19th International Conference on
Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
3-6 June 2019, Bruges, Belgium

EXCESS MORTALITY ESTIMATES OVER EUROPE: UNCERTAINTIES FROM MODELLING, EMISSIONS AND AEROSOL SOURCES

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Abstract: Assessment of health impacts associated with airborne particulate matter smaller than 2.5 μm in diameter (PM2.5) relies on aerosol concentrations derived either from monitoring networks, satellite observations, numerical models, or a combination thereof. When global chemistry-transport models are used for estimating PM2.5, their relatively coarse resolution has been implied to lead to underestimation of health impacts for densely populated and industrialized areas. In this study the role of model configuration, emission data and aerosol sources is investigated.
Using coarse spatial resolution modelling (100km) yields about 535 000 annual premature deaths over the extended European domain (242 000 within the EU-28), while approximately 2.4 % higher numbers are derived by using finer resolution (20km). Using the surface (i.e. lowest) layer of the model for PM2.5 yields about 0.6 % higher mortality rates compared with PM2.5 averaged over the first 200m above ground. Further, the calculation of relative risks (RR) or hazard ratios from PM2.5, using 0.1 μg/m^3 size resolution bins compared to 1 μg/m^3 (commonly used) is associated with ±0.8 % uncertainty in estimated deaths. Thus, model uncertainties contribute a small part of the overall uncertainty expressed by the 95% confidence intervals, which are of order ±30%, mostly related to the RR calculations based on epidemiological data. We further analyse the significance of emissions from energy production and agricultural sector, as well as naturally derived aerosols, on premature deaths over Europe. The health burden of CPP emission-induced PM2.5 in Europe is estimated to lead to 7,200-21,100 excess deaths per year, which is equivalent to to 8.9 - 25.8 excess deaths per year per Terrawatt-hour (TWh) of produced electricity. An assumed agricultural activity enhancement of 20% showed that the perturbed emissions (not only from agriculture but also other sectors affected by this change) affect European countries differently, depending on background pollution, the location downwind of major pollution sources and the magnitude of national emissions from the agricultural sector. Furthermore, southern European countries are affected by natural aerosols in desert dust storms that, albeit occurring in episodes of short duration, can increase mean annual PM2.5 concentrations by 1-4μg/m^3 and contribute significantly to excess mortality.

Key words: *Air pollution, premature mortality, aerosol modelling, coal power plants, agricultural emissions.*

INTRODUCTION

Exposure to airborne fine particulate matter (diameter less than 2.5 μm – PM2.5) has been associated with a number of short- and long-term adverse health outcomes varying from respiratory illnesses to premature death (WHO, 2013, Beelen et al. 2014). The assessment of health impacts from ambient (outdoor) air pollution relies on an integrated methodology that uses observations and/or air quality models to determine pollutant concentration distributions, and synthesize this information with exposure and population vulnerability on national and global scales (Lelieveld et al., 2015; Giannadaki et al, 2017, Pozzer et al. 2017). Use of atmospheric modelling systems is necessary to fill the gap in regions where air quality is not monitored, and to investigate alternative scenarios related to factors such as emissions, air quality regulations and population development. The use of coarse grid resolutions, forced by computational resource limitations and global model parameterizations, may result in underestimation of peak concentrations in densely populated and industrialized areas (Punger and West, 2013). This could influence mortality estimates by misrepresenting the gradients between pollution and population distributions leading to errors in estimates of health impacts.

In this study, we initially perform sensitivity tests to identify the uncertainty range, introduced to the mortality calculations, related to the configuration of the modelling system. We also calculate excess (or premature) mortality rates from aerosol concentrations derived from satellite retrievals of the aerosol optical depth (AOD) to assess the relative contribution of natural versus anthropogenic aerosols. We finally investigate the impact of two scenarios applied to the industrial sectors of energy production and agriculture over Europe.

