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Spatial and temporal variability in urban fine particulate matter concentrations

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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

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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 Clear 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.

To separate the regional atmospheric transport component and evaluate evidence for local source contributions, we first subtracted off concentrations at the PS219 monitor in Queens from the $PM_{2.5}$ concentrations at each monitor. While the PS219 monitor is not a background monitor (it is an EPA population exposure monitor) and was chosen somewhat arbitrarily for this analysis, it had the lowest average concentrations of all monitors under consideration, and we can use this approach to examine the patterns of the relative concentration differences between monitors (both positive and negative). By applying the statistical approach described above to the difference terms, we can understand the wind speed/wind direction conditions under which certain monitors have concentrations that deviate from those at PS219 as well as at other monitors (either positively or negatively). By comparing these patterns with known local sources near key monitors, we can determine if there is evidence of local source contributions to measured $PM_{2.5}$ concentrations.

3. Results

The articles found within our literature review are summarized in Table 1. All of these articles involved evaluation of monitoring observations rather than use of dispersion modeling, potentially related in part to the keywords selected and the focus on a specific geographic area rather than a larger region. In addition, the averaging times used in the studies ranged from 1-h to three-year averages, and the monitor placement strategies varied widely. More generally, it is interesting to note the substantial differences in methods used across the studies to evaluate variability, even when only considering monitoring observations (Table 1). While some of these differences simply reflected alternative statistical methods to achieve the same aims, others reflected differences in the authors' perceptions about the likely applications of the monitoring observations. Methods included:

- Evaluation of correlations among monitor observations, relevant to evaluating time-series epidemiology
- Land-use regression of long-term average concentrations, relevant to evaluating or conducting cohort epidemiology
- ANOVA methods to quantitatively separate spatial and temporal aspects of variability, applicable to short-term average concentrations across a limited number of sites
- Direct comparison of means, medians, or other distributional measures across sites, applicable to addressing quantitative measures of relative or absolute variability
- Factor analysis methods, which can potentially disentangle the effects of traffic and other local sources from the effects of regional transport.

In general, this literature reinforces the well-established conclusion that there is a large regional transport contribution to $PM_{2.5}$ concentrations in New York City. When there is a major contribution of regional transport along the eastern seaboard, the plume is likely to be broad and with high concentrations, with

Table 1
Summary of findings from New York City fine particulate matter exposure studies.

Study	Avg. time	Number of monitors	Distribution of monitors	Concept of spatial heterogeneity	Key findings
(Ito et al., 2007)	24-h	30 FRM, 24 TEOM[a]	Urban/Suburban	Correlation, CV of means	High monitor–monitor correlation (>0.9), ~10% spatial variation in mean
(Ross et al., 2007)	3-year	62	Urban/Suburban	Land-use regression	Traffic within 300–500 m buffer explained 37–44% of variance across models; statistical models imply ~ 5 μg/m^3 gradient across NYC
(Lall and Thurston, 2006)	24-h	3	Urban/Rural (Manhattan)	Correlation, factor analysis	Correlation between rural monitor and NYC monitor of 0.82; traffic factor contributes 5–6 μg/m^3 in NYC, similar to rural-NYC difference
(Maciejczyk et al., 2004)	24-h	6 (mobile + fixed)	Urban (Bronx)	Comparison of medians/means	Median concentrations across monitors within 20%, difference in means significant for all sites in summer, some sites in spring/fall, none in winter
(Ito et al., 2004)	24-h	3	Urban (Bronx/Queens)	Correlation, factor analysis	High monitor–monitor correlation (>0.9), traffic factor contributes 2.5–6.2 μg/m^3 across sites
(Restrepo et al., 2004)	24-h	4 (mobile + fixed)	Urban (Bronx)	Comparison of means	No significant difference across mobile van and 3 fixed sites in South Bronx (magnitude of mean difference = 0.4–1.5 μg/m^3)
(DeGaetano and Doherty, 2004)	Hourly	20	Urban/Suburban/Rural	Factor analysis, comparison across percentiles	Most between-station correlations >0.85, 90% of variation across monitors explained by a single principal component with similar weight for each monitoring site. Concentrations consistently higher in lower Manhattan, with secondary maximum in upper Manhattan/Bronx.
(Bari et al., 2003)	Hourly, 24-h	2	Urban (Manhattan/Bronx)	Correlation	Correlation for hourly data of 0.79, 24-h data of 0.96
(Lena et al., 2002)	12-h	7	Urban (Bronx)	ANOVA, comparison of means	Intersite differences account for 24% of total variance, average concentrations range 11 μg/m^3 across sites
(Kinney et al., 2000)	8-h	4	Urban (Harlem)	ANOVA, comparison of means	Intersite differences account for 14% of total variance, average concentrations range 10.5 μg/m^3 across sites
(Qin et al., 2006)	24-h	5	Urban/Suburban (Bronx/Queens/NJ)	Correlation, comparison of means, factor analysis	3 NYC sites correlated 0.91–0.93, average concentrations range 0.7 μg/m^3 across sites, traffic factors contribute 1.5–2.5 μg/m^3 across sites
(Venkatachari et al., 2006)	Hourly	2	Urban (Bronx/Queens)	Correlation, CD	Correlation of 0.77, coefficient of divergence (CD) of 0.15 (moderate spatial heterogeneity)

