living in a volcanically active area, and the other not exposed, found that there was a severe increase in chronic bronchitis in the exposed group (Amaral and Rodrigues, 2007) and even indications that cancers of the mouth and larynx were more prevalent in the exposed group, compared with the non-exposed group (Amaral et al., 2006).

For both the explosive eruptions of Eyjafjallajökull and the 2011 Grímsvötn Icelandic eruption, associations between different PM sources (including volcanic) and emergency hospital visits for cardiorespiratory causes, showed that the high PM_{10} levels from volcanic ash were significantly associated with daily emergency hospital admissions in Iceland (Carlsen et al., 2015). Health impacts can be felt far from the volcanic eruption site; an eruption of Mount Ruapehu in New Zealand in 1996 was associated with increased respiratory mortality in the cities of Hamilton and Auckland, 166-282 km from the volcano (Newnham et al., 2010).

The risk to the UK population from Icelandic volcanoes is listed on the UK National Risk Register, although no formal health risk assessment of the potential health impacts associated with effusive material from an Icelandic type eruption has been published. We present results of a health risk assessment to estimate the potential number of premature deaths and hospitalizations in the UK that could be expected from exposure to SO_2 and SO_4 aerosol based on modelled simulations of a hypothetical effusive volcanic eruption in Iceland. We focus on short-term exposure effects, accumulated over a number of weeks or months.

2. Data and Methods

2.1 Modelled simulations

We used simulated concentrations of SO_2 and SO_4, extracted from output from the NAME (Numerical Atmospheric-dispersion Modelling Environment) atmospheric dispersion model (Jones et al., 2007), run by the UK Met Office. The NAME model contains a chemistry scheme that was originally developed for air quality forecasting purposes (Redington et al., 2009) and includes the necessary gas and aqueous phase chemical reactions for simulating volcanic SO_2 and SO_4. Work by Heard et al. (2012) and Schmidt et al. (2014) has verified NAME simulations of SO_2 and SO_4 against satellite and airborne observations from several volcanic eruptions and shown that the model is suitable for this application.

We assume a precautionary “reasonable worst case” eruption scenario based on the 1783-1784 Laki eruption. The scenario was based on the results of an expert elicitation of scientists produced to support the UK national risk register process and consisted of a time-varying eruption source term covering a period of 6 weeks, (Witham et al., 2015) (Figure 1). The total emitted mass of SO_2 in this scenario is 47.309 Mt, with the maximum SO_2 emission on any one day at 2.248 Mt. This compares to the 120 Mt released during the 9-month Laki eruption (Thordarson and Self, 2003) and the 11.8 Mt emitted by the Bárðarbunga eruption (Gíslason et al., 2015). The eruption of the volcano was represented in the model by the release of material from a 100m diameter cylinder above the volcano. Daily varying quantities of SO_2 were emitted in different vertical layers as defined by the scenario. Over the whole eruption, approximately 24% of the SO_2 was emitted into the stratosphere and 76% was emitted into the troposphere. The location of the volcano was taken to be N64.064° and W18.22° and the model was run over a domain of 25°-85°N and 60°W to 60°S to cover the European and North Atlantic region. The model output resolution was 0.25° by 0.25° and simulations included both wet and dry deposition of materials, as well as chemical transformations. The model simulations are described in more detail in (Witham et al., 2015).

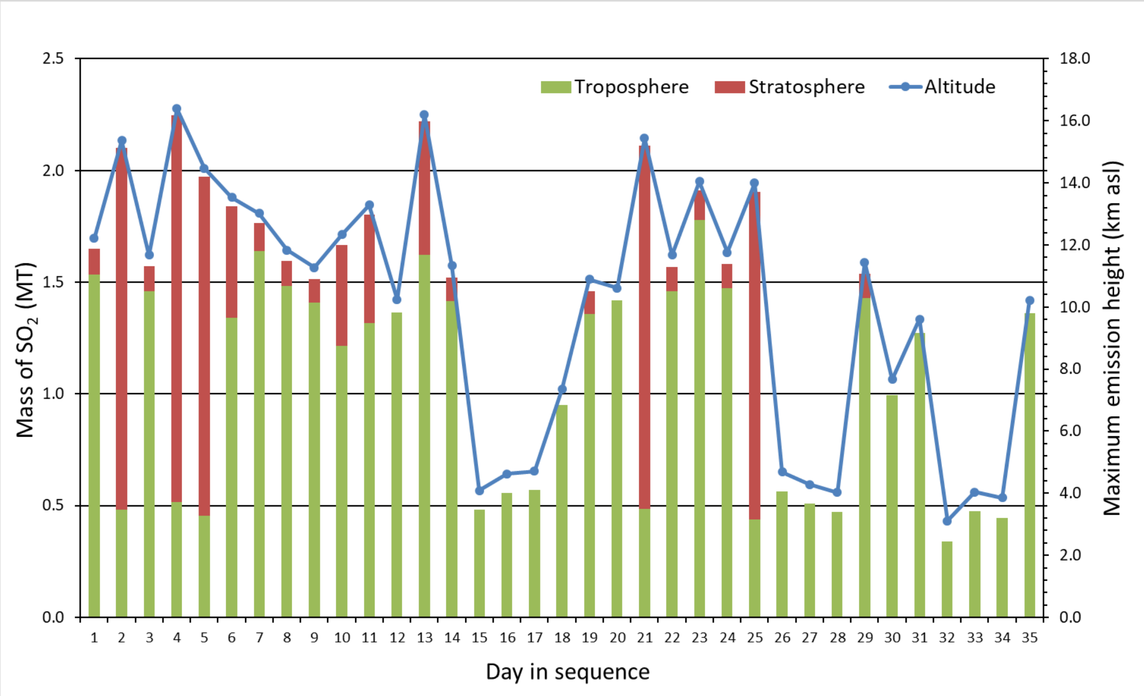


Figure 1: The mass of SO_2 released into the troposphere (green) and stratosphere (red) for each 24-hour emission (assuming that the tropopause is at 10 km above sea level over Iceland). The scenario included 5 weeks of eruption followed by one week of no emissions (not shown). The maximum emission height on each day is shown by the blue line.