METHODOLOGY

We use the integrated Weather Research and Forecast model coupled with Chemistry (WRF-Chem) for an annual simulation of particulate matter over Europe (Grell et al, 2005). For the configuration uncertainties analysis WRF-Chem was configured utilizing two domains, one with a horizontal resolution of 100km and the other with 20km, nested into the coarse grid domain (Fig 1a). The initial and boundary conditions for the meteorological data are provided by the National Center for Environmental Prediction (NCEP) global forecast system (GFS) at a resolution of 0.5° x 0.5°. The initial and boundary conditions for the chemical species are provided from global simulations with MOZART-4 (Model for Ozone And Related chemical Tracers version 4) model (Emmons et al., 2010). Emissions are calculated from the global emission dataset EDGAR-HTAP v2 (Janssens-Maenhout et al., 2012) that consists of 0.1° x 0.1° gridded annual anthropogenic emissions of NOx, SOx, non-methane volatile organic compounds (NMVOC), CO, NH_3, PM2.5 and PM10. Simulated PM2.5 concentrations are used to derive estimates of mortality from ischemic heart disease, cerebrovascular disease from ischaemic and haemorrhagic stroke, chronic obstructive pulmonary disease, lung cancer, and acute lower respiratory infections. The methodology for the calculation of the mortality and incidence rates requires country level baseline mortality rates for the diseases and population data (adopted from the WHO Global Health Observatory for 2010) and concentration – response functions calculated following the methodology of Burnett et al. (2014).

RESULTS AND DISCUSSION

We initially compare mean annual PM2.5 modelled concentrations to measurements reported by European countries to the European Environment Agency (EEA). The results from the two domains differ slightly, with mean annual PM2.5 concentrations of 16.3 μg m^{-3} and 17.2 μg m^{-3} over the coarse and fine resolution domains, respectively, while the observed mean is 14.3 μg m^{-3}. The mean model bias at the station locations varies from 2 to 2.9 μg m^{-3} for the 20km to the 100km resolution domain and the root mean square error ranges from 6.4 to 6.6 μg m^{-3} respectively. Satisfactory model performance for this application is indicated by the 95% of the data points falling within a factor of two (Fig 1b) for both the coarse and fine domain.

When comparing the number of excess deaths based on the pollutant concentrations from the two domains, at country level, we obtain a minor but non-linear response for the mortality estimates, with the majority of countries exhibiting lower mortality rates at 100 km than at 20 km-resolution domain. The differences reach -6% in Italy, -5% in Malta, -4.7% in Luxemburg, -7% in Slovenia and Spain and -9% in Portugal. In general, the countries with the largest biases cover small geographical areas where the use of a higher resolution for PM2.5 is important to represent national boundaries. We perform the same country-based analysis by using PM2.5 concentrations at ground level (L1) and concentrations averaged over the near-surface layer of approximately 200 m (L3) to test possible differences of the model results in view of vertical exchange processes. The use of the first lower model layer or the 200m layer PM2.5 concentrations yields statistically non-significant differences in excess mortality estimates with most of the countries exhibiting uncertainties less than 1% (0.58%). The calculation of RR (relative risk or hazard ratio) in 1μg m^{-3} bins yields slightly higher mortality rates than the in 0.1 μg m^{-3}. However, in total over the EU-28 the differences in the annual number of deaths from particulate matter pollution, driven by the resolution of the RR calculation, are within 0.8%. We additionally calculated excess mortality rates based on PM2.5 concentrations derived from satellite observations, with and without assimilation of ground observational data, as described in van Donkelaar et al. (2016). In general, satellite derived aerosol levels yield lower mortality rates over the EU-28 by approximately 10%. The use of the assimilated satellite PM2.5 values leads to improved agreement between the satellite-based and model-derived excess mortality, which in the present application does not use data assimilation. For the six of the top seven countries that account for almost half of the excess deaths in EU-28 (Italy, Poland, France, Romania, Spain, and Hungary) the data assimilation process in the satellite output brings satellite mortality rates closer to the modelled estimates. In general model uncertainties contribute a small part of the overall uncertainty expressed by the 95% confidence intervals, which are of order ±30%, mostly related to the RR calculations based on epidemiological data as summarized in Fig 2.