[a] FRM = Federal Reference Method, TEOM = Tapered Element Oscillating Microbalance.

spatial variability of perhaps ±10 or 20%. At slightly smaller scales (such as 50–100 km), there are many large $PM_{2.5}$ sources in New Jersey, just to the southwest of New York City, and these can cause relatively large variations in concentrations in New York City as the wind direction meanders by 10 or 20° and as stability changes from day to night. Nevertheless, the $PM_{2.5}$ monitoring observations suggest that there remains a fairly large variation in $PM_{2.5}$ concentrations within the street canyons and crowded roads of New York City, due to the combination of local sources and natural random variability, especially at shorter averaging times. The studies that found the largest variability across sites (Kinney et al., 2000; Lena et al., 2002) measured short-term average concentrations across sites that were selected by the authors explicitly to capture a gradient of traffic densities. In contrast, many of the studies that concluded that there was relatively little spatial variation in $PM_{2.5}$ concentrations across New York City (Bari et al., 2003; Ito et al., 2004; Qin et al., 2006) used a relatively small number of monitors at official monitoring sites (from either the US EPA or the New York Department of Environmental Conservation). All of the monitors used in these latter studies were characterized by EPA as population exposure or general/background monitors, indicating that they were explicitly sited to avoid major roadways and other local sources. Thus, the degree of spatial variability in $PM_{2.5}$ is likely greater than captured in these studies.

The literature review also suggests that there is no agreed upon criterion for deciding whether the spatial or temporal variability is "large" or "small". Different authors draw the line at different levels of fractional variability, and as a consequence, one author may find concentrations that are 20% over background and conclude that there is limited variability, while another may consider this to be significant. In addition, the methods of accounting for regional background vary substantially, with various statistical approaches and available monitors. In reality, the background varies from day to day and from area to area, depending on what is considered to be the local scale being subjected to the statistical analysis.

Our statistical analyses of 1-h average $PM_{2.5}$ concentrations across 12 monitors distributed across the various boroughs of New York City revealed strong correlations among the monitors (correlation coefficients between 0.70 and 0.94) and good concordance in the wind speed/wind direction combinations associated with elevated concentrations across monitors (Fig. 1). In all cases, westerly winds were associated with elevated concentrations relative to other prevailing wind directions, reflective of the contribution of regional atmospheric transport. All monitors also showed elevated concentrations at low wind speeds, indicative of either enhanced local source contributions or general meteorological conditions and stability characteristics associated with low wind speeds. Holding all other conditions constant, basic theory suggests that the concentration due to local sources tends to be inversely proportional to wind speed, a conclusion supported by our analyses. Annual average concentrations across monitors were also similar, ranging from 10.4 to 12.6 $\mu g/m^3$, with all but two monitors falling within 1 $\mu g/m^3$ of one another.

