



Influence of spatial resolution on population PM_{2.5} exposure and health impacts

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Abstract

Health effect estimates depend on the methods of evaluating exposures. Due to non-linearities in the exposure-response relationships, both the predicted mean exposures as well as its spatial variability are significant. The aim of this work is to systematically quantify the impact of the spatial resolution on population-weighted mean concentration (PWC), its variance, and mortality attributable to fine particulate matter (PM_{2.5}) exposure in Finland in 2015. The atmospheric chemical transport model SILAM was used to estimate the ambient air PM_{2.5} concentrations at 0.02° longitudinal × 0.01° latitudinal resolution (ca. 1 km), including both the national PM_{2.5} emissions and the long-range transport. The decision-support model FRES source-receptor matrices applied at 250-m resolution was used to model the ambient air concentrations of primary fine particulate matter (PPM_{2.5}) from local and regional sources up to 10 km and 20 km distances. Numerical averaging of population and concentrations was used to produce the results for coarser resolutions. Population-weighted PM_{2.5} concentration was 11% lower at a resolution of 50 km, compared with the corresponding computations at a resolution of 1 km. However, considering only the national emissions, the influences of spatial averaging were substantially larger. The average population-weighted local PPM_{2.5} concentration originated from Finnish sources was 70% lower at a resolution of 50 km, compared with the corresponding result obtained using a resolution of 250 m. The sensitivity to spatial averaging, between the finest 250-m and the coarsest 50-km resolution, was highest for the emissions of PPM_{2.5} originated from national vehicular traffic (about 80% decrease) and lowest for

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the national residential combustion (60% decrease). Exposure estimates in urban areas were more sensitive to the changes of model resolution (14% and 74% decrease for $PM_{2.5}$ and local $PPM_{2.5}$, respectively), compared with estimates in rural areas (2% decrease for $PM_{2.5}$ and 36% decrease for $PPM_{2.5}$). We conclude that for the evaluation of the health impacts of air pollution, the resolution of the model computations is an important factor, which can potentially influence the predicted health impacts by tens of percent or more, especially when assessing the impacts of national emissions.

Keywords Air quality model · FRES · SILAM · Particulate matter · $PM_{2.5}$ · Resolution · Exposure · Mortality

Introduction

Air pollution is one of the biggest environmental health risks globally (Gakidou et al. 2017). In Finland, fine particles ($PM_{2.5}$) were recently evaluated to be the most harmful ambient air pollutant (Lehtomäki et al. 2018). Health impact estimates of air pollution are based on ambient concentrations which are used as exposure estimates. Concentration-response functions are needed to link the exposure to health outcomes.

Several health outcomes are related to $PM_{2.5}$ exposure. The associations are typically quantified as relative risks or hazard ratios in epidemiological studies. Traditionally, concentration-response relationships for $PM_{2.5}$ exposure have been assumed to be linear or log-linear (Pope 3rd et al. 2015). These mainly work for low-exposure levels but lead to unrealistically large impacts in areas where the concentrations are very high (Burnett et al. 2014).

In recent years, integrated exposure-response (IER) functions have been developed to estimate the health impacts in whole exposure range, up to annual averages of $300 \mu\text{g}/\text{m}^3$ (Burnett et al. 2014). These functions combine exposures from several sources: ambient air pollution, household air pollution, second-hand smoking, and active smoking. The functions have a non-linear form which varies between the modelled health endpoints: ischemic heart disease, stroke, lung cancer, chronic obstructive pulmonary disease, and acute lower respiratory infections (children). The IER functions include theoretical thresholds under which no health impacts are calculated.

Outdoor air pollutant concentrations can be estimated by several methods such as observations, observation-based approaches like statistical interpolation and land-use regression, or with air quality models that can operate at various spatial resolutions (Jerrett et al. 2005). It has been suggested that both resulting mean exposure levels as well as their variability may depend on spatial resolution. The concepts of grid spacing and resolution are also fundamental for chemical transport models (Kukkonen et al. 2012). Grid spacing for Eulerian chemical transport models can be simply defined as the distance between numerical grid points. Resolution commonly refers to the smallest spatial or temporal scale, on which various phenomena can be resolved by the model or modelling system.

The resolution or grid spacing can be different for the emission, meteorological, land use, or other input data, as well as for the computational and receptor grid of the model. The effective grid spacing can be determined by the meteorological fields that the model uses and by the grid spacing of the emissions. In general, for both Lagrangian and Eulerian chemical transport models, the effective resolution of the modelling system is closely related to the grids that are employed by the numerical weather prediction model, the emissions processing model, and the chemical transport model (Kukkonen et al. 2012). The increasing of the air quality model resolution should therefore go hand in hand with improved resolution of input data (Schaap et al. 2015).

Computational cost has been the most common restricting factor when deciding the spatial resolution. On a continental scale, 10 km and coarser resolutions have been commonly used whereas finer resolutions are needed to model concentration variations in or between individual cities (Colette et al. 2014). For instance, on a European scale, resolution of 50 km has been used by the Meteorological Synthesising Centre-West (MSC-W) of the European Monitoring and Evaluation Programme (EMEP) to evaluate concentrations of long-range transport (LRT) of the particulate matter (Simpson et al. 2012). European Environment Agency (EEA) has estimated concentration levels of $PM_{2.5}$ at 10-km resolution (Horálek et al. 2018) using observations measured at background stations, supplemented with concentrations estimated at PM_{10} station locations and interpolated with linear regression model followed by residual kriging (Horálek et al. 2007; Denby et al. 2011a, b). In national, local, and urban scale modelling exercises resolutions, less than 5 km are often used (Thunis et al. 2016; de Hoogh et al. 2016).