The model was run for 80 separate simulations to represent individual eruptions, each based on UK Met Office numerical weather prediction data from a consecutive 6-week period, from the start of 2003 until late 2012. The resulting ensemble of 80 different model runs over 10 years gives a wide range of possible scenarios for dispersion of volcanic products, which account for different meteorological conditions throughout the decade. This is important because the prevailing meteorological conditions influence which parts of the UK could be affected by the eruption.

2.2 Health risk assessment methodology

The metrics of the modelled chemical species used for the health risk assessment, and thus extracted from the modelled runs, are the 24-hour mean SO_2 and 24-hour mean SO_4 concentrations, output at the near surface (0-200 m). For the purposes of this health risk assessment and due to the availability of modelled data, we assume that the health risk due to particulate matter ($PM_{2.5}$) associated with the volcanic eruption is entirely due to SO_4, and hence we calculate health impacts using the exposure-response coefficient for $PM_{2.5}$ to represent the health burden due to sulphates. This is a simplification, since there are likely to be other harmful constituents of the $PM_{2.5}$, however there are no widely used exposure-response coefficients for SO_4, and it is not practical to model total $PM_{2.5}$ emitted from an effusive volcanic eruption due to a lack of knowledge of all the constituent emissions.

The health risk assessment was carried out for each of the 80 consecutive 6-week periods throughout the ten-years separately for SO_2 and SO_4 to represent short-term exposure impacts on mortality and morbidity, and in addition, we estimated mortality impacts attributable to long-term exposure over an extended 5-month period.

To calculate mortality and morbidity associated with short-term exposure to emissions from volcanic eruptions, we used daily (24 hour mean) data for both SO_2 and SO_4, which is consistent with the design of the relevant epidemiological studies (Department of Health, 1998). It is plausible that there could be health impacts relating to 'peaks' in SO_2 exposure over shorter durations (e.g. 15 minute periods) (WHO, 2006), but the atmospheric model output was not available at such a fine temporal resolution. There is some evidence to suggest that exposure to high levels of SO_2 over time-scales of 15 minutes or less may lead to an increase in asthma episodes (WHO, 2006), although attempts have not been made to formally quantify this. However, it is likely to be the case that by the time the SO_2 reaches the UK from Iceland, it is well mixed throughout the boundary layer, and high short-lived peaks are likely to be rare (Witham et al., 2015).

We carried out population weighting to produce more accurate estimates of population exposure to the pollutants within the UK. This was done by re-gridding the 1x1 km resolution 2011 gridded UK census data onto the 0.25° by 0.25° NAME model output grid and summing the total population in each resulting grid cell. The population weighted exposure was calculated by multiplying the total population in each cell with the simulated air pollution concentration in that cell (Figure 2), then summing the values for all grid cells and dividing by the total UK population. This calculation was done for each day of the modelled simulation. Figure 2 shows the daily mean concentrations of SO_2 and SO_4 for an example day of the simulations.

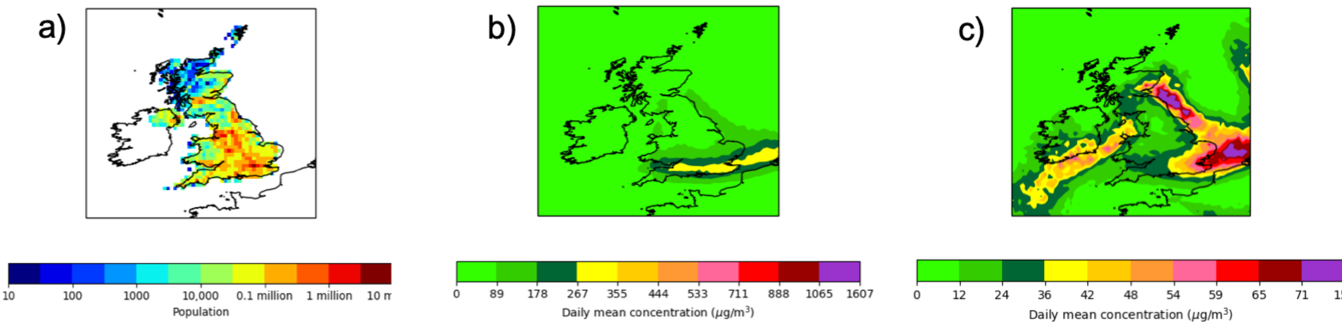


Figure 2: (a) Re-gridded UK population data, (b) an example of the modelled SO_2 concentration data and (c) an example of the modelled SO_4 concentration data, both displayed using the respective UK Air Quality Index contour scales, daily mean for 15th August 2003.