However, the 1-h average concentrations varied substantially across monitors. Each monitor was at least 25 $\mu g/m^3$ lower than the PS219 monitor on some hour during the year, and each monitor was at least 31 $\mu g/m^3$ higher than the PS219 monitor on some hour during the year. Moreover, the concentrations with PS219 subtracted off were less strongly correlated across monitors than the raw concentrations (correlation coefficients between 0.19 and 0.75, with most values under 0.5), providing some indication of differential local contributions. The patterns of the difference terms with respect to wind speed and wind direction vary significantly across monitors, in a manner that corresponds reasonably with hypothesized local sources (Fig. 2). For example, the monitor at PS154 is located approximately 50 m north of a major highway, and it displays systematically higher concentrations than the monitor at PS219 with winds from the south, especially at low wind speeds. This pattern would have been difficult to ascertain from the raw concentration data modeled in Fig. 1. Similarly, the monitor at

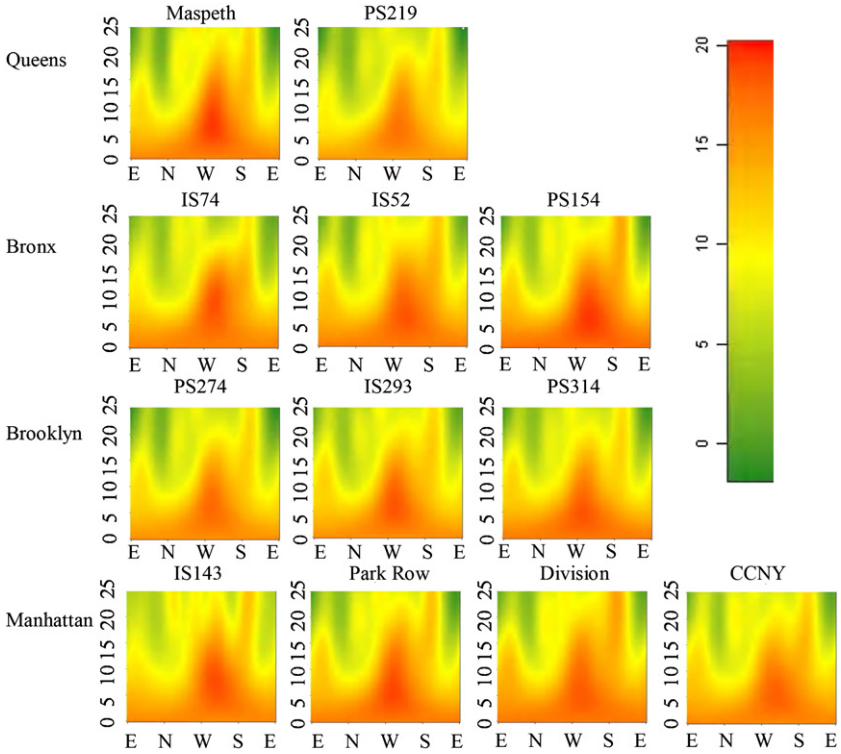

Fig. 1. One-hour average $PM_{2.5}$ concentrations ($\mu g/m^3$) as a smoothed function of wind speed (*y*-axes, in mph) and wind direction (*x*-axes).

