Environmental Pollution 159 (2011) 2009–2015

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Spatial and temporal variability in urban fine particulate matter concentrations

Jonathan I. Levy [1],*, Steven R. Hanna

Harvard School of Public Health, Department of Environmental Health, Landmark Center 4th Floor West, Boston, MA 02215, USA

ARTICLE INFO

Article history:
Received 14 August 2010
Received in revised form
10 November 2010
Accepted 11 November 2010

Keywords:
Fine particulate matter
Hot spot
Traffic
Urban air pollution
Variability

ABSTRACT

Identification of hot spots for urban fine particulate matter ($PM_{2.5}$) concentrations is complicated by the significant contributions from regional atmospheric transport and the dependence of spatial and temporal variability on averaging time. We focus on $PM_{2.5}$ patterns in New York City, which includes significant local sources, street canyons, and upwind contributions to concentrations. A literature synthesis demonstrates that long-term (e.g., one-year) average $PM_{2.5}$ concentrations at a small number of widely-distributed monitoring sites would not show substantial variability, whereas short-term (e.g., 1-h) average measurements with high spatial density would show significant variability. Statistical analyses of ambient monitoring data as a function of wind speed and direction reinforce the significance of regional transport but show evidence of local contributions. We conclude that current monitor siting may not adequately capture $PM_{2.5}$ variability in an urban area, especially in a mega-city, reinforcing the necessity of dispersion modeling and methods for analyzing high-resolution monitoring observations.

1. Introduction

In recent years, there has been growing interest in the exposure and health implications of living near major roadways (Brauer et al., 2002; Gordian et al., 2006; Lin et al., 2002; Zmirou et al., 2004), as well as in related questions of whether some locations have systematically higher concentrations than others for health-relevant pollutants. Particular attention has been paid to urban areas because of the traffic volumes and high population density. Because of these and other issues, there has been rapid growth in the literature describing analysis of spatial and temporal variations in observed pollutant concentrations in urban areas, with interest in patterns of fine particulate matter ($PM_{2.5}$). While other pollutants (e.g., primary pollutants such as ultrafine particles, carbon monoxide, and nitric oxide) have greater spatial variability, $PM_{2.5}$, which is composed of both primary and secondary contributions, is of interest in light of its well-characterized health effects and regulatory significance (Laden et al., 2006; Schwartz et al., 2008; US Environmental Protection Agency, 2006; Woodruff et al., 2006). The recent literature addressing $PM_{2.5}$ variability observed by monitoring networks has taken many forms, including land-use regression analyses of integrated samples (Clougherty et al., 2008; Henderson et al., 2007; Morgenstern et al., 2007; Ross et al., 2007) and statistical analyses of short-term average monitoring data (Levy et al., 2001; Venkatachari et al., 2006). There has also been evaluation of remote sensing data (Paciorek et al., 2008) and atmospheric modeling ranging from national-scale (Phillips and Finkelstein, 2006; Yu et al., 2007) to urban-scale (Hodzic et al., 2005).

This wide-ranging recent literature has led to conclusions about observed $PM_{2.5}$ variability that at times appear discordant. One recent review article (Wilson et al., 2005) concluded that $PM_{2.5}$ spatial variability may be present in many urban areas, but that the findings from prior studies were influenced by the placement, spacing, and number of monitors included in the analysis, whether the investigators used correlation coefficients or absolute concentration differences to assess variability, and the assumed criteria for deciding whether the variability is large or small. While the Wilson et al. (2005) study addressed many overarching issues in evaluating $PM_{2.5}$ variability, it was constrained by the relatively limited number of available publications concerning a given city and its focus on only monitoring studies with their attendant limitations. Another review article focused on the spatial extent of roadway impacts (Zhou and Levy, 2007) and found that sometimes the conclusions resulting from the applications of dispersion models differed from the conclusions resulting from the analysis of monitoring observations. Part of the reason for different conclusions may be due to difficulties in defining and characterizing background concentrations in either type of approach. Environmental variables are naturally variable in

* Corresponding author.
E-mail address: jonlevy@bu.edu (J.I. Levy).
[1] Present address: Boston University School of Public Health, 715 Albany St., T4 W, Boston, MA 02118-2526, USA. Tel.: +1 617 638 4663; fax: +1 617 638 4857. jonlevy@bu.edu.

0269-7491/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.envpol.2010.11.013

time and space over a wide range of scales, and the concept of a "constant" background concentration is not realistic.

Both of these reviews emphasized that the way in which the observed $PM_{2.5}$ concentration variability is defined and analyzed can greatly influence the resulting conclusions. Because of the variety of definitions and analytical methods, it is difficult to determine whether an exposure "hot spot" would be anticipated in a given setting, or even how a hot spot should be formally defined. A hot spot can be considered as a relatively small area with concentrations significantly higher than the concentrations at a routine monitor site intended to represent the broad area, usually attributable to proximity to a significant local source, but there are numerous ways in which this general definition can be interpreted and implemented. The California Air Resources Board (California Air Resources Board, 2009) defines a hot spot as a location where emissions from specific sources may expose individuals or local population groups to elevated risks of adverse health effects, but this is oriented around cancer risks from air toxics. For $PM_{2.5}$, which is thought to have largely non-carcinogenic health effects at current ambient concentrations without evidence of a threshold (Schwartz et al., 2008), this definition is difficult to implement. When evaluating whether roadway projects conform with Clean Air Act requirements for $PM_{2.5}$ and other criteria pollutants, a hot spot analysis involves evaluation of whether near-roadway pollutant concentrations associated with a project would lead to violations of ambient air quality standards or increase the frequency of existing violations (US Environmental Protection Agency, 2004). This clearly has regulatory import but lacks a strong conceptual basis, as a large local source may not constitute a hot spot if background concentrations were either very low or very high. Others have used explicit quantitative criteria, such as an observed 20% elevation over background concentrations (Blanchard et al., 1999), but this is hard to justify, would be difficult to generalize to all settings and averaging times, and may lead to some strange conclusions (e.g., less-polluted cities would have more hot spots by definition).