After estimating mortality and morbidity (cardiovascular and respiratory hospital admissions) separately for SO_2 and SO_4, the estimates were summed for SO_2 and SO_4 for each separate 6-week period, to give a combined mortality or morbidity estimate. The health impacts of

SO_2 and SO_4 are considered to be separate in this case. The mortality and morbidity estimates for each 6-week period were calculated as follows:

$$M = \sum_{i=1}^{N} E_i B\, R_e$$

Where *M* is the total mortality associated with the volcanic eruption, calculated over the 6-week period, *i* is the day within the period, *N* is the number of days in the period, E_i is the daily mean population weighted SO_2 or SO_4 concentration, *B* is an estimate of UK daily baseline mortality or morbidity and R_e is the exposure-response coefficient for SO_2 or SO_4 for a 24-hour period.

Specifically, the baseline mortality, *B* is 1,513 deaths per day in the UK (based on an annual UK death total of approximately 550,000 for 2011 taken from the Office for National Statistics: http://www.ons.gov.uk/ons/dcp171778_317087.pdf). The exposure concentration (E_i) for SO_2 or SO_4 was calculated by taking the population weighted SO_2 and SO_4 concentrations for the UK for each 24 hour period, and the exposure-response coefficient R_e was based on published literature: for SO_2, epidemiological evidence indicates an increase in mortality of 0.45% for an increase in SO_2 of 10 µg/m^3 (Anderson et al., 2007). For the calculation of the mortality related to SO_4, we used the $PM_{2.5}$ exposure-response relationship, which assumes a 1.04% increase in mortality for a 10 µg/m^3 increase in $PM_{2.5}$ (in this case SO_4) (Atkinson et al., 2014). We assumed the exposure-response relationships are linear and there is no threshold below which there is no health impact.

As part of a sensitivity analysis for the health impacts of SO_2 and SO_4, we include results of the analysis using alternative published exposure-response relationships in the supplementary material. For SO_2 the alternative R_e is an increase in mortality of 0.6% for an increase in SO_2 of 10 µg/m^3 (Department of Health, 1998). For SO_4, the alternative R_e is an increase in mortality of 0.96% for an increase in $PM_{2.5}$ of 10 µg/m^3, which was previously used by (A Schmidt et al., 2011). The use of these alternative exposure-response relationships as sensitivity analyses gives a wider estimate of potential excess mortality.

In addition to mortality estimates, the health risk assessment was extended to include morbidity. We used a similar method to calculate emergency cardiovascular and emergency respiratory hospital admissions, using different coefficients. The baseline morbidity figures we used were 1,515 (mean daily emergency cardiovascular hospital admissions for the UK) and 1,871 (mean daily emergency respiratory hospital admissions for the UK) from the 2011/12 Hospital Episode Statistics figures for England, scaled for the UK, provided by the Health and Social Care Information Centre (HSCIC, 2012). We used emergency hospital admissions since this is more likely to be of relevance for health impacts from an effusive volcano, and excludes routine hospital admissions which are unlikely to relate to any volcanic emissions.

The exposure-response coefficients for SO_2 related morbidity is based on a 0.96% increase in emergency cardiovascular hospital admissions for a 10 µg/m^3 increase in SO_2 (Anderson et al., 2007). For SO_4, the exposure-response relationship is based on a 0.90% increase in emergency cardiovascular admissions for a 10 µg/m^3 increase in $PM_{2.5}$ (Atkinson, R.W. et al., 2014).

For emergency respiratory hospital admissions, the relationships are based on an increase of 1.51% for a 10 µg/m^3 increase in SO_2 (Anderson et al., 2007). For SO_4, a 0.96% increase in emergency respiratory hospital admissions for a 10 µg/m^3 increase in $PM_{2.5}$ has been used (however this relationship, whilst positive, is not statistically significant) (Atkinson, R.W. et al., 2014).

To estimate the burden from short-term exposure but over a prolonged volcanic eruption exposure period, we calculated the health impacts due to a potential 5-month long exposure period. There was no modelled data specifically covering this scenario, so instead, the results for health impacts using the short-term exposure coefficients for the 6-weekly periods were scaled up to cover a 5-month period. This assumes that the concentrations of SO_2 and SO_4 over a 5-month period would be to the same as those over the 6-week period but lasting over a longer time.

3. Results

3.1 Modelled concentrations

Figure 3 shows simulated population weighted daily mean SO_2 and SO_4 concentrations for each of the consecutive 80 modelled periods for the UK, each plotted starting when the eruption occurs, and continuing for six weeks (42 days). There are a few peaks in 24-hour mean SO_2 and SO_4, mainly in the second half of the 6-week period, but overall, daily mean population weighted SO_2 and SO_4 concentrations are 1.8 µg/m^3 and 3.5 µg/m^3 respectively. Differences between concentrations for each simulation are driven by the differences in the underlying meteorology used in each of the 80 simulations.

