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Estimation of daily PM_{10} concentrations in Italy (2006–2012) using finely resolved satellite data, land use variables and meteorology

Massimo Stafoggia [a,b,*], Joel Schwartz [c], Chiara Badaloni [a], Tom Bellander [b,d], Ester Alessandrini [a], Giorgio Cattani [e], Francesca de' Donato [a], Alessandra Gaeta [e], Gianluca Leone [e], Alexei Lyapustin [f], Meytar Sorek-Hamer [g,h], Kees de Hoogh [i,j], Qian Di [c], Francesco Forastiere [a], Itai Kloog [h]

[a] Department of Epidemiology, Lazio Regional Health Service/ASL Roma 1, Via C. Colombo 112, 00147 Rome, Italy
[b] Karolinska Institutet, Institute of Environmental Medicine, Stockholm, Sweden
[c] Department of Environmental Health, Harvard T. H. Chan School of Public Health, Cambridge, MA, USA
[d] Stockholm County Council, Centre for Occupational and Environmental Medicine, Stockholm, Sweden
[e] Italian National Institute for Environmental Protection and Research, Rome, Italy
[f] National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC), Greenbelt, MD, USA
[g] Civil and Environmental Engineering, Technion, Haifa, Israel
[h] Department of Geography and Environmental Development, Ben-Gurion University of the Negev, Beer Sheva, Israel
[i] Swiss Tropical and Public Health Institute, Basel, Switzerland
[j] University of Basel, Basel, Switzerland

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ABSTRACT

Health effects of air pollution, especially particulate matter (PM), have been widely investigated. However, most of the studies rely on few monitors located in urban areas for short-term assessments, or land use/dispersion modelling for long-term evaluations, again mostly in cities. Recently, the availability of finely resolved satellite data provides an opportunity to estimate daily concentrations of air pollutants over wide spatio-temporal domains. Italy lacks a robust and validated high resolution spatio-temporally resolved model of particulate matter. The complex topography and the air mixture from both natural and anthropogenic sources are great challenges difficult to be addressed. We combined finely resolved data on Aerosol Optical Depth (AOD) from the Multi-Angle Implementation of Atmospheric Correction (MAIAC) algorithm, ground-level PM_{10} measurements, land-use variables and meteorological parameters into a four-stage mixed model framework to derive estimates of daily PM_{10} concentrations at 1-km2 grid over Italy, for the years 2006–2012. We checked performance of our models by applying 10-fold cross-validation (CV) for each year. Our models displayed good fitting, with mean CV-R2 = 0.65 and little bias (average slope of predicted VS observed PM_{10} = 0.99). Out-of-sample predictions were more accurate in Northern Italy (Po valley) and large conurbations (e.g. Rome), for background monitoring stations, and in the winter season. Resulting concentration maps showed highest average PM_{10} levels in specific areas (Po river valley, main industrial and metropolitan areas) with decreasing trends over time. Our daily predictions of PM_{10} concentrations across the whole Italy will allow, for the first time, estimation of long-term and short-term effects of air pollution nationwide, even in areas lacking monitoring data.

1. Introduction

Particulate matter (PM) air pollution is the sixth cause of premature mortality worldwide (Lim et al., 2012) and it has been recently declared carcinogenic to humans by the International Agency for Research on Cancer (IARC, 2013). In Italy, fine particles ($PM_{2.5}$, PM < 2.5 μm) were responsible for over 20,000 premature deaths in 2010, which are projected to increase to almost 30,000 by 2020, under current legislation scenario (VIIAS project, 2011).