Identification of hot spots is further complicated by the dependence of conclusions on the averaging time and the magnitude and variability of background concentrations relative to the concentrations contributed by local sources. Concerning averaging time, a simple power law relation (Turner, 1967) has been widely used to estimate the variation of the maximum concentration as a function of averaging time, reinforcing that the turbulence which may be reasonable to capture when averaged across a sampling period may be difficult to predict on a short-term time scale. While techniques such as land-use regression modeling or kriging have been used to create spatial surfaces for longer averaging times (e.g., annual averages), these approaches are more challenging and less predictive when significant temporal variability exists as well.

Concerning the background concentration, the concept can be elusive, given that $PM_{2.5}$ may have contributions from non-anthropogenic background, intercontinental transport, regional transport, and the urban and neighborhood scale. Further, this background concentration varies over time as a function of gross wind direction and speed, mixing depth, sunlight, and other factors. Characterizing hot spots in the presence of background concentrations is challenging using either dispersion modeling or statistical analysis of monitoring data. Dispersion models are affected by general deficiencies in emissions inventory databases and in adequately capturing long-range transport in high-resolution models. Regression-based analyses of monitoring data often use covariates to represent source strength that are fairly simple proxy variables (such as traffic volume within a defined radius of the roadway), and meteorological characteristics are often either ignored or represented with simple covariates (Jerrett et al., 2005; Morgenstern et al., 2007; Nethery et al., 2008). This leads to challenges in separating background from local contributions, as well as in providing regression equations that are physically interpretable and able to be extrapolated to other settings.

New York City is an interesting case study of the potential for $PM_{2.5}$ hot spots and the sensitivity of conclusions about hot spots to the methods applied. As a city in the eastern United States (US), it has a significant contribution of regional transport to $PM_{2.5}$ concentrations. The upwind source region of influence extends for 1000 km or more. At the same time, as a densely populated urban area with numerous street canyons and complex terrain, it would be expected to have significant local contributions and near-roadway effects, some of which would be short in duration while others would influence long-term average concentrations. Within the literature review by Wilson et al. (2005), New York City was the only location to have multiple publications evaluating observed $PM_{2.5}$ variability, and the conclusions differed across publications. Moreover, beyond the monitoring studies evaluated in Wilson et al. and represented in the peer-reviewed literature, there have also been studies related to near-field dispersion tied to homeland security issues (Hanna and Baja, 2009; Hanna et al., 2007; Lioy et al., 2007). New York City is therefore amenable to a more formal literature synthesis than would be available for other cities, and the availability of extensive monitoring data affords the opportunity for new statistical analyses.

In this paper, we demonstrate the implications of some of the different approaches used to assess contributors to spatial and temporal variability in urban $PM_{2.5}$ concentrations by considering the published literature analyzing $PM_{2.5}$ concentration patterns in New York City. We also conduct new statistical analyses of ambient monitoring data in New York City to illustrate the information value that can be obtained through application of methods that may better highlight local source contributions in the presence of significant regional atmospheric transport, even when evaluating monitors sited to limit local source contributions by definition. We conclude by determining under what definitions and circumstances $PM_{2.5}$ hot spots may exist in an urban mega-city, which would provide useful insight for monitor siting, model development, and policy formulation.

2. Material and methods

To illustrate the degree to which various factors could lead to differing conclusions about spatial and/or temporal variability in $PM_{2.5}$ concentrations in New York City, we conducted a literature search using Science Citation Index in June 2008, using the keywords "air pollution" and "New York City". Of the articles found, we removed those that were not related to spatial patterns of $PM_{2.5}$ in New York City, and we added to this list additional publications known by the authors that addressed the same topic. With this refined list of publications, we examined each to determine the conclusions of the authors regarding the degree of spatial and/or temporal variability in $PM_{2.5}$ concentrations in New York City, as well as to determine the basis for those conclusions (e.g., whether they used monitoring data or dispersion modeling, the spatial density of the concentration measurements or model estimates, the statistical methods applied, the implicit or explicit definition of what would constitute significant variability).

We reinforced conclusions from the literature review by applying novel statistical approaches to reveal patterns in short-term average monitoring data and potentially identify local source contributions in the presence of significant regional atmospheric transport. We extracted all 1-h average $PM_{2.5}$ concentration data for calendar year 2008 from EPA monitoring sites in New York City (US Environmental Protection Agency, 2009), and we obtained hourly meteorological data measured at LaGuardia Airport in New York City. We applied statistical methods described elsewhere (Dodson et al., 2009) to ascertain the joint influence of wind speed and direction on concentrations at each monitor. Briefly, this involved creating vectors of wind speed in the east-west and north-south directions, and using those vectors as jointly nonparametric smooth terms in generalized additive models, implemented using linear mixed effect models with thin-plate splines for the smooth terms. These models characterized the wind speed–wind direction combinations linked with higher or lower concentrations at each monitor, and the degree of concordance in patterns across monitors can be interpreted as the extent of regional contributions to ambient concentrations.