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Spatial $PM_{2.5}$, NO_2, O_3 and BC models for Western Europe – Evaluation of spatiotemporal stability

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ABSTRACT

Background: In order to investigate associations between air pollution and adverse health effects consistent fine spatial air pollution surfaces are needed across large areas to provide cohorts with comparable exposures. The aim of this paper is to develop and evaluate fine spatial scale land use regression models for four major health relevant air pollutants ($PM_{2.5}$, NO_2, BC, O_3) across Europe.

Methods: We developed West-European land use regression models (LUR) for 2010 estimating annual mean $PM_{2.5}$, NO_2, BC and O_3 concentrations (including cold and warm season estimates for O_3). The models were based on AirBase routine monitoring data ($PM_{2.5}$, NO_2 and O_3) and ESCAPE monitoring data (BC), and incorporated satellite observations, dispersion model estimates, land use and traffic data. Kriging was performed

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Abbreviations: CTM, chemical transport models; SAT, satellite-derived predictions; FULL, models developed using 100% of the monitoring sites; HOV, hold-out-validation models developed on 80% of the number of sites

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on the residual spatial variation from the LUR models and added to the exposure estimates. One model was developed using all sites (100%). Robustness of the models was evaluated by performing a five-fold hold-out validation and for $PM_{2.5}$ and NO_2 additionally with independent comparison at ESCAPE measurements. To evaluate the stability of each model's spatial structure over time, separate models were developed for different years (NO_2 and O_3: 2000 and 2005; $PM_{2.5}$: 2013).

Results: The $PM_{2.5}$, BC, NO_2, O_3 annual, O_3 warm season and O_3 cold season models explained respectively 72%, 54%, 59%, 65%, 69% and 83% of spatial variation in the measured concentrations. Kriging proved an efficient technique to explain a part of residual spatial variation for the pollutants with a strong regional component explaining respectively 10%, 24% and 16% of the R^2 in the $PM_{2.5}$, O_3 warm and O_3 cold models. Explained variance at fully independent sites vs the internal hold-out validation was slightly lower for $PM_{2.5}$ (65% vs 66%) and lower for NO_2 (49% vs 57%). Predictions from the 2010 model correlated highly with models developed in other years at the overall European scale.

Conclusions: We developed robust $PM_{2.5}$, NO_2, O_3 and BC hybrid LUR models. At the West-European scale models were robust in time, becoming less robust at smaller spatial scales. Models were applied to 100 × 100 m surfaces across Western Europe to allow for exposure assignment for 35 million participants from 18 European cohorts participating in the ELAPSE study.

1. Introduction

Ambient air pollution remains one of the main causes of morbidity and mortality in the world (Cohen et al., 2017). WHO's global assessment of ambient air pollution exposure estimated that one in nine deaths annually are caused by ambient air pollution (WHO, 2016). More recently, there is evidence showing that associations between mortality and morbidity and long-term exposure to outdoor air pollution might have no threshold, and extend to concentrations below current air quality limit values of the US EPA and EU (Beelen et al., 2015). Recent studies conducted in North-America have shown that long-term exposure to $PM_{2.5}$ is associated with mortality also at low exposures (i.e. below the current WHO guideline of $10\,\mu g/m^3$) (Crouse et al., 2015; Di et al., 2017; Pinault et al., 2017). Particularly in North-America and Europe, tougher air quality policies have led to a reduction in emissions and a gradual decline in ambient air pollution concentrations (EEA, 2017). Little, however, is known about the shape of the exposure-response curve at low concentrations, and thus the impact of low level concentrations on large populations remains uncertain.

The ELAPSE (Effects of Low-Level Air Pollution: A Study in Europe) study aims to fill this gap by investigating the relationship between long term air pollution and morbidity and mortality at low $PM_{2.5}$ (Particulate Matter < 2.5 µg), nitrogen dioxide (NO_2), black carbon (BC) and ozone (O_3) exposures. Low levels are defined as air pollutant concentrations below EU and/or US air quality limit values and/or WHO guidelines. ELAPSE includes 11 cohorts with in-depth individual data on lifestyle and 7 large administrative/national cohorts across Europe (http://www.elapseproject.eu/). Cohorts were selected to represent a contrast in air pollution exposures between and within study areas. The 11 detailed individual-level cohorts will be analyzed as a pooled cohort, whereas the administrative cohorts will be analyzed separately. Taken together, the evidence should allow collective consideration and evaluation. This study therefore needs consistent models that can provide valid exposures at two different spatial extents in Western Europe: combining all study regions of the detailed individual-level cohorts for the pooled analysis; and the national extents for the administrative/national cohorts. The previously developed ESCAPE LUR models (Beelen et al., 2013; Eeftens et al., 2012a) do not meet the requirements for the ELAPSE project because they do not cover the full national study areas. Secondly, methodological work by Basagana and Wang has shown that more stable models can be developed based on a larger number of model training sites than the 20 sites that the ESCAPE PM models were based upon (Basagaña et al., 2012; M Wang et al. 2013). Finally, ESCAPE did not evaluate ozone."

Cohorts in the ELAPSE study have different recruitment and follow-up periods going back as early as the 1990's. Epidemiological studies have used the back-extrapolation method to estimate exposures back in time (Beelen et al., 2014; Chen et al., 2017). The method uses a well validated air pollution surface as the base and assumes that the spatial structure of this surface remains stable over time. Monitoring data from routine monitoring sites are then used to re-scale the surface back or forward in time (Cesaroni et al., 2012; Chen et al., 2010). Few studies have been able to document the stability of spatial surfaces, mostly focusing on NO_2 and at the city level (Cesaroni et al., 2012; Eeftens et al., 2011; R Wang et al. 2013) or national scale (Gulliver et al., 2013). We thus evaluated the stability of these surfaces over time by comparing modelled estimates with historic monitoring data and by developing models for other years.

The aims of the paper are to:

1. develop and evaluate performance of fine spatial scale hybrid land use regression models for four major health relevant pollutants $PM_{2.5}$, NO_2, BC, O_3 across Western Europe;
2. investigate the temporal stability of the spatial contrast at the West-European and national scale.

This paper follows our recently published West-European fine scale air pollution exposure models for $PM_{2.5}$ and NO_2 (de Hoogh et al., 2016). Models were based on both 2010 ESCAPE and the European Environment Agency (EEA) AirBase routine monitoring data, and documented the contribution of satellite data and chemical transport models (CTM) to LUR models. An important finding was that models performed well when validated with data from the other measurement network (i.e. ESCAPE model validated with AirBase sites and vice versa). In the current paper we substantially extended this work, firstly by adding BCO_3 which are both health relevant pollutants. We also improved the testing of the robustness of models by evaluating structure and predictions using five-fold hold-out-validation (HOV), following a study on land use regression models for ultrafine particles (van Nunen et al., 2017). We further assessed improving the LUR models using kriging and added new predictor variables with improved granularity, including 1 × 1 km satellite-derived $PM_{2.5}$ to the previously used 10 × 10 km satellite data. Finally we added an assessment of the temporal stability of the models.

2. Materials and methods

2.1. Air pollution monitoring data

$PM_{2.5}$, NO_2 and O_3 daily concentration data for 2010 were derived from the AirBase v8 dataset (EEA, 2015). Only sites with ≥75% completeness of the total hours (NO_2 and O_3) or days ($PM_{2.5}$) were accepted, and an annual average was calculated for $PM_{2.5}$ and NO_2. For O_3, we calculated the maximum running 8-hour mean for each day and then averaged to obtain an annual, warm season (April through September) and cold season (January through March and October through