Karvosenoja et al. (2011) studied population-weighted concentrations (PWC) of primary fine particles ($PPM_{2.5}$) from national traffic and wood combustion sources. Concentrations of $PPM_{2.5}$ were estimated using source-receptor matrices (SRMs) based on two different dispersion models and horizontal grid resolutions: urban dispersion modelling system developed at Finnish Meteorological Institute (UDM-FMI) and system for integrated modelling of atmospheric composition (SILAM) with the resolutions of 1 and 10 km, respectively. Resulting PWCs calculated with the finer resolution were 14-fold higher for traffic sources and 1.6-, 6.6-, and 10-fold

higher for wood combustion sources (recreational, residential supplementary, and primary wood heating, respectively). They proposed that the observed large differences in PWCs may have been attributable to the different model resolutions. Other possible causes for the differences included the treatment of vertical mixing of the emissions, spatial resolution of meteorological inputs, and mathematical treatment of advection and atmospheric dispersion. Tainio et al. (2009b) elaborated the same question partly further by applying the same model (SILAM 3.8.1) at 5- and 30-km resolution, but still using different emission data sources and meteorology. They observed 1.3 times higher intake fraction (iF) of primary PM_{2.5} from Finnish emission sources at the finer resolution.

Punger and West (2013) came up with an advanced yet simple approach to avoid the possible effects from different input data or models. They assessed the effect of resolution to population-weighted PM_{2.5} concentrations in the USA by using modelled concentrations of Community Multiscale Air Quality model (CMAQ version 4.7.1) at a 12-km resolution for eastern and western domains of the USA and 36-km resolution for the whole USA. Coarser grid resolutions (from 24 up to 408 km) were created in 12 km increments by simple averaging concentrations within the larger cell. Population exposure increased with modelled concentrations from 12 to 36-km resolution (10.6 to 11.1 $\mu\text{g}/\text{m}^3$). Population exposures, maximum concentrations, and standard deviations calculated with averaged resolutions were decreasing when going to coarser resolutions. At 408-km resolution, population exposure was 27% lower than 12-km output. In particular, the maximum concentration decreased by 71%. The largest difference between fine and coarse resolution estimates was found to be near highly populated areas. Mortality attributable to PM_{2.5} got smaller as resolution got coarser.

Fenech et al. (2018) used concentrations modelled with HadGEM3–UKCA chemistry–climate model at ca.140-km and ca.50-km resolutions to study health impacts of PM_{2.5} in Europe and found that total mortality estimates are sensitive to a model resolution by up to $\pm 5\%$ across Europe. Li et al. (2016) used both air quality modelled (GEOS-Chem) and re-gridded concentrations at various resolutions ($0.5 \times 0.66^\circ$, $1 \times 1.25^\circ$, $2 \times 2.5^\circ$, and $4 \times 5^\circ$) to estimate health impacts over the USA. Their findings suggested that coarse resolutions may result in underestimation of PM_{2.5} attributable mortality. In contrast to other studies, Thompson et al. (2014) evaluated health impacts using 4-, 12-, and 36-km resolutions and came to a conclusion that mortality attributable to PM_{2.5} exposure is not sensitive to resolution when uncertainties are considered. A possible reason for this may be that the range of resolutions was relatively small compared with other studies (Fenech et al. 2018).

The overall aim of this work is to study the impact of spatial averaging on the annual estimates of population exposures and the associated health impacts. The specific aims are (i)

to study the sensitivity of the model resolution on the exposure and attributable mortality estimates for PM_{2.5}; (ii) to inter-compare this sensitivity in urban and rural areas; (iii) quantify the effects of resolution on bias and variance of exposures and impacts; and (iv) discuss the reasons for the differences of such sensitivities for the selected models and in terms of the national emission source categories.

Material and methods

We apply the method used by Punger and West (2013) on two modelled air quality datasets for Finland in 2015. We study the sensitivities of predicted population-weighted PM_{2.5} concentrations, originated (i) from the national Finnish sources and dispersion and the long-range transport modelled with SILAM, and (ii) from local Finnish sources modelled with FRES. The chemical and physical transformation of particulate matter and gaseous pollutants are included in the computations by the SILAM model, but these are not allowed for by the FRES model. We also investigate the influences of the spatial resolution on the associated predicted health impacts.

We have used predicted fine-resolution concentration datasets and spatial population distributions as input datasets in this analysis. Based on these fine-resolution datasets, we have produced aggregated datasets at coarser resolutions (1, 5, 10, 30, and 50 km), simply by spatially averaging the modelled concentrations. The results of this study therefore include the impacts of the spatial averaging of the dispersion simulations with 1-km grid cell size computed with a combination of high-resolution emission fields (250 m) and coarse-resolution of meteorological data (15 km). Therefore, the results present the lower limits of the influence of model resolution. For actual model computations that would also use finer scale meteorological data, the influence of the coarser resolution on the population-weighted concentrations and the associated health impacts (in comparison with a finer resolution) would most likely be relatively larger.

National and regional particle emissions and concentrations

The high-resolution modelling relied on the national PM_{2.5} emission data, calculated at the Finnish Environment Institute (SYKE) with the FRES model (Karvosenoja 2008), at 250-m spatial resolution for area sources and an exhaustive list ($n = 581$) of point sources in Finland. The total annual primary PM_{2.5} emissions in 2015 in Finland were 22 Gg (point sources 3.4 Gg; area sources 18.7 Gg) (Fig. 1).

Two separate modelling systems were used to estimate the PM_{2.5} concentrations and the impacts of the Finnish emission sources. These were (i) the chemical transport model SILAM, which was used to estimate the PM_{2.5} concentrations

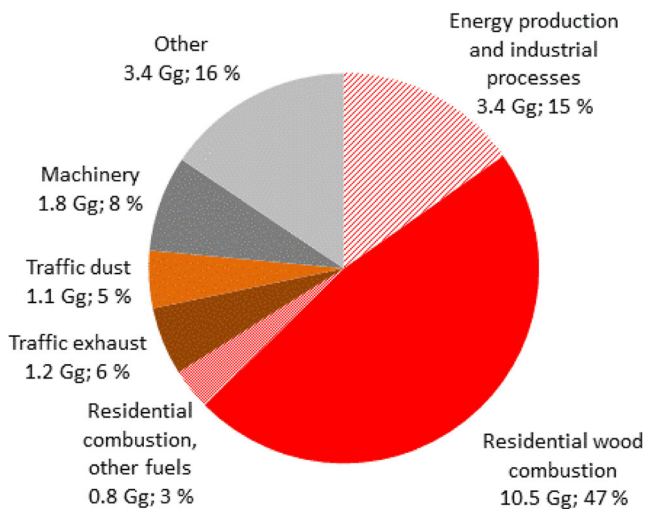


Fig. 1 Total annual primary $PM_{2.5}$ emissions (22 Gg) by sources in Finland in 2015 calculated with FRES model at 250-m resolution

originated both from the local and the regional sources and (ii) the source-receptor matrices (SRMs) included in the FRES model to estimate the concentrations caused by local primary $PM_{2.5}$ sources. The computations using the SILAM model include also the secondary particulate matter, whereas the FRES computations include only the local primary particulate matter emissions up to 10 (traffic) and 20 km (residential combustion) distances.

