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Trends in population exposure to particulate matter in urban areas of Greece during the last decade

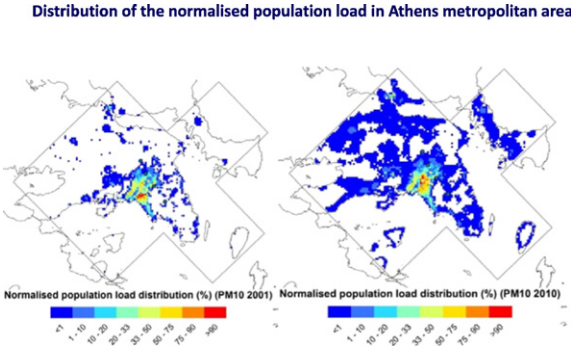
Aleksandropoulou V., Lazaridis M. *

Department of Environmental Engineering, Technical University of Crete, Chania, Polytechneioupolis, 73100, Greece

HIGHLIGHTS

- A methodology for assessing population exposure to particulate matter (PM) has been applied.
- Population exposure trends in urban areas have been evaluated.
- Spatial distribution trends of population exposure have been derived.
- Population exposure is a complex function of PM ambient concentrations and spatiotemporal emission characteristics.
- Population exposed to PM_{10} and $PM_{2.5}$ concentrations above the annual air quality standards, has dropped significantly in the period 2001 – 2010.

GRAPHICAL ABSTRACT



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ABSTRACT

Assessment of population exposure is very important for the evaluation of the adverse health effects of particulate matter (PM) ambient levels. In this work population exposure to PM_{10} and $PM_{2.5}$ has been evaluated in outdoor environments in the Athens (AMA) and Thessaloniki (TMA) metropolitan areas during the period 2001–2010. The methodology used is based on combining spatiotemporally allocated PM_{10} and $PM_{2.5}$ concentration fields with the geographical distribution of population. The results showed that the number of people living in the AMA exposed to PM_{10} and $PM_{2.5}$ concentrations above the annual air quality standards (AQS), has dropped 18% since 2001 and 98% since 2008, respectively. Likewise, in 2010 8% less, compared to 2001, of the AMA population lived in areas where the daily AQS for PM_{10} was exceeded >35 times a year. The results as regards TMA indicated a decrease in the number of people exposed to PM_{10} concentrations over the annual AQS value (78% decrease). However, the number of people living in areas with PM_{10} concentrations over the daily AQS for >35 times in a year doubled since 2001. Finally, the spatial distribution of the normalised population load which reflects populated areas with concentrations above the daily AQS was evaluated. The hot spots for both AMA and TMA areas correspond to urban areas and areas with significant primary PM_{10} emissions.

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1. Introduction

Air pollution by particulate matter (PM) in the atmosphere of urban areas results from emissions directly by sources (primary particles) such as fuel combustion (e.g. transportation, domestic and commercial

* Corresponding author.
E-mail address: lazaridi@mred.tuc.gr (M. Lazaridis).

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heating), resuspension of settled particles, pollen and sea salt, or from particles formed in the atmosphere (secondary particles) by transformation of gaseous particulate precursors (NOx, SOx, NH_3, VOCs) emitted from a variety of sources (Hinds, 1999). The sources of air pollution can be local, placed in the vicinity of the urban area, or particles that have been regionally or long-range transported to the urban atmosphere.

Ambient PM exerts a significant impact on climate biogeochemical cycles, atmospheric chemistry and adversely affects public health (Pope et al., 2002; Almeida et al., 2007). Inhaled particles may cause adverse health effects such as pulmonary function decrements, respiratory symptoms, heart attacks, arrhythmias, neurological dysfunction, reproductive system dysfunction and cancer (US EPA, 2004). In particular, for the European Union, the average life expectancy has been estimated by the World Health Organisation (WHO) to be 8.6 months lower due to exposure to $PM_{2.5}$ resulting from human activities (EEA, 2012).

There is no threshold value for PM exposure below which no adverse health effects are expected. Possible health effects are estimated based on dose-response equations. In order to protect human health, the governments establish air quality standards (AQS) and target values for annual and daily mean concentrations. The European Union has set limit values for PM_{10} annual (40 μg/m^3) and daily (50 μg/m^3; must not be exceeded >35 times in a calendar year) concentration averages and an annual limit value (25 μg/m^3) for $PM_{2.5}$ concentrations has come into force since 2015 with the Directive 2008/50/EC.

Furthermore, WHO has set air quality guideline (AQG) values, more stringent than current EU limit values, for the protection of human health. The AQGs set for PM_{10} are 20 μg/m^3 for annual concentrations and 50 μg/m^3 for a 24-h period (not be exceeded >3 times in a calendar year), whereas for $PM_{2.5}$ are 10 μg/m^3 and 25 μg/m^3 for annual and daily mean values, respectively (WHO, 2006). Besides the guideline values, WHO has also set interim target values (IT) for annual and 24-h $PM_{2.5}$ and PM_{10} concentrations, in order to help countries gauge progress in processes adopted to reduce population exposure to PM. These target values are based on the results reported in studies of long-term and short-term mortality and health effects associated with exposure to $PM_{2.5}$ and PM_{10}. The recommended IT-1, IT-2 and IT-3 values for annual mean concentrations are 70 μg/m^3, 50 μg/m^3 and 30 μg/m^3 for PM_{10} and 35 μg/m^3, 25 μg/m^3 and 15 μg/m^3 for $PM_{2.5}$, respectively, which correspond to IT-1: 15% higher long-term mortality risk relative to the AQG level, IT2: reduced premature mortality risk 6% compared to IT-1, and IT-3: reduced premature mortality risk 6% compared to IT-2. Likewise, the recommended IT-1, IT-2 and IT-3 values for 24-h concentrations are 150 μg/m^3, 100 μg/m^3 and 75 μg/m^3 for PM_{10} and 75 μg/m^3, 50 μg/m^3 and 37.5 μg/m^3 for $PM_{2.5}$, respectively, which correspond to 5%, 2.5% and 1.2% increase of short-term mortality risk over the AQG level, respectively.