The health effects of PM in Italy have been widely investigated in multi-centre projects evaluating short-term associations between daily PM concentrations and mortality/hospitalizations across several Italian cities: MISA (Biggeri et al., 2005), EPIAIR (Alessandrini et al., 2013; Stafoggia et al., 2009) and MED-PARTICLES (Samoli et al., 2013; Stafoggia et al., 2013). The ESCAPE project involved several Italian cohort studies and detected significant associations between long-term PM exposure, as estimated from land-use regression (LUR) models, and different health endpoints including natural mortality (Beelen et al., 2014), lung cancer (Raaschou-Nielsen et al., 2013), incidence of

* Corresponding author at: Department of Epidemiology, Lazio Regional Health Service/ASL Roma 1, Via C. Colombo 112, 00147 Rome, Italy.
E-mail address: m.stafoggia@deplazio.it (M. Stafoggia).

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cardiovascular (Cesaroni et al., 2014) and cerebrovascular diseases (Stafoggia et al., 2014). Similar results had been already found in a large cohort study involving 1.2 million subjects resident of the Rome metropolitan area (Cesaroni et al., 2013).

One limitation of many epidemiological investigations is the lack of fine spatial and temporal resolution in air pollution assessment. Time-series study designs commonly use data available from routine monitoring networks, and rely on the simplistic assumption that daily variability in air pollution exposure is captured by averages across monitors. When spatial contrasts differ day-by-day across locations (as within urban areas or between urban and suburban/rural settings), such assumption may introduce downward bias in health effect estimates due to misalignment between PM monitors and individual exposures (Gryparis et al., 2009; Zeger et al., 2000). Furthermore, studies on short-term effects based on monitoring networks can only be implemented in areas with good coverage, e.g. cities, whereas there is a need of investigating PM-related health effects in rural areas or in municipalities close to main industrial plants, as the recent case of the "ILVA" steel plant in the Taranto area, Southern Italy, made clear (Mataloni et al., 2012; Pirastu et al., 2013).

Most cohort studies of long-term air pollution exposure and survival assessed exposure as annual average concentrations at the individual address level, based on inverse-distance weighting (simple kriging) procedures, LUR models (a form of universal kriging which incorporates information from spatial parameters), or dispersion and chemical transport models (Cesaroni et al., 2013; Crouse et al., 2015). Simple kriging suffers errors because important sources located between monitors can boost concentrations above the estimates. LUR models capture these sources, but are generally based on a single year of intensive monitoring. Changes over time in the relation between land use terms and the emissions they are surrogates for can cause spatio-temporal errors in the predictions for other years. For example, the imposition of improved pollution controls on a source may differentially lower concentrations nearby, causing the spatial surface to change over time. In addition these models are usually limited to annual averages estimation and fail to capture differential sub-annual contrasts over space. These might be important in relation to health endpoints whose relevant exposure window is shorter than a year, such as seasonal exposures during pregnancy and maternal or birth adverse outcomes (Stieb et al., 2016).

In the last 10–15 years, data from satellite observations have been made available providing relevant information to supplement ground-level measurements. One of the most important parameters retrieved by satellite sensors for air quality modelling is Aerosol Optical Depth (AOD), a measure of light extinction (scattering plus absorbance) from columnar suspended aerosol. The Moderate-Resolution Imaging Spectroradiometer (MODIS), a sensor onboard the NASA satellites "Terra" and "Aqua", provides daily AOD data worldwide at a nadir resolution of 10-km^2 since March 2000, and has been extensively used to estimate ground-level PM concentrations, especially in the US (Chang et al.; 2014; Kloog et al., 2011, 2012), but also in the Po river valley, in Northern Italy (Arvani et al., 2015, 2016; Barnaba et al., 2010; Nordio et al., 2013). Recently, a new processing algorithm has been developed, the Multi-Angle Implementation of Atmospheric Correction (MAIAC), which downscaled AOD data at 1-km^2 resolution (Lyapustin et al., 2011a, 2011b). This has been used in combination with land-use terms, height of the planetary boundary layer (PBL) and meteorological parameters in several US areas (Kloog et al., 2014; Lee et al., 2016), Mexico City (Just et al., 2015) and Israel (Kloog et al., 2015), in order to provide reliable predictions of daily PM_{10} (PM < 10 μm) and $PM_{2.5}$ over large spatio-temporal domains. Further, it has been recently validated against PM data in Italy (Sorek-Hamer et al., 2016), with good results. Other algorithms that provide 1-km^2 resolution AOD data were also used for PM estimation (Beloconi et al., 2016; Lin et al., 2016).