The SILAM v5.5 dispersion model developed at the Finnish Meteorological Institute (FMI) (Sofiev et al. 2015) was used to estimate the $PM_{2.5}$ concentrations, including also the LRT contributions. It is currently exploited on a daily basis in the national operational services, providing the air quality forecasts in global, European, and Fennoscandian domains. The set-up used for the SILAM model computations in this study contains four computational domains. The largest domain is global. The second largest domain is European, including the whole Europe, parts of the Northern Africa, and the western parts of Asia. The third domain includes Northern Europe, and the fourth domain includes the geographical area of Finland. Large-scale computations over the globe and Europe (1.44 degree and 0.5 degree, respectively) were required to generate physically realistic boundary conditions for the nested model runs for the Finnish domain. For the computations in the highest-resolution domain, we selected the internal model time step to be 1.5 min and 1 h for the model output. The spatial resolutions of the model output were 0.02° in longitudinal and 0.01° in latitudinal dimensions (these correspond to distances of the order of 1.1 km).

In vertical direction, the model considered 11 layers of different thickness from 20 m near the ground up to 2000 m outside of planetary boundary layer (Sofiev 2002; Sofiev et al. 2010). The chemical transformations of atmospheric

constituents were taken into account, and wet and dry depositions from the atmosphere to the underlying surfaces were calculated on every time step (Kouznetsov and Sofiev 2012; Sofiev et al. 2011). The meteorological fields were extracted from the European Centre of Medium-Range Weather Forecast (ECMWF) integrated forecast system (IFS). These data had the spatial resolution of about 15 km, with an update frequency of 3 h.

To describe the emissions outside Finland, the Netherlands Organisation for Applied Scientific Research, Copernicus Atmospheric Services (TNO CAMS) inventory was used (Kuenen et al. 2014). The gaseous biomass burning emissions originating from the European vegetation fires were included with the use of the Global Fire Assimilation System (GFAS) (Kaiser et al. 2012); this data contained the modified Copernicus Atmosphere Monitoring Service Information for 2015. The fire-induced particulate matter emissions were taken from the FMI IS4FIRES (Integrated Monitoring and Modelling System for wildland fires) database (Soares et al. 2015). The Ship Traffic Emission Assessment Model (STEAM) (Jalkanen et al. 2014) was used to supply the time-resolved ship emission fields on resolutions of 1 km and 1 h. This system is based on tracking of every major vessel in the Baltic Sea and the evaluation of the emissions of the main harbours and shipping on the rivers in the area, using the automatic identification system (AIS) reports.

The primary fine particulate matter ($PPM_{2.5}$) concentrations originating from Finnish sources were estimated with the FRES model, using SRMs that were based on computations using a Gaussian dispersion model UDM-FMI. For computing the SRM's, meteorological data for ten different locations in Finland, for a period of 5 to 6 years (2000–2005) were used. The emissions and dispersion were taken into account on a resolution of $250\text{ m} \times 250\text{ m}$. Separate SRMs were created for emission sources with release heights of 2 m, dispersion extending to $20\text{ km} \times 20\text{ km}$ area from each emission grid cell (vehicular traffic exhaust and dust and machinery), and 7.5 m release height extending to $40\text{ km} \times 40\text{ km}$ area (residential combustion and other area sources, e.g., agriculture, peat production, small heating plants). The source-receptor matrices were evaluated separately on a monthly level, for ten spatial domains which correspond to the abovementioned locations in Finland. The computation of the previously used coarser SRMs at 1-km resolution has been presented in Karvosenoja et al. (2011).

Population data and exposures

Population grid data at 1-km resolution presented in ETRS-TM35FIN coordinate reference system were obtained from Statistics Finland for December 31, 2015 (Statistics Finland 2017). The number of total population is available for all inhabited cells (100,338). Population-

weighted concentrations were calculated for (i) whole of Finland and divided into (ii) urban and (iii) rural areas, using 200 inhabitants per square kilometre as a threshold value between urban and rural areas.

Population count at 1-km resolution was used to calculate PWC of PM_{2.5} and local PPM_{2.5} to all areas at 1- to 50-km resolution. Population data at 1-km resolution was also used to calculate PWC of primary PM_{2.5} for five emission sectors divided to urban and rural areas at resolutions ranging from 250 to 50 km. In addition, Building and Dwelling Register 2014 (BDR) population data was used to calculate PWC of overall local and source-specific PPM_{2.5} to whole of Finland at 250-m resolution to get more accurate estimate of exposure.

PWCs in Finland in 2015 for PM_{2.5} were estimated with Eq. (1).

$$PWC = \frac{\sum_{i=1}^N C_{m,i} P_i}{\sum_{i=1}^N P_i} \quad (1)$$

where N is the number of population in each grid cell, $C_{m,i}$ is the modelled concentration in i^{th} cell and P_i is the population in i^{th} cell.

Averaging of modelled concentrations was done with the R software (version 3.3.3) and RStudio (version 1.0.143). Combining the concentration data to the population data at 1-km resolution was done by using QGIS software (2.14.13-Essen) and RStudio.