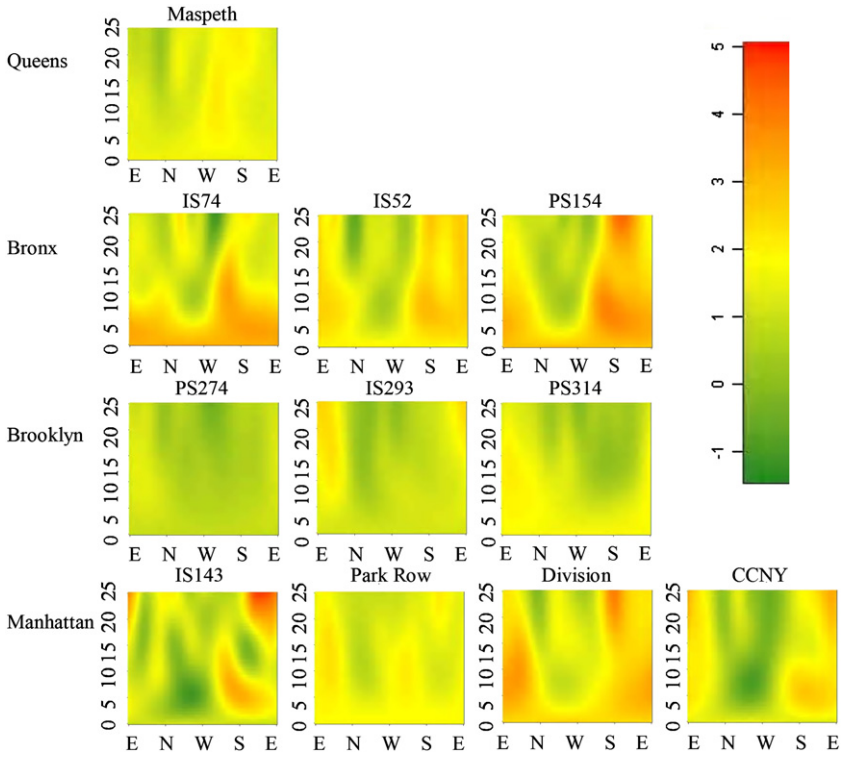

Fig. 2. Differences between 1-h average $PM_{2.5}$ concentrations ($\mu g/m^3$) at each monitor and $PM_{2.5}$ concentrations at PS219, as a smoothed function of wind speed (*y*-axes, in mph) and wind direction (*x*-axes).

Division shows systematically higher concentrations than the monitor at PS219, with the greatest differential with winds from the east/northeast, and the monitor is located 100 m west of a major bridge. In general, the monitors with the smallest ranges in concentrations after subtracting off concentrations measured at PS219 (e.g., PS274, IS293) are located at least 500 m from any major roadways, whereas those with the greatest ranges in concentrations after subtracting off concentrations measured at PS219 (e.g., PS154, Division) are located within 200 m of major roadways.

4. Discussion and conclusions

Our literature synthesis for New York City emphasizes that drawing conclusions about the degree of spatial and temporal variability of $PM_{2.5}$ is complicated by a number of factors, including the influence of averaging time, spatial density of measurements or model outputs, characterization of background, and statistical criteria employed. As such, there is no straightforward answer to the question of whether $PM_{2.5}$ concentrations in a city like New York City should be considered to be relatively homogeneous or heterogeneous. That being said, empirical evidence and atmospheric dispersion concepts emphasize that long-term average concentrations at a small number of widely-distributed monitoring sites not proximate to major roadways would not likely yield substantial variability (i.e., exceeding more than $\pm$ 20% or so), whereas short-term average concentrations with high spatial density would tend to show variability (as much as $\pm$ a factor of 2), especially in a dense urban area with street canyons. The implication is that any analysis leading to conclusions on this topic in the literature should very carefully explain the underlying assumptions and methods to avoid seemingly contradictory findings that are in fact internally consistent.

It is noteworthy that studies relying on the US EPA or state monitoring networks generally concluded that $PM_{2.5}$ concentrations in New York City were relatively homogeneous ($\pm$10 or 20%), a conclusion that is largely determined by the criteria by which these monitoring sites were chosen and the analytical methods applied. Our statistical analyses of EPA monitoring data illustrated that, while between-monitor correlations are relatively high (especially as averaging times increase) and annual average concentrations are similar, there are differences in the short-term average concentration patterns characteristic of local source contributions. This begs the question of whether the magnitudes of these differences are large enough to constitute “hot spots”, but there were clearly numerous hours across the year when each of the monitors differed substantially from the other monitors. This conclusion is reinforced by recent monitoring efforts conducted by the New York City Department of Health and Mental Hygiene, which found a significant gradient in $PM_{2.5}$ concentrations within the city given a dense network of measurements representing varying proximities to multiple local sources (New York City Department of Health and Mental Hygiene, 2009).

Furthermore, while our literature review only uncovered analyses of monitoring observations of air quality variables, multiple other field experiments and dispersion modeling studies in New York City have demonstrated that local hot spots could exist for $PM_{2.5}$ even given the contribution of regional atmospheric transport. For example, a short-term intensive study was undertaken in 2005 near Madison Square Garden in Manhattan, and focused on tracer releases and their fate and transport given potential homeland security implications (Hanna et al., 2006; Lioy et al., 2007). Given the homeland security application, short-term concentrations were evaluated in the near field (distances less than about 1 km). The study found complex wind fields and significant spatiotemporal concentration variability (an order of magnitude difference between “hot spot” tracer concentrations and levels a few blocks away), with local buildings greatly affecting fate and transport and local turbulence dominating concentration variability (Lioy et al., 2007). While

conclusions about the magnitude of variability would clearly not generalize to $PM_{2.5}$, given large differences in local source strength relative to background concentrations, these studies illustrate that local sources in New York City may have unpredictable contributions to ambient concentrations at high spatiotemporal resolution, with the potential for local hot spots.