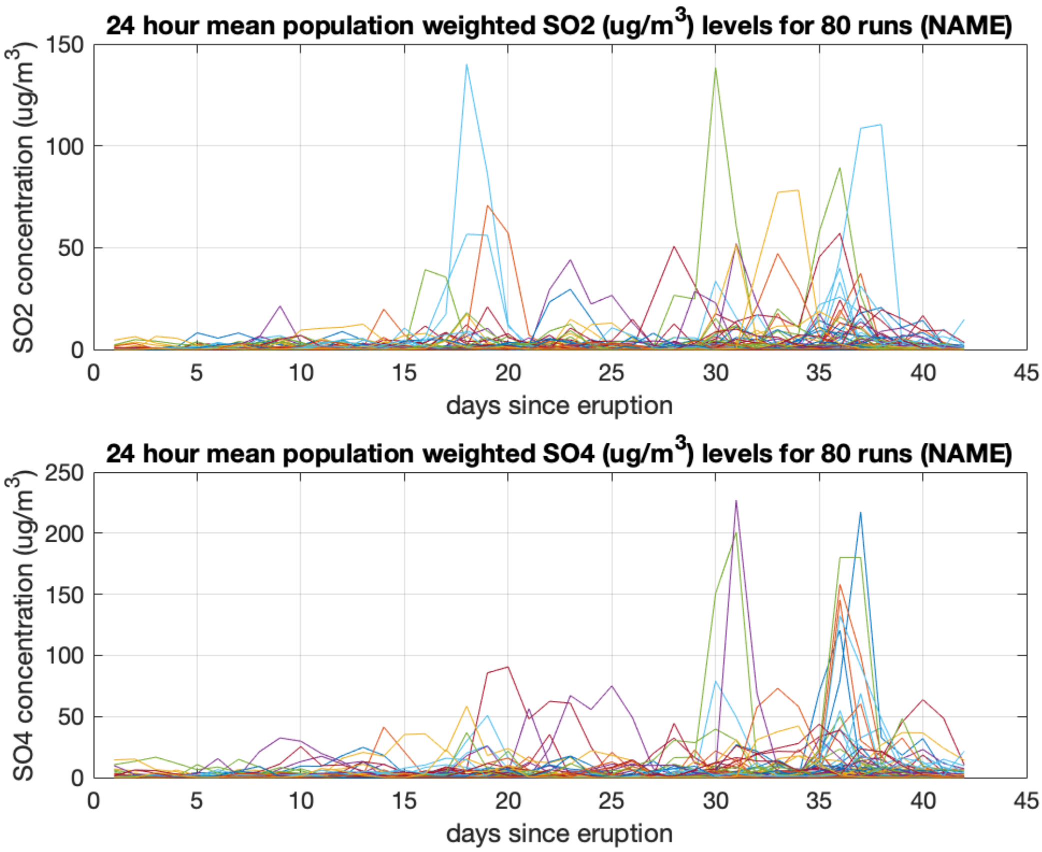


Figure 3. Population weighted 24-hour mean SO_2 (top) and SO_4 (bottom) over 6 week periods. Each of the 80 simulated eruption periods, representing different meteorological conditions, is illustrated by a different line.

3.2 Health risk assessment results

3.2.1 Mortality estimates

The health risk assessment was carried out for each of the 80 6-week periods separately, and results of the estimated number of deaths are presented for SO_2 and SO_4 health impacts independently (Figure 4). The histograms show that in the majority of cases, the number of deaths associated with SO_2 over the 6-week periods total fewer than around 100 for each model run for the UK. For SO_4, in the majority of cases, the number of deaths totals fewer than around 200. The 6-week period with the highest SO_2 concentrations is associated with 313 deaths, and the period with the highest SO_4 concentrations is associated with 826 deaths. The single 6-week period which relates to the highest combined SO_2 and SO_4 levels is associated with 925 deaths. These figures represent a worst-case scenario for our simulations (Figure 4) and are the equivalent of around 1 death per 100,000 population in the UK in each case.