Comparison of health impacts

Deaths attributable to PM_{2.5} exposure in the whole of Finland were evaluated using PWCs from SILAM and FRES models. For both models, the PWCs were evaluated on the following resolutions: 1 km, 5 km, 10 km, 30 km, and 50 km. For the FRES results, 250-m resolution was used as well. Attributable deaths were estimated using log-linear concentration-response function (relative risk (RR): 1.062) from Heroux et al. (2015). In addition, we used supra-linear integrated exposure-response functions (IER) for ischemic heart disease, stroke, chronic obstructive pulmonary disease, and acute lower respiratory infections (children) (Burnett et al. 2014) for SILAM estimates. Due to the non-linearities in the IER functions, we took into account the exposure distribution by assuming a normal distribution. Deaths calculated with IER functions were summed up and the total attributable deaths were presented.

Deaths attributable to PM_{2.5} are calculated using attributable incidence (AI) approach shown in Eq. (2).

$$AI = PAF \times I = \frac{f \times (RR_E - 1)}{f \times (RR_E - 1) + 1} \times I \quad (2)$$

where AI is deaths attributable to PM_{2.5} exposure, PAF is the population attributable fraction, I is the background incidence rate (in this case, mortality), and f is the fraction of the target population exposed to PM_{2.5} (100%), RR_E is the relative risk of the population at the prevailing exposure level, calculated as $RR_E = \exp(E \times \ln(RR_1))$ in which RR_1 is the relative risk estimate per unit of exposure and E is the mean population exposure.

Results

Sensitivities of PWCs of PM_{2.5} and primary PM_{2.5} and attributable mortality to resolution change were studied. Concentrations modelled with SILAM at 0.02° longitudinal × 0.01° latitudinal resolution and FRES with 250 m resolution were averaged to coarser resolutions (1–50 km).

Population-weighted concentrations

Annual population-weighted concentration (PWC) of PM_{2.5} calculated with the SILAM model was 5.1 μg/m³ at 1-km resolution (Table 1). The decrease in population-weighted concentrations between the 1-km and averaged 50-km resolution was 12%. The decrease of maximum concentration in populated grid cells was 57% between finest and coarsest resolution.

Population-weighted primary fine particulate concentration originated from local emission sources, calculated with the FRES model concentrations at 250-m resolution was 1.6 μg/m³. Difference to the corresponding results computed on 1-km resolution was modest, but decrease of estimated concentration was substantially larger for the results computed on coarser resolutions. Exposure estimate calculated with 50-km resolution was 70% lower than estimation done with 250-m resolution. Maximum concentration of PPM_{2.5} in populated grid cells decreased with coarser resolution and was about 80% lower at 50-km resolution compared with 1 km.

Residential combustion had the highest contribution to the overall concentration of primary PM_{2.5} at all resolutions. With the exception of PPM_{2.5} concentrations originating from machinery and other traffic sources (ca. 15% decrease), there was no great difference in exposures between 250-m and 1-km resolutions. Population-weighted concentration originated from traffic dust was least affected to resolution change between 1- and 5-km resolution and PWC of residential combustion at resolutions coarser than 5 km. Population-weighted primary PM_{2.5} concentration of residential combustion calculated at 50-km resolution was about 40% of those estimated with 250-m resolution. PWCs originated from traffic sources at 50-km resolution were only ca. 15–20% of those calculated at original 250-m resolution. Decrease of maximum concentrations in populated grid squares was also greater from traffic

Table 1 Annual population-weighted concentrations (PWC) in Finland in 2015 at selected spatial resolutions from SILAM including long-range transport (first three rows) and FRES accounting only for local primary PM_{2.5} by five emission categories

	0.25 km μg/m ³	1 km μg/m ³ (%)	5 km μg/m ³ (%)	10 km μg/m ³ (%)	30 km μg/m ³ (%)	50 km μg/m ³ (%)
PWC, PM _{2.5}		5.1	4.9 (−2)	4.8 (−5)	4.5 (−11)	4.4 (−12)
Max		13.9	8.5 (−39)	7.0 (−50)	6.0 (−57)	6.0 (−57)
sd		1.2	1.2 (−1)	1.2 (−5)	1.0 (−19)	1.0 (−22)
PWC, local PPM _{2.5}	1.62	1.55 (−5)	1.22 (−25)	0.99 (−39)	0.65 (−60)	0.46 (−72)
Max		4.57	3.22 (−29)	2.44 (−47)	1.26 (−72)	0.99 (−78)
sd		0.89	0.74 (−17)	0.59 (−33)	0.38 (−57)	0.28 (−68)
PWC, residential combustion	0.73	0.70 (−4)	0.57 (−21)	0.48 (−33)	0.37 (−49)	0.28 (−61)
Max		2.12	1.48 (−30)	1.25 (−41)	0.75 (−64)	0.58 (−73)
sd		0.40	0.33 (−19)	0.27 (−32)	0.17 (−57)	0.17 (−56)
PWC, traffic dust	0.19	0.19 (0)	0.15 (−20)	0.12 (−37)	0.06 (−66)	0.04 (−81)
Max		1.17	0.52 (−55)	0.36 (−70)	0.18 (−85)	0.11 (−91)
sd		0.16	0.13 (−20)	0.1 (−36)	0.06 (−63)	0.03 (−81)
PWC, traffic exhaust	0.27	0.27 (−2)	0.21 (−25)	0.16 (−43)	0.08 (−71)	0.05 (−83)
Max		1.46	0.75 (−48)	0.46 (−68)	0.22 (−85)	0.13 (−91)
sd		0.22	0.18 (−21)	0.14 (−39)	0.07 (−67)	0.04 (−83)
PWC, machinery	0.24	0.21 (−14)	0.15 (−38)	0.11 (−52)	0.06 (−73)	0.04 (−83)
Max		1.05	0.49 (−53)	0.31 (−71)	0.16 (−85)	0.09 (−91)
sd		0.16	0.11 (−29)	0.09 (−44)	0.05 (−69)	0.02 (−85)
PWC, other sources	0.19	0.18 (−6)	0.14 (−27)	0.12 (−39)	0.08 (−60)	0.05 (−71)
Max		1.51	1.05 (−30)	0.73 (−52)	0.43 (−71)	0.32 (−79)
sd		0.13	0.1 (−21)	0.09 (−33)	0.06 (−56)	0.04 (−68)

Relative changes (%) are in comparison with finest respective resolution

sources compared with residential combustion and other sources.