In this study, we applied a four-staged mixed-model framework to estimate daily concentrations of PM_{10} (2006–2012) at 1-km^2 resolution over Italy (approximately 300,000 km^2) taking into account the unique geo-climate of Italy. We chose PM_{10} because of the greater availability of monitoring data during the period. In particular, AOD data were first calibrated to PM_{10} concentrations, while adjusting for land-use and meteorological variables (Stage 1), the resulting model was then applied to predict daily PM_{10} over cells-days with (Stage 2) or without (Stage 3) available AOD. An additional step (Stage 4) has been finally applied to capture the impact of very local sources of air pollution, which can be used to provide individual address specific estimates where data is available. To this aim, we assembled a large national geodatabase including spatio-temporal parameters (PM data, AOD, meteorology, PBL height, monthly data on Normalized Difference Vegetation Index [NDVI], Saharan dust advection estimates) and spatial predictors (population density, industrial emissions, road networks, land-cover terms, elevation and impervious surfaces) for each 1 × 1-km cell and day. On its own, this database represents a powerful resource for multiple environmental applications in Italy.

2. Materials and methods

2.1. Study area

Italy is a boot-shaped peninsula located in Southern Europe, between latitudes 35° and 47°N, and longitudes 6° and 19°E. The countrytotal area is 307,635 km^2. One of the main peculiarities of Italy is its wide variety of landscapes and climatic zones which, combined with a complex mixture of anthropogenic and natural sources of air pollution, affect air quality differently across space (north to south, on the mountains versus coastal areas) and over seasons.

A map of the study area is reported in Appendix, part A, Fig. A.1. Fig. A.2 depicts four sample areas characterized by contrasting situations in terms of orography and main source profiles of air pollution.

2.2. PM monitoring sites

We retrieved daily data on 24-hour mean PM_{10} concentrations, 2006–2012, from 686 different monitoring sites belonging to the Environmental Protection Agencies (ARPA) of the 20 Italian regions, as collected and standardized by the Italian Institute for Environmental Protection and Research (ISPRA). The number of monitors increased over the study period, from 308 in 2006 to 504 in 2012, with highest availability in Northern Italy. The distribution of ground stations is displayed in Fig. A.1. PM_{10} mass concentration measurements were carried out using Beta attenuation or Tapered Element Oscillating Microbalance (TEOM) mass monitors, certified as equivalent to the reference manual gravimetric method. QA/QC procedures were strictly followed, as stated in the legislation in force for the air quality monitoring national (European) network (2008/50/EC). During the study period 279 monitors were influenced by traffic sources in urban and suburban areas, 125 were close to industrial sites, and 275 were representative of urban, suburban and rural background PM concentrations (Table 1). 188 monitors had data on all years (Table B.1 of the Appendix, part B).

2.3. Aerosol Optical Depth data

Spectral AOD (sometime referred to as Aerosol Optical Thickness-AOT) is a global level 2 daily product of MODIS. The details of the standard "Dark Target" (DT) MODIS algorithm over land providing 10-km^2 resolution AOD have been previously reported (Levy et al., 2007; Remer et al., 2005). Recently a new processing algorithm, MAIAC, has been developed that provides a high 1-km^2 resolution AOD from MODIS data (Lyapustin et al., 2011a, 2011b). MAIAC processing begins with gridding MODIS L1B data to a fixed 1-km^2 grid, and accumulation of up to 16 days of measurements in the memory. Then it uses time series analysis and processing of groups of pixels to derive a surface bidirectional reflectance distribution function (BRDF) and aerosol