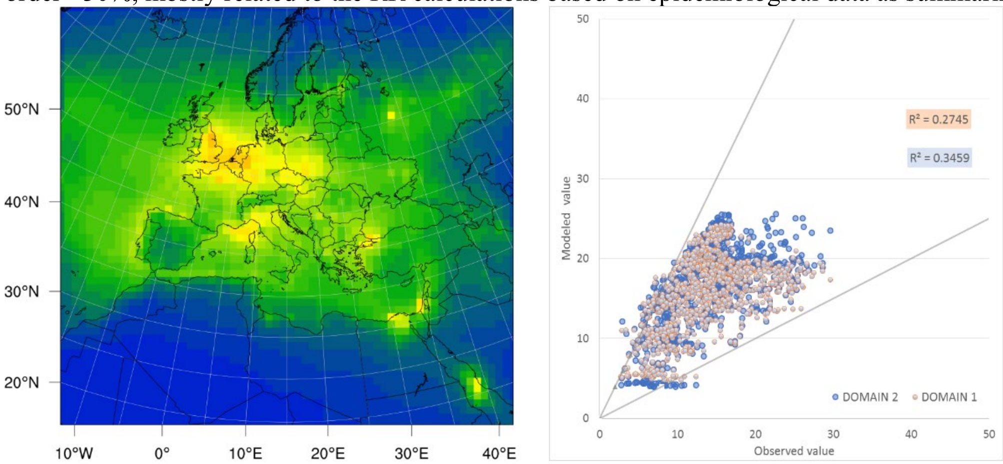

Figure 1. Domain utilized in the study (left) and modelled versus observed mean annual PM2.5 concentrations over AirBase stations over Europe for the year 2014 (right). 100km/20km domains in orange/blue-contoured circles.

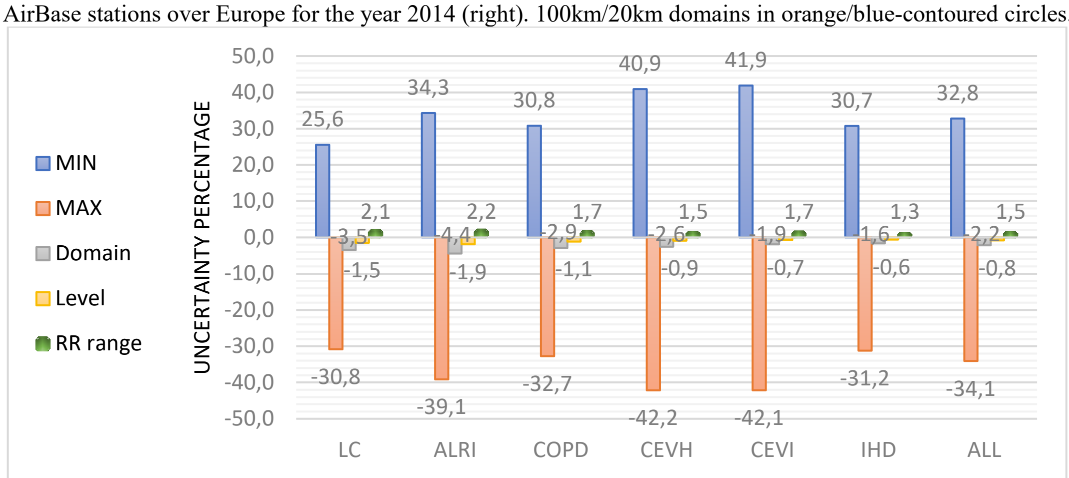

Figure 2. Uncertainties in mortality estimates related to model configuration (domain grid spacing in grey, level of PM2.5 concentration in yellow), RR concentrations step (in green) and the 95% confidence interval in IER functions.