When resolution was changed to be coarser, the exposure distribution shifted towards lower concentrations (Fig. 2). Number of people (ca. 1.3 million) exposed to PM_{2.5}

concentrations that were, e.g., over 6.0 μg/m³ calculated at 1-km resolution was considerably higher, when compared with the corresponding results computed using averaged 50-km resolution (ca. 100 k). Averaging the local primary fine particle exposures to coarser resolution had much greater

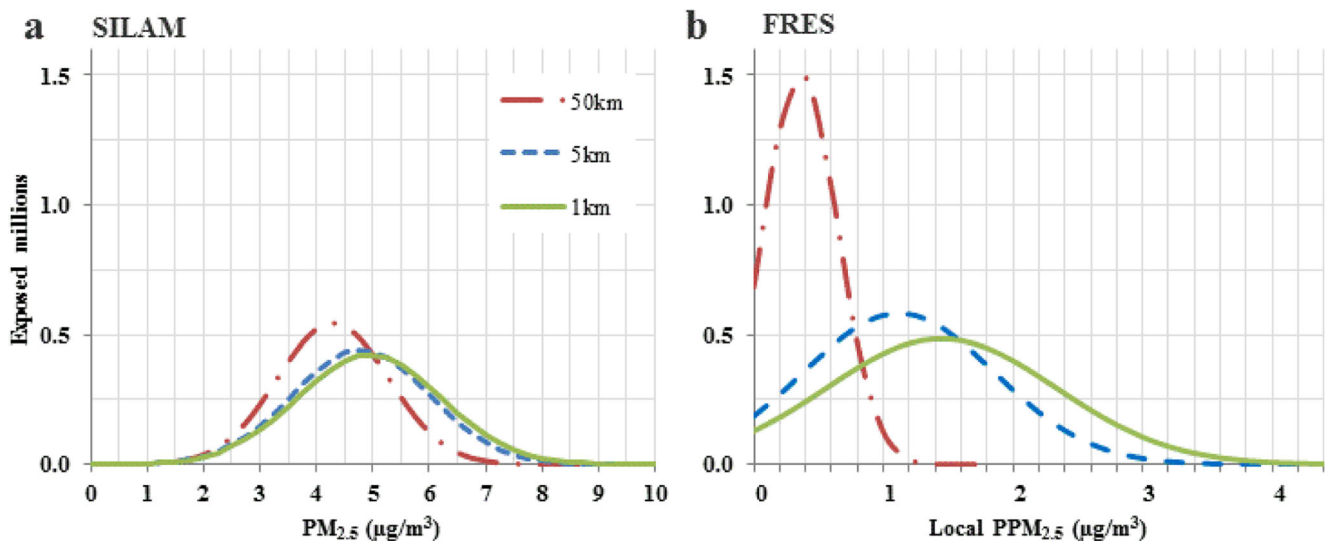


Fig. 2 Exposure distributions of **a** PM_{2.5} and **b** local primary PM_{2.5} in 2015, modelled with SILAM and FRES at 1-km and 250-m resolution, respectively and averaged to coarser resolutions of 1 km, 5 km, and 50 km

influence to exposure distribution compared with the results for particulate matter (PM_{2.5}) exposure distribution. At 50-km resolution, almost whole population was exposed to PPM_{2.5} levels under 1 µg/m³, whereas at the resolution of 1 km, the highest exposures were over 4 µg/m³ and at 5-km resolution over 3 µg/m³.

Population-weighted PM_{2.5} concentration estimated at 1-km resolution in urban areas (≥200 inhabitants/km²) was 1.3 µg/m³ higher than those in rural regions (<200 inhabitants/km²) (Fig. 3a). At averaged 50 km resolution, this difference was 0.6 µg/m³. Exposure calculated with 1-km resolution was 18% higher in urban areas when compared with estimate at 50-km resolution. Three out of four (4.1 million) of Finnish people were living in urban areas, consisting around 4000 km² of the country. In rural areas with 1.3 million inhabitants, there was only 3% decrease in PWCs between 1 and 50 km. Population-weighted concentration of overall PPM_{2.5} at 250-m resolution was about three times higher in urban than in rural areas, but at 50-km resolution, PWC in urban areas was only 30% higher. In rural areas, population-weighted concentration was 36% lower, and in urban areas, 75% lower between 250-m and 50-km resolution.

In urban areas, when comparing the impacts of emissions from various source categories, the residential combustion was least sensitive to resolution change, with 63% decrease in between 250 m and averaged 50-km resolution while decrease in traffic exposures was over 80% (Fig. 4a). In rural areas, other sources were least affected to a resolution change with only 9% decrease in between finest and coarsest resolution (Fig. 4b). In urban areas, this decline was much higher (74%). Residential combustion and machinery exposures at 250-m resolution in rural areas were about one-third and traffic dust and exhaust exposures about 50% lower compared with the coarsest resolution.

Variation of PM_{2.5} and local primary PM_{2.5} concentrations in Helsinki region were studied and compared with population density (Fig. 5). Concentrations of PM_{2.5} ranged from 5 to 8 µg/m³ in the Helsinki region modelled with SILAM at 1-km resolution (Fig. 5a). Concentrations were highest at the vicinity of the ring and major roads (6–8 µg/m³). Inside ring road one (the ring road that is closest to the city centre), exposures were around 7 µg/m³. In rural areas, concentrations were approximately 5–6 µg/m³.

Concentrations of local primary PM_{2.5} ranged approximately from 0.4 to 5.5 µg/m³ in the Helsinki region modelled with FRES at 250-m resolution (Fig. 5b); these computations do not include long-range and regional background concentrations. Concentrations were highest at the ring roads and main roads leading out of the centre area where concentrations were around 3–5 µg/m³. In the northern part of the Helsinki region around major roads and in Kerava, Tuusula and Nurmijärvi (Klaukkala) municipalities PPM_{2.5} concentrations ranged from 2 to 4 µg/m³ and over 50% of total exposure was originated from residential combustion (Fig. S1). In between the ring roads, residential combustion was also significant PPM_{2.5} source. Inside the ring road one traffic exhaust, machinery and other sources were the major sources of PPM_{2.5} whereas residential combustion had only a minor influence. Outside of major roads and urban areas, the concentrations originated from urban sources were below 1 µg/m³.