In addition, the Operational Street Pollution Model (OSPM) has been used to simulate $PM_{2.5}$ dispersion in street canyons in New York City (Zhou and Levy, 2008). That study did not attempt to characterize background concentrations or source strengths, but concluded that the marginal contribution of traffic sources in street canyons is roughly three times greater than the marginal contribution of the same emissions in a non-street canyon setting, increasing the likelihood for hot spots in a setting like midtown Manhattan. It should be noted that long-term spatial variability in concentrations could be low in a setting with many street canyons and similar source strengths across canyons, but this would be determined by similar local contributions rather than long-range transport, and the spatial variability would likely increase with shorter averaging times.

Our literature review and statistical analysis have some clear limitations. We lacked the primary raw concentration data from the various published studies, which prevented us from determining whether using similar statistical methods across studies would reconcile some of the differences in findings. However, it is likely that study differences were more strongly related to the averaging time and where the monitors were located than the statistical methods used. Our statistical analysis indicated that correlations among monitors were extremely high for 24-h average concentrations (between 0.81 and 0.98), decreasing somewhat for 1-h average concentrations (between 0.70 and 0.94), and decreasing further when examining 1-h average concentrations with a "background" monitor subtracted off (between 0.19 and 0.75). This reinforces that concentration hot spots are far more likely with shorter averaging times and given monitors located at close proximity to major roadways, supporting the conclusions from our literature review.

Our statistical analyses of ambient monitoring data in New York City were limited by the available covariates to predict concentrations, and in particular, the lack of time-resolved source characterization that could have strengthened causal conclusions about local sources in our models of monitor differences. Availability of 1-h average traffic volume or emissions data would have allowed us to evaluate whether the hypothesized local sources identified through wind speed/wind direction patterns contributed to observed concentration patterns. Moreover, our consideration of only wind speed and direction was relatively simplistic, and did not provide outputs with strong physical interpretability. Some investigators have used regression modeling formulations that include elements of the Gaussian plume model (i.e., accounting for the inverse dependence on wind speed and on mixing depth, and the decrease in concentration with distance following an inverse power law relation between -1 and -2), with non-linear relationships among covariates, or have used spline models or time-series methods to allow for more complex relationships between predictors and concentrations than would be characterized by the Gaussian plume model (deCastro et al., 2008; Dodson et al., 2009). These studies have the benefit of relying on empirical data but providing a more physically interpretable model, potentially even offering additional empirical evidence supporting key theories. While the data available to us could not support these models, future studies that are able to collect more detailed site and location data should take advantage of these statistical techniques to maximize interpretability.

Our focus on $PM_{2.5}$ was also somewhat constraining, in that ascertaining hot spots for a pollutant with significant regional atmospheric transport is challenging. For pollutants such as ultrafine particulate matter or traffic-related particle constituents, the background contribution would be diminished and the degree of spatial variability would be significantly greater, with clear implications for the extent to which available monitoring networks could be used to assess variability. If the epidemiological literature and regulatory constructs evolve to address these pollutants to a greater extent, methods for fine-scale spatiotemporal modeling will be required, and such methods will need to rely on insights from both monitoring observations and dispersion models given analytical challenges for both approaches. As analyses that are highly resolved in both space and time are more challenging with both approaches, we recommend that future analyses use blended strategies where possible, collecting observations but using dispersion modeling outputs or concepts to structure the analyses of observations.

In spite of these issues, our analysis allowed us to conclude that the influence of local sources on ambient $PM_{2.5}$ concentrations can be clearly ascertained in urban mega-cities such as New York City, under certain definitions and at high spatiotemporal resolution. Analyses of long-term average concentrations at established ambient monitoring networks may not capture these hot spots. While these hot spots may be less meaningful when considering the type of epidemiological evidence currently used in regulatory analyses, this is in part because the epidemiological evidence is largely derived from ambient monitoring networks that lack sufficient spatiotemporal resolution. To the extent that health outcomes may be influenced by short-term concentration changes or higher exposures due to local hot spots not captured by the existing monitoring network, the health implications of $PM_{2.5}$ may be understated, though it is difficult to draw definitive conclusions given the available epidemiology. Refined exposure characterization in space and time will tend to reduce exposure misclassification and improve the ability to determine the benefits of air pollution control strategies and to design health-protective regulations. With increased understanding of near-roadway health impacts, the necessity of developing methods to characterize spatial variations of specific pollutants will continue to increase, and the combination of dispersion modeling concepts and analytical methods for high-resolution monitoring observations should prove valuable.

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