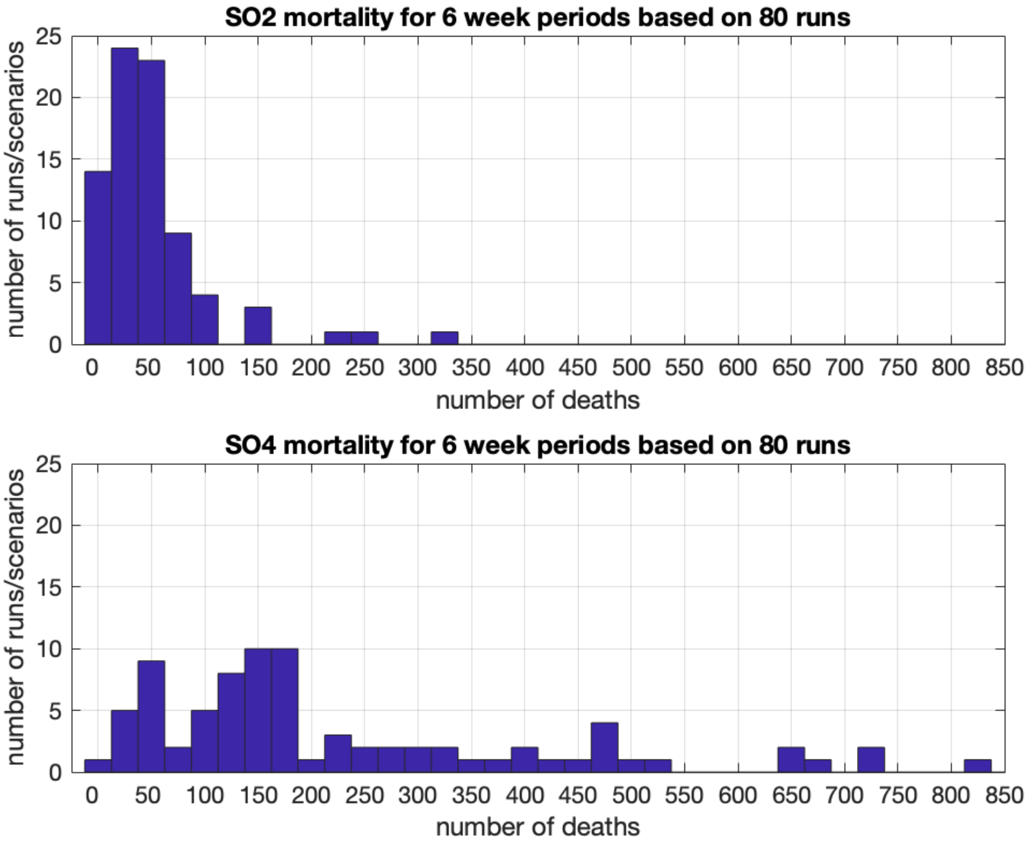


Figure 4. Distribution of the total number of deaths in the UK across each of the 80 simulated 6-week runs associated with exposure to SO_2 (top) and SO_4 (bottom).

The box and whisker plots in Figure 5 show that the results are weighted at the lower end, i.e. there are more simulation periods, and hence weather conditions, which would result in smaller numbers of deaths rather than larger numbers of deaths. This is shown by the median number of deaths being positioned towards the lower end of the distribution (red horizontal lines, Figure 5). The median number of deaths over the 80 model runs gives a more appropriate measure of the most likely number of deaths than the mean, which are biased by a few high exposure simulations (shown as crosses in Figure 5). Median values of estimated deaths are summarised in Table 1. The estimated number of deaths associated with SO_4 are higher than those associated with SO_2, since SO_4 concentrations are generally higher than SO_2 concentrations, and the exposure-response coefficient for SO_4 (in this case, $PM_{2.5}$) is around twice as large as for SO_2 (Figures 4-5 and Table 1). The median number of estimated deaths over a 6-week period for SO_2 is 39 and for SO_4 is 163; the combined estimate for the number of deaths is also included in Figure 5. In this case, the estimated deaths from SO_2 and SO_4 in each particular 6-week period are summed. The average combined median estimate is 213 total deaths. However, the combined median estimate is not simply the sum of the SO_2 and SO_4 medians, rather it was calculated by considering the total impact of SO_2 and SO_4 for each of the 80 individual periods and then calculating the median value based on these total estimates. This is because the two pollutants are not likely to be at a maximum at the same time, due to the transport and the chemistry of the plume. The reaction of SO_2 to form SO_4 means that the concentration of SO_4 increases with time, whilst the concentration of SO_2 decreases. Therefore, higher concentrations of SO_2 are more likely to occur in plumes that are relatively young when they reach the UK (hours to a few days), whereas higher concentrations of SO_4 are more likely to occur in older plumes.

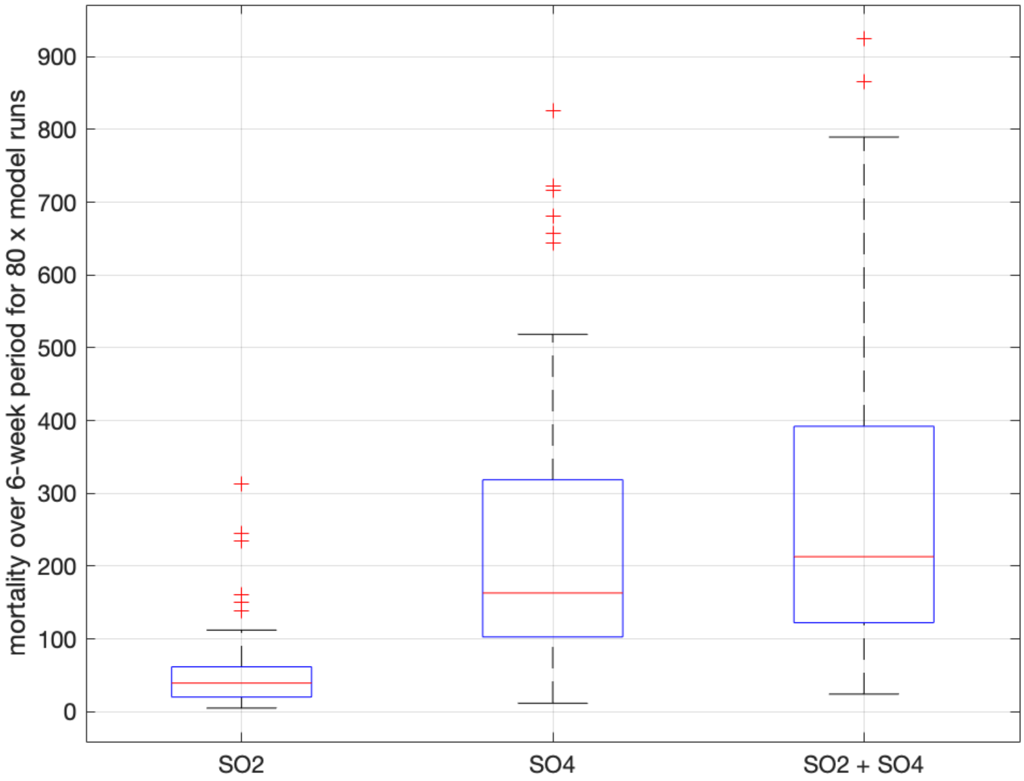


Figure 5. Estimates of the total number of deaths across each of the 80 simulated 6 week runs associated with SO_2 (left), SO_4, (middle) and for SO_2 and SO_4 in each simulation combined (right).