When compared with population density (Fig. 5c), high concentrations of local primary PM_{2.5} and PM_{2.5} were mostly, but not entirely, in areas where population density was high. In previous analyses, it was found that local PPM_{2.5} population-weighted concentrations were more sensitive to the changes of resolution than the population-weighted concentrations of PM_{2.5} originated from both national and long-range transported sources. In sparsely populated areas, local

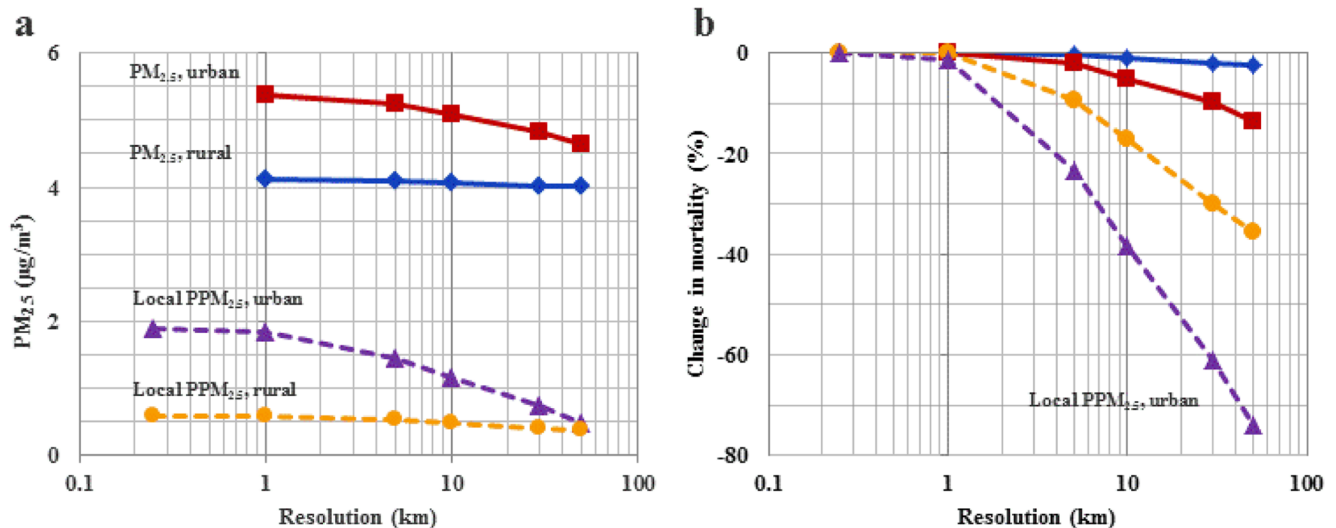


Fig. 3 Population-weighted **a** PM_{2.5} and local primary PM_{2.5} concentrations in urban and rural areas in 2015 modelled with SILAM and FRES and **b** difference in attributable mortality (log-linear relative risk function) as a function of averaged resolution

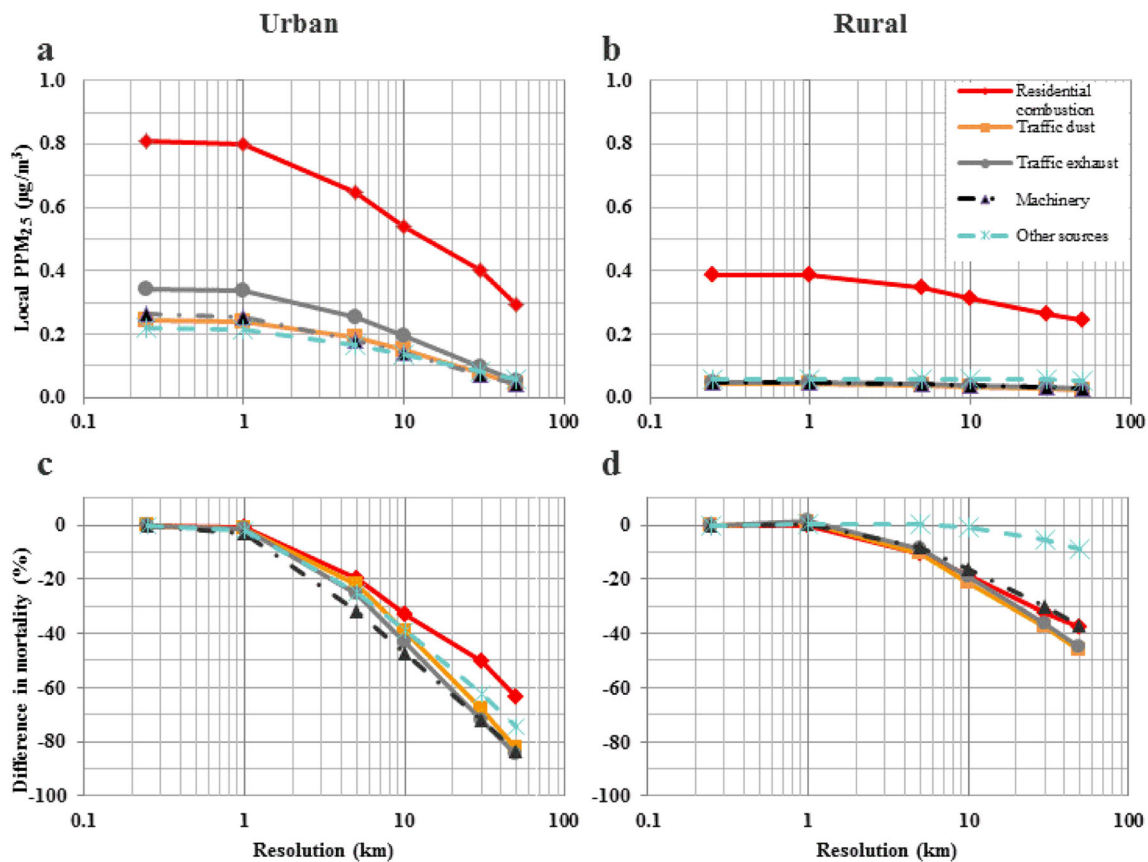


Fig. 4 Population-weighted local primary PM_{2.5} concentrations in 2015 and attributable mortality (log-linear relative risk function) from five emission sectors in urban (**a, c**) and rural areas (**b, d**) as a function of averaged resolution

PPM_{2.5} concentrations were mostly around or below 1 µg/m³, while in densely populated areas, concentrations were 2–14 times higher. Concentration variation of PM_{2.5} between rural and urban areas was much more moderate and concentrations were around 20 to 50% higher in areas with high population density.