In the European Union, 18–41% of the urban population was exposed to PM_{10} concentrations in excess of the EU daily AQS in the period 2001–2010 (EEA, 2012). Specifically, in Greece the Average Exposure Indicator (defined in Directive 2008/50/EC) for 2010 was 20 μg/m^3 (De Leeuw, 2002). In the AMA and TMA, PM_{10} levels have dropped significantly during the decade 2001–2010, however there are still areas where the EU AQS for the protection of human health are frequently exceeded (Aleksandropoulou et al., 2012a). In addition, $PM_{2.5}$ concentrations in the AMA exceeded the target value of 25 μg/m^3 in 2010.

A number of studies have focused on the population exposure (Georgopoulos et al., 2005; Bravo et al., 2012) and health effects (Lee et al., 2015; Geels et al., 2015) arising from ambient particulate matter concentrations. Georgopoulos et al. (2005) determined the population exposure by matching people's activity patterns and using Geographical Information System (GIS) mapping. Van Donkelaar et al. (2015) made use of satellite data for assessing exposure to fine particles. Furthermore, Miranda et al. (2016) applied integrated assessment methodologies for determining the effect of emission reductions to population exposure in urban areas. A dynamic model for air pollution in conjunction with population density data was applied in Rome, Italy, using also mobile phone traffic (Gariazzo et al., 2016). Finally, Soares et al. (2014) presented a population exposure model for urban settings with application to the city of Helsinki.

In this work a robust methodology is used with the objective to evaluate the population exposure to PM_{10} and $PM_{2.5}$ in outdoor environments in Athens and Thessaloniki, during the period 2000–2010.

2. Methodology

The methodology for the assessment of population exposure is based on combining population maps with maps of the PM concentrations. Consequently, the uncertainty of the results mainly relies on the accuracy of the spatiotemporal PM concentration fields which were derived from modelling and monitoring data using data interpolation techniques. The originality of the proposed work is the use of combined population maps with maps of PM concentrations and the scaling using PM emissions. A review of interpolation and assimilation methods for air quality assessment and mapping on European scale is presented by the European Topic Centre on Air Pollution and Climate Change Mitigation (ETC/ACM) (Denby et al., 2005; Denby et al., 2008). Although the data interpolation approach probably cannot capture the spatial variation within the urban area, it is based on common procedures and is appropriate for calculating population exposure estimates (Horalek et al., 2007; Denby et al., 2011). Several interpolation approaches with different supplementary data have been initially used to derive spatiotemporal PM concentrations over the AMA. The variables included in the proposed spatial disaggregation models for particulate matter concentrations were selected based on the evaluation of model performance criteria in terms of the root mean square error (*RMSE*) and the index of agreement (*d*; Willmott, 1981). Also, it must be noted that the exposure calculations in this study are based on the current AQS.

2.1. Data

The exposure concentration was estimated using measured and modelled data. Measured data were available from the Hellenic Ministry for the Environment, Energy and Climate Change (H.M.E.E.C.C., 2011) and the European Air quality database (AirBase), whereas the PM_{10} background levels were retrieved from the EMEP Unified model results database (EMEP/MSC-W). The metropolitan area was divided into rural and urban/suburban land based on the Corine Land Cover (CLC) 2000 database. The geographical distribution of population was derived from the EEA dataset (based on 2001 census and considered unchanged throughout the period). Additionally, spatially (1×1 km^2) and temporally (1 h) distributed emission inventories of particulate matter from anthropogenic and natural sources for the AMA and the TMA for the period 2001–2010 were used to derive weighting factors for the interpolation. The methodology for inventory compilation is given in Aleksandropoulou et al. (2011, 2013a). The emissions of secondary particles were estimated as PM_{10} equivalents using the methodology of de Leeuw (2002). According to the above methodology emissions of each precursor gas can be weighted to account for potential secondary aerosol formation. The weighting factors account for the fraction of emissions of pollutant changing into aerosol and the molecular weight difference. Their values have been derived on European level and are 1 for primary PM, 0.54 for SO_2, 0.88 for NOx, 0.64 for NH_3 and 0.02 for NMVOCs. Emissions of each pollutant are multiplied by the aerosol formation potential and the results are reported in PM_{10} equivalents.

2.2. Spatial mapping of air quality

Multivariate statistical analysis was used for the spatiotemporal allocation of PM_{10} concentrations at rural areas, using as variables the background PM_{10} concentrations, the anthropogenic primary emissions of PM_{10} (in particular zonal aggregates of emissions within an area of

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