Although median estimates are more likely to occur, this health risk assessment indicates that there is a chance of much higher numbers of deaths in a few scenarios, as indicated by the crosses in Figure 5. This means that there could potentially be situations where an effusive volcanic eruption in Iceland leads to mortality peaks of 925 people over a 6-week period, according to this analysis.

Estimation of mortality impact over a 5-month period

In order to provide estimates of the potential health impacts relating to a 5-month long exposure period, similar to the 2014-15 Holuhraun Icelandic eruption, the results for each of the 6-week periods were scaled up accordingly, under the assumption that a 5-month long eruption would have similar daily impacts as a 6-week long eruption, but extended over a longer time-period. This assumption is necessary because no specific modelling data are available for a 5-month long eruption period, but caution should be exercised when interpreting the results (Figure 6).

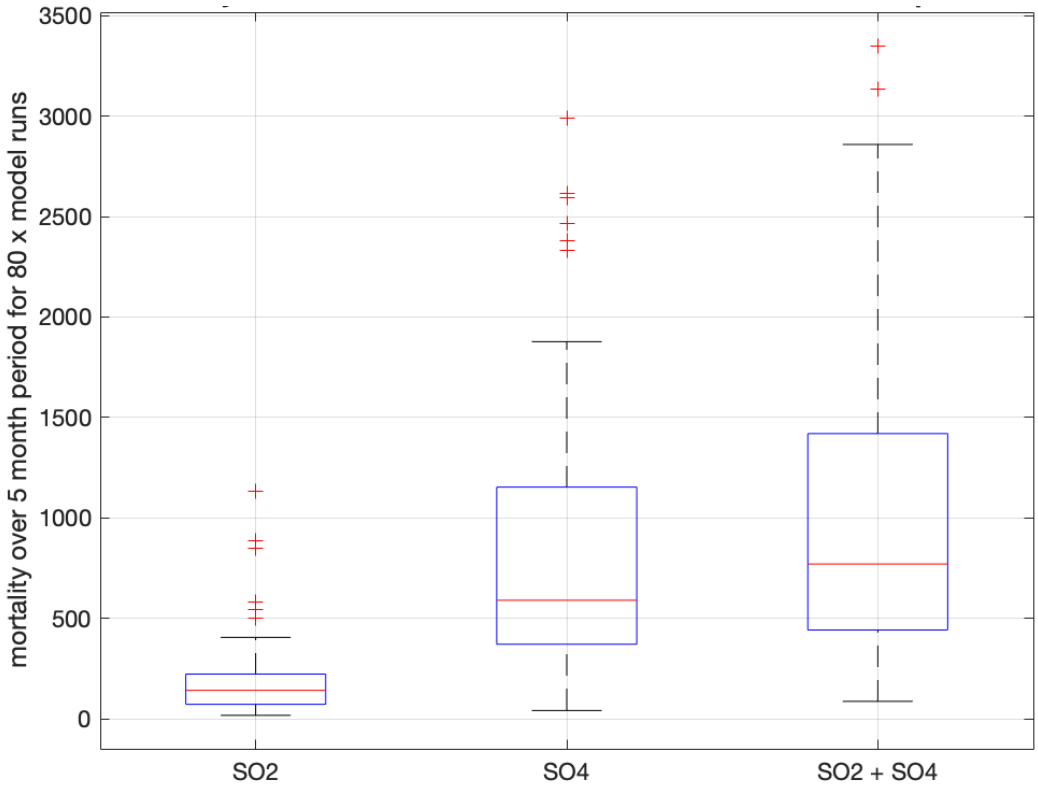


Figure 6. Estimates of the total number of deaths across each of the 80 simulated runs, scaled for a 5-month eruption, for SO_2 (left), SO_4, (middle) and for SO_2 and SO_4 in each simulation combined (right).

Table 1. Summary of estimated health impacts (mortality) from SO_2 and SO_4 and combined, for 6-weekly and 5-monthly periods.

	Median estimate of number of deaths over period		
	SO_2	SO_4	SO_2 and SO_4 combined*
6-weekly periods	39	163	213
5-monthly periods	143	591	772

**The combined median estimate is calculated by calculating the impacts of both SO_2 and SO_4 for each modelled period before calculating the median, and is not the sum of the separate SO_2 and SO_4 median estimates.*

Figure 6 and Table 1 show the estimated number of deaths which may be expected over a 5-month exposure period, scaled from a 6-week exposure period. In this 5-month case, the median (average) estimated deaths for SO_2 are 143, for SO_4 are 591 and for the total SO_2

and SO_4 are 772 (Table 1). A worst-case scenario could be 3,350 deaths over a 5-month period, according to this analysis.

3.2.2 Morbidity estimates – emergency hospital admissions

Table 2 summarises cardiovascular morbidity over 6-week and 5-month periods, which ranges from 305 emergency admissions for SO_2 to 512 emergency admissions for SO_4 and with a combined estimate of 896 (over 5 months). Similarly, table 3 shows emergency respiratory hospital admissions over the same periods, with a combined estimate of 1,354 admissions over 5 months. The respiratory admissions are around double the cardiovascular morbidity estimates for SO_2, and of the same order as cardiovascular morbidity estimates for SO_4.