Comparison of health impacts

To characterise the impact on health, we calculated mortality estimates. Attributable deaths were estimated using two previously used approaches, log-linear parametric function and numerically simulated integrated exposure-response function (IER). At 1 km exposures, the estimated deaths were 1520 and 105 in 2015, using log-linear model, and IER, respectively (Table 2). The difference is over 10-fold, caused by (i) theoretical threshold (5.8–8.8 µg/m³) applied in IER, (ii) inclusion of all non-accidental causes of deaths in the log-linear model versus five specific causes in IER, and (iii) differences in the shapes of the concentrations-response functions.

In particular, the IER estimates are substantially more sensitive to the exposure resolution. Log-linear concentration-response deaths decreased only about 14% when lowering resolution from 1 to 50 km while the corresponding IER estimate

decreased by almost 90% (Table 2). IER functions are more sensitive to resolution changes due to theoretical threshold applied. The theoretical threshold is close to the Finnish exposure levels; and therefore, even small changes in exposure can clearly affect the health impacts. Averaging of the resolution lowers the exposures in the high exposure cells, which can lead those exposures to drop under the theoretical threshold.

Deaths attributable to PPM_{2.5} exposure from Finnish sources were associated with about 500 premature deaths (Table 3). Decrease between estimates calculated with finest and coarsest resolution was 70%. Increasing the grid size had the highest impact on mortality estimates attributable to exposures from traffic sources with 80% decrease from 250-m to averaged 50-km resolution and lowest impact from residential combustion (60% decrease).

Around 80% of PM_{2.5}-attributable mortality cases occurred in urban areas, and mortality estimate decrease was about 10% between 1-km estimation ($n = 1183$) and averaged 50-km resolution (Fig. 3b). In rural areas, mortality estimates attributable to PM_{2.5} exposure were less sensitive to resolution change. Decrease was only 2% between 1 km ($n = 285$) and averaged 50-km resolution. Mortality attributable to local PPM_{2.5} was much more sensitive to resolution change with

Table 3 Deaths attributable to local primary PM_{2.5} with various resolutions in Finland in 2015 calculated with log-linear relative risk function and decrease (%) in mortality estimates

Resolution (km)	PPM _{2.5} <i>n</i> (%)	Residential combustion <i>n</i> (%)	Traffic dust <i>n</i> (%)	Traffic exhaust <i>n</i> (%)	Machinery <i>n</i> (%)	Other <i>n</i> (%)
0.25	475	214	57	81	70	56
1	453 (−5)	206 (−4)	57 (0)	79 (−2)	60 (−14)	52 (−6)
5	357 (−25)	169 (−21)	45 (−20)	60 (−25)	43 (−38)	41 (−27)
10	291 (−39)	142 (−33)	36 (−37)	46 (−43)	34 (−52)	34 (−39)
30	192 (−60)	108 (−49)	19 (−66)	24 (−71)	19 (−73)	22 (−60)
50	135 (−72)	83 (−61)	11 (−81)	14 (−83)	12 (−83)	16 (−71)

attributable to local primary PM_{2.5} decrease much more drastically than PWCs and mortality due to PM_{2.5} that includes also secondary species. In Finland, a major fraction of PM_{2.5} concentration is originated from long-range transport (Kukkonen et al. 2018; Aarnio et al. 2016; Joana Soares et al. 2014) and is the biggest reason to the modest decline of population-weighted PM_{2.5} concentration when grid size is increased.

Due to the higher variation in concentrations of PM_{2.5} in urban areas (≥ 200 inhabitants/km²), averaging grid cell to coarser resolution dilutes peak concentrations and finer resolution is needed to prevent underestimation of exposures in these areas. Estimating exposures and health impacts of PM_{2.5} at finest 1-km resolution in grid cells less than 200 inhabitants/km² have almost no effect when compared with averaged 50-km resolution. Therefore, coarser resolution seems adequate when estimating exposures and health impacts of PM_{2.5} in rural areas as there is not that great variation on concentrations.

Tainio et al. (2009a) pointed out that traffic emissions are mostly originated from city streets and major roads connecting largest towns and are closely correlated with population densities. In this study, concentrations of local primary PM_{2.5} in Helsinki region from traffic sources were also high in vicinity of major roads and in areas with dense population. Residential combustion concentrations were the major contributor to local PPM_{2.5} concentration in sub-urban areas and in smaller towns, but in Helsinki city centre area, residential combustion had the smallest impact to PPM_{2.5} concentration. Primary residential wood heating is common mainly in rural areas and in small towns and supplementary wood heating in sub-urban areas in larger cities (Karvosenoja et al. 2011).

Population-weighted local primary PM_{2.5} concentrations and attributable mortality originated from traffic sources were found to be the most sensitive and residential wood combustion least sensitive to resolution change. Reason to this difference may be in the emission release heights and how emissions are released and dispersed in the Gaussian models. Traffic emissions are released near the ground level thus causing sharp concentration

gradients near the emission source, whereas residential combustion emissions are released from roof level and are dispersed to a clearly larger area than traffic emissions. Furthermore, much of the residential wood combustion emissions take place in non-urban areas, where gradients of population densities are quite modest and therefore PWCs are not so sensitive to changing grid resolution.