We further analyse the impact that aerosols of natural origin can have on premature mortality. To highlight the significance on natural sources of pollution we used PM2.5 concentrations derived from satellite retrievals of the aerosol optical depth (AOD) with ground correction as in Van Donkelaar et al. (2016). Intense dust events (even of short duration) can increase the mean annual PM2.5 level by 1 to 4 μg m^{-3} with significant associated health impacts especially in the mostly affected southern European countries. Excess mortality calculations with and without the contribution of natural sources (mineral dust and sea salt) indicate that the presence of natural particles can increase national mortality estimates up to threefold, especially for countries located in the Mediterranean basin.

As a final test, we focus on two industrial sectors that are main emitters of aerosol and their precursors, namely energy production from coal power plants and agriculture. In the first case we estimate the excess pollution and related excess mortality from the operation of approximately 250 coal-fired power plants

(CPPs) in Europe. Excluding the CPP emissions mostly influences nitrate levels in the vicinity of the emission sources (Fig 3a) while the impact of CPPs on the sulphate aerosols is more uniform over all Eastern and South-eastern Europe (Fig 3b). The CPP influence on the distribution of emission fluxes of the gaseous pollutants SO2/NOx affects the distribution of the ammonium aerosols with the largest changes following the changes in the nitrate component (Fig 3c).

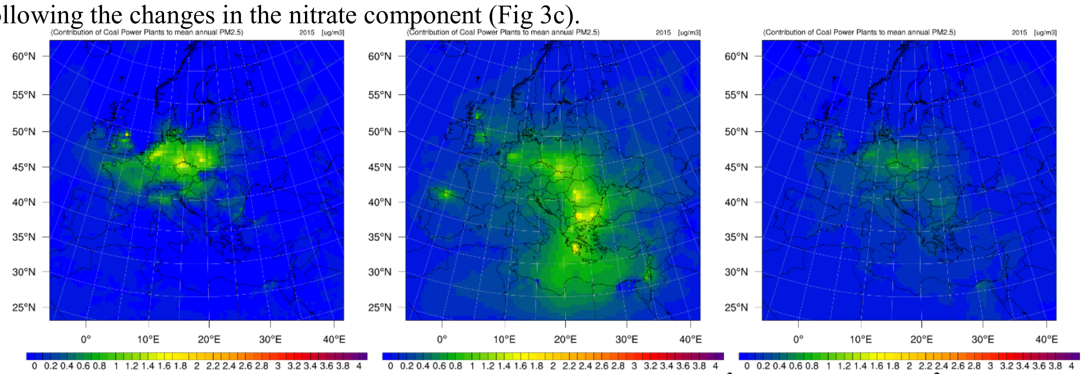

Figure 3. Annual mean contribution of coal fired power plants (in µg m^{-3}) on a) NO_3^-, b) SO_4^{-2} and c) NH_4^+

Integrating the electrical power of the excluded CPP units per EU-28 member state, and calculating the number of excess deaths due to emissions from the CPPs of that country to the total electricity power of the country we produce a 'coal phase-out benefit index' expressed as excess deaths per electricity power unit (Fig 4a). Austria, Belgium, Croatia, Hungary and Slovakia will have the largest benefit in terms of fewer excess mortality relative to the electricity range they decarbonize from coal (>0.5). On the other hand, Denmark, Finland, the Netherlands, Slovenia and Spain will have the smaller reductions in excess mortality relative to the total electricity potential needed to be replaced by other sustainable and less polluting source fuels. This occurs when either the national coal-related emissions are small, or when the country is not affected by large upwind CPP emitters. This index however must not be taken as a measure of national achievement, as the reduction in excess mortality in each country is not a result of the reduction of the respective emissions from that country alone, but rather a collective effort from all EU-28 member states. Further, it cannot be used as a 'cost-benefit' index as this ratio is strongly influenced by the non-linearity of the relationship between national coal-fired power plant productivity and excess mortality due to the transboundary transport of pollution. It should also be noted that due to the non-linearity of the IERs especially at lower concentrations, the estimates of our study represent lower limits of benefit in terms of decreasing excess mortality attributable to air pollution. The estimates could be significantly larger if additional reductions are applied simultaneously in other major emitting sectors.