Table 2. Summary of estimated health impacts (emergency cardiovascular hospital admissions) from SO_2 and SO_4 and combined, for 6-weekly and 5-monthly periods.

	Median estimate of number of hospitalisations over period		
	SO_2	SO_4	SO_2 and SO_4 combined*
6-weekly periods	84	142	247
5-monthly periods	305	512	896

**The combined median estimate is not the sum of the separate SO_2 and SO_4 median estimates.*

Table 3. Summary of estimated health impacts (emergency respiratory hospital admissions) from SO_2 and SO_4 and combined, for 6-weekly and 5-monthly periods.

	Median estimate of number of hospitalisations over period		
	SO_2	SO_4	SO_2 and SO_4 combined*
6-weekly periods	164	186	374
5-monthly periods	593	675	1354

**The combined median estimate is not the sum of the separate SO_2 and SO_4 median estimates.*

Tables 2 and 3 report median estimates of emergency cardiovascular and respiratory hospital admissions. The upper end scenarios, based on the 6-weekly period with the maximum combined impacts from SO_2 and SO_4 correspond to 1,113 cardiovascular admissions and 1,793 respiratory admissions. Over 5 months, these maximum values reach 4,030 and 6,493, admissions respectively.

4. Discussion and conclusions

We estimated the potential number of UK deaths and emergency hospital admissions associated with SO_2 and SO_4 emissions from a hypothetical effusive volcanic eruption in Iceland. By using an ensemble of 80 modelled simulations, we were able to capture a wide range of exposure scenarios, each driven by different meteorological conditions. The large variability of SO_2 and SO_4 concentrations across all model simulations clearly demonstrates the role of meteorology in controlling surface level concentrations of these pollutants in the UK (figure 3). As well as estimating the mortality and morbidity impacts related to a 6-week effusive volcanic eruption, we also considered the potential impacts of a longer eruption period, by calculating effects could be associated with a 5-month long exposure period.

We estimated the numbers of deaths brought forward and emergency respiratory and cardiovascular hospital admissions as median estimates, and also gave maximum estimates, based on the simulation with the highest levels of both SO_2 and SO_4. Over a 6-week effusive eruption period, the median estimated total deaths from SO_2 are 39, and from SO_4 are 163. The median estimated combined number of deaths from SO_2 and SO_4 for a 6-week exposure period is 213. However, when considering the maximum impact scenario, there could be up to 925 deaths brought forward as a result of exposure to volcanic gases and particles.

When scaling the mortality estimates up to cover a 5-month period, to reflect the nature of Icelandic effusive volcanic eruptions, the estimated combined number of deaths brought forward for both SO_2 and SO_4 is approximately 772. The upper-end estimate over 5 months is 3,350 deaths brought forward. The inclusion of a sensitivity analysis using alternative exposure-response coefficients for SO_2 and SO_4 gives an indication of a range of possible outcomes (supplementary material). Characterising the influence of uncertainty in the exposure-response relationship is difficult due to the limited epidemiological studies in this area, but results generated using an alternative exposure-response coefficient for SO_2 and SO_4 (supplementary material) show higher deaths from SO_2 (~36% increase) and slightly lower deaths from SO_4 (~7% decrease).

The median number of estimated emergency cardiovascular admissions for both pollutants combined was 896 over 5 months. For emergency respiratory admissions, the equivalent number was 1,354. The upper-end scenario gives maximum values of emergency cardiovascular admissions of 4,030 and maximum respiratory emergency emissions of 6,493.

A related analysis based on similar methods for the Laki eruption of 1783-84 estimates 142,000 additional cardiopulmonary fatalities could have occurred across Europe as a result of the eruption (Anja Schmidt et al., 2011). Even given the larger population of Europe compared to the UK (the UK is around 10% of the population of Europe), our results are smaller than Schmidt et al, although of the same order of magnitude.

The estimates presented here are based on a number of assumptions and simplifications, and rely on modelled exposure data and published exposure-response coefficients. As such, the estimated mortality and morbidity figures should be interpreted with caution. A smaller or larger volcanic eruption would lead to variations in health impacts. Since it is not possible to predict the magnitude and duration of future effusive volcanic eruptions, we can only estimate health impacts associated with a particular simulated effusive eruption. We have used 80 scenarios in order to try to represent a range of conditions, although even this number of scenarios does not capture the entire range of variability. For example, we have not considered the effects of different eruption heights, or different temporal variability in emissions in our ensemble. However, the variability in results shows the importance of considering an ensemble approach in a risk assessment of this type, and allows for median and maximum impacts to be presented. Although we have presented worst case scenarios based on our modelled ensembles, it is of course possible that larger eruptions could lead to much more severe health impacts.