Coarser resolutions in this study were made by simple averaging modelled fine-resolution concentrations, meaning that there was no change in model set-ups or input data between resolution changes. The use of actual modelled concentration data could lead to different results. Li et al. (2016) compared modelled (GEOS-Chem) and averaged PM_{2.5} concentrations at the same 2° × 2.5° resolution. Mortality estimate calculated with averaged PM_{2.5} concentrations was only 2% higher than estimate calculated with model output. However, for different PM_{2.5} species, estimates varied. For dust, averaged output produced mortality estimate 27% less and for sulphate, 20% greater than estimates calculated with model output, but for black carbon, ammonium, nitrate, and organic carbon, results were similar.

Overall uncertainties in modelled exposure estimates contain, besides the resolution component assessed in detail in this work, also other model and parametric uncertainties (Hänninen et al. 2005). These are often challenging to be quantified due to lack of representative measurements and good understanding of the measurement errors. Therefore, e.g., the fractional biases are calculated in relationship to the mean of observed and predicted values. Noting that epidemiological estimates are based on mainly monitoring data or estimates calibrated against monitoring, it can be reasonably assumed that the epidemiological confidence intervals cover errors related to observations and their representativeness. Thus, it can be argued that exposure errors in air pollution health impact assessments should be evaluated against monitoring data. We aim to supplement the current work on a resolution with wider comparison of monitored and predicted levels.

Due to theoretical thresholds used in IER functions, the resolution of the exposure assessments becomes more

important. This is especially the case in areas where the population-weighted concentrations are close to the theoretical threshold. The number of deaths is reduced by 90% from 1-km resolution to 50-km resolution. This is due to the shift of the exposure distribution towards lower concentrations with coarser resolution. With the coarser resolution, the concentrations are closer and under the threshold resulting to significantly lower number attributable deaths due to PM_{2.5} exposure.

Epidemiological studies often use community level air quality data averaged across available monitoring stations (Kioumourtzoglou et al. 2016), or at best, residential address-based concentrations from various types of modeling (e.g., land use regression: (Beelen et al. 2014)). Similarly, health risk assessments are to large extent based on population density data, also based on residential addresses or even coarser community level geospatial location. The actual health effects associated with air pollution exposures are naturally affected by population mobility, e.g., commuting to work, exposure at work and hobbies, shopping, and other everyday life activities. For the active age populations such exposure modification by mobility can be substantial, even though even the working age population spends roughly 50% of their time at the home address, e.g., 13.75 h during weekdays in Helsinki (Schweizer et al. 2007).

However, acknowledging the dominant role of mortality as endpoint in health impact assessments, it is especially interesting to evaluate the relevance of exposure assessment for the population group that is at highest mortality risk. This is the elderly and sedentary population; the frailer people are more likely to spend increased time at the direct vicinity of their home. This is at least the case before potentially becoming hospitalised or institutionalised; which is another interesting aspect in exposure analysis for premature mortality assessments and should be addressed in more detail. Therefore, the traditional practices for using residential address-based exposures can be defended.

Conclusions

Population exposure and health impact estimates have been suggested to be sensitive to the resolution at which they are evaluated. We quantified this sensitivity in Finland by averaging populations and concentrations at various resolutions, and calculated the corresponding numbers of deaths using two common mortality models.

The sensitivity was modest for the overall national exposure to PM_{2.5} originated from both national sources and long-range transport, with only 12% reduction in exposures from modelled 1 km to averaged 50-km resolution. Most of PM_{2.5} concentrations in Finland originate from long-range transport. This is a major reason why the population-weighted PM_{2.5}

concentrations are relatively less sensitive to resolution change, compared with the corresponding population-weighted concentrations originated solely from local sources. The long-range transport, combined with secondary aerosol formation, results in more uniformly distributed concentrations. Population density, or urbanity, affects clearly the sensitivity of the population-weighted concentrations on the resolution. For PM_{2.5} from national and long-range transported sources, there was a higher sensitivity in urban areas with 15% reduction. In rural areas, sensitivity of exposures to resolution change was almost negligible and therefore finer resolution is needed especially in urban areas to avoid underestimation of exposures and health impacts.

Considering only the local sources of primary PM_{2.5}, the sensitivity to a change in spatial averaging was substantially larger between the finest and the coarsest resolution. Exposure and mortality reduction from the results at a resolution of 250 m to those at 50 km was 70% in the whole country, 74% in urban areas and considerably lower in rural areas with a reduction of 36%. At 1 km, resolution decrease in results was only 5%, but at 5 km, resolution results were already 25% smaller. The sensitivity of the population-weighted concentrations on the resolution varied also by emission sector. It was highest for vehicular traffic dust and traffic exhausts, with over 80% reduction and lowest for residential combustion sector, with about 60% reduction in estimates in the whole country.

We also evaluated the impacts of the spatial averaging on the mortality associated with air pollution. We conclude that exposure assessment and especially the assessment of the variability of exposure in the target population is critically important, when applying non-linear models, such as the integrated exposure-response (IER) models for health impact assessment. These models contain numerical discontinuities at exposure levels that are relevant for Finland and other regions of relatively clean air.

This study applied an averaging of the results provided by the chemical transport and atmospheric dispersion models. This procedure implies that the meteorological, emission, and other input data used by the dispersion models were the same for the aggregated datasets. However, this is commonly not the case in the actual dispersion computations when resolution is changed. For actual dispersion model computations that would adopt the finer scale input data, the influence of using a coarser resolution would most likely be relatively larger, compared with the values that were obtained in the current study.

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- Nomenclature: PM_{2.5} fine particle concentration, including local and regional components from all sources, calculated with system for integrated modelling of atmospheric composition (SILAM) model; local primary fine particle (PPM_{2.5}) concentration from national emissions, calculated with Finnish Regional Emission Scenario (FRES) model, using source-receptor matrices (SRMs) based on computations of urban scale dispersion model (UDM-FMI); source-specific fractional PPM_{2.5} concentration from specific local Finnish sources (traffic dust and exhaust; residential wood combustion; machinery; others);
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