Regarding the impact of an enhancement of 20% applied to the agricultural sector productivity, and the direct and indirect changes in emissions of all industrial sectors linked to agriculture, we find that several northern countries are amongst the least affected (<15% increase in excess mortality rates) (Fig4b). These countries are less influenced by the enhancement of the agricultural sector due to their location in view of atmospheric circulation patterns and pollution transport, despite similar increases in the emission fluxes of the main aerosol precursors. The respective increases in SO_2 vary from 22-50%, however due to the nature of the sulphate aerosol formation processes (remote from source regions) the impact of this increase is more evident downwind. Malta, Cyprus, Greece and Spain are the countries affected mostly by the changes in emissions and enhanced PM2.5 concentrations, mainly due to their location downwind of major pollution sources and own significant emissions from the agricultural sector. The increase in excess mortality in these countries ranges from 49.5% (Cyprus) to 89.1% (Malta).

CONCLUSIONS

This study focused on the excess mortality estimates calculated from modelling applications and the uncertainties related to the applied configuration. We showed that mortality rates differ by 2.4% due to horizontal grid resolution (20 and 100 km), 0.6% due to the vertical distribution of PM2.5 and 0.8% due to the resolution of RR. Estimates based on PM2.5 concentrations derived from satellite data are within 10% of the model results. The use of data assimilation in the satellite estimates brings excess mortality rates for the majority of the high-death-rate countries closer to the model results. On the other hand, the 95% confidence intervals of the integrated exposure-response functions for these diseases give rise to statistical uncertainties in the estimates within about 30%. These results indicate that the uncertainties of excess mortality estimates are dominated by the estimated response of population to air pollution, derived from epidemiological data, rather than the representation of annual mean PM2.5 values by air quality models and/or observations.

Further, we assessed the impact of natural sources of pollution and showed that for southern European countries, which are mostly affected by episodes of desert dust with high concentrations but short duration, the mean annual PM2.5 concentrations can be increased by 1-4 μg m^{-3}, resulting in some countries in a threefold increase in excess mortality. Regarding coal-fired power plants and agriculture, two major industrial sectors in terms of pollution, we showed that they can significantly modify the pollution and related health burden landscape over Europe both in countries with pronounced emissions of the respective sectors and in downwind locations.

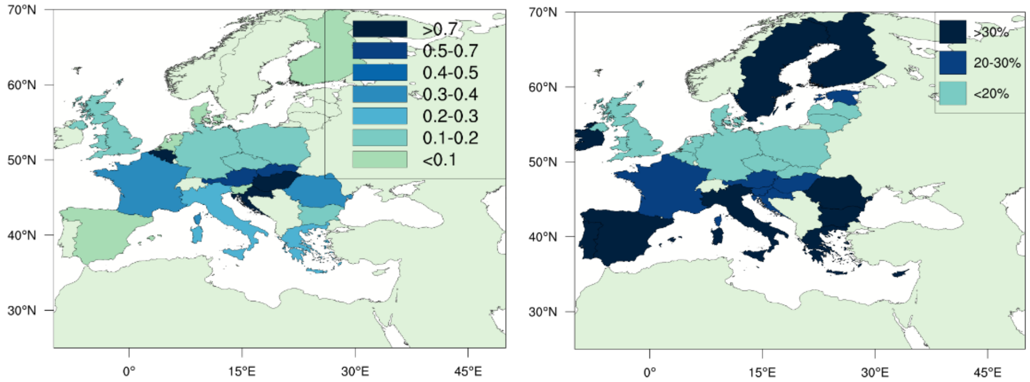

Figure 4. a) Benefit index expressed as number of excess deaths that can be avoided per electricity power unit produced from coal-fired power plants per country in the EU-28 and b) country-level excess mortality rate estimates in the EU-28 due to enhanced outdoor air pollution levels of PM2.5 from perturbed agricultural emissions.

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