We calculated mortality and emergency hospital admissions based on daily mean SO_2 and SO_4 exposures only; it was not possible to investigate other health endpoints (such as asthma exacerbation) or to calculate effects over time periods shorter than 24 hours. The concentration-response coefficients for SO_2 and $PM_{2.5}$ (assumed for SO_4) were used in the health risk calculation since these are likely to be the species of most relevance for health impacts. However, this assumes that sulphate aerosols (SO_4) are of the same toxicity as $PM_{2.5}$ which may contain a range of other constituents. This simplification was necessary because there is no suitable exposure-response function for SO_4, and there is uncertainty as to the exact composition of volcanic particles. Research suggests that particulate matter from different sources is likely to vary in its toxic potency, although it is difficult to quantitatively assess the impacts of specific $PM_{2.5}$ constituents in health effect studies (Johnston et al., 2019; Park et al., 2018). We have presented our health impact results for SO_4 and SO_2 separately, as well as in total. There are some considerations when combining the effect estimates: the exposure-response coefficients we have used for SO_2 and SO_4 are each derived from single pollutant models and so have not been adjusted to take account of mutual confounding, and there is likely to be some level of correlation between the pollutants. Therefore, our estimate for the combined effect from both pollutants, gives a guide to the maximum health impacts which could occur on the same day of exposure. This should only be used as guidance for potential maximum impacts based on our scenarios, because adding the impacts from each pollutant may lead to over-estimation of impacts.

Finally, by extrapolating the health impacts to cover a 5-month period, we have assumed the daily exposure over the 6-week period is representative of a longer exposure period, which has allowed a simple scaling in time to estimate total numbers of deaths over 5 months. The total number of estimated deaths would increase over this extended period, however, the average daily death rate combined for SO_2 and SO_4 would remain the same over the exposure period. The method we have used to estimate short term impacts over periods of weeks or months may lead to over-estimations of health impacts, if we assume that there are mortality displacement effects, i.e. that exposure and deaths brought forward each day depletes the size of the population most at risk, and therefore mortality rates may fall later in the exposure period, as the susceptible group gets smaller. Health effects of air pollutants over the medium term (several-day-periods to months) are not well understood, although calculations of short-term impacts are often based on accumulated daily impacts over the exposure period e.g. (Fenech et al., 2019; Heal et al., 2013; Macintyre et al., 2016). Mortality displacement may lead to the over-estimation of impacts over several days or months based on exposure-response functions for single days. On the other hand, our estimates do not capture any cumulative impacts of prolonged exposure because exposure-response coefficients for long term health impacts are available only for exposure periods of one year or more

The type of quantitative risk assessment methodology demonstrated here can be applied to other geographical settings to estimate the potential impact of effusive volcanic eruptions on mortality and morbidity in affected populations over long distances. As well as estimates based on the median calculated health impacts, the inclusion of maximum, 'worst-case' or higher range scenarios here can be used to prepare health facilities for severe impacts in case of an Icelandic volcanic eruption in future.

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Supplementary material:

Sensitivity test using alternative exposure-response relationships for SO_2 and SO_4 (expressed as $PM_{2.5}$)

Alternative SO_2 health impact calculation

Table S1 shows the results of the health impact assessment using the alternative exposure-response relationship recommended by COMEAP (1998) of an increase in mortality of 0.60% for a 10 µg/m^3 increase in SO_2. This estimate is slightly higher than the relationship used in the core analysis above (0.45% increase per µg/m^3 increase in SO_2) and hence gives a slightly higher estimate for health impacts for SO_2. The impacts for SO_4 in this case remain as in Table 1. The impact of using this higher exposure-response coefficient is an increase in the median estimate SO_2 deaths from 39 to 53 for a 6-week period, and an increase from 143 to 191 for a 5-month period. The combined SO_2 and SO_4 estimates also increase based on this alternative relationship from 213 to 229 (6-week period) and 772 to 828 (5-month period).

Alternative SO_4 health impact calculation

Table S2 shows the results of the health impact assessment using the exposure-response coefficient used by Schmidt *et al.* (2011) of an increase in mortality of 0.96% for a 10 µg/m^3 increase in $PM_{2.5}$, or in this case, SO_4. This estimate is slightly lower than the relationship used above (1.04% increase per 10 µg/m^3 increase in $PM_{2.5}$) and hence gives a slightly lower estimate for health impacts for SO_4. The impacts for SO_2 in this case remain as in Table 1. The impact of using this alternative exposure-response relationship is a decrease in the median estimate for SO_4 deaths from 163 to 151 for a 6-week period, and a decrease from 591 to 546 for a 5-month period. The combined SO_2 and SO_4 estimates also decrease based on this alternative relationship from 213 to 200 (6-week period) and 772 to 723 (5-month period).

Table S1. Sensitivity test: Summary of estimated health impacts (mortality) from SO_2 and SO_4 and combined, for 6-weekly and 5-monthly periods using alternative exposure response relationship for SO_2. Estimates for SO_4 remain unchanged.

	Median estimate of number of deaths over period		
	SO_2	SO_4	SO_2 and SO_4 combined*
6-weekly periods	53	163	229
5-monthly periods	191	591	828

*The combined median estimate is calculated by calculating the impacts of both SO_2 and SO_4 for each modelled period before calculating the median, and is not the sum of the separate SO_2 and SO_4 median estimates.

Table S2. Sensitivity test: Summary of estimated health impacts (mortality) from SO_2 and SO_4 and combined, for 6-weekly and 5-monthly periods using alternative exposure response relationship for SO_4. Estimates for SO_2 remain unchanged.

	Median estimate of number of deaths over period		
	SO_2	SO_4	SO_2 and SO_4 combined*
6-weekly periods	39	151	200
5-monthly periods	143	546	723

*The combined median estimate is calculated by calculating the impacts of both SO_2 and SO_4 for each modelled period before calculating the median, and is not the sum of the separate SO_2 and SO_4 median estimates.