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ORIGINAL ARTICLE

Monitoring intraurban spatial patterns of multiple combustion air pollutants in New York City: Design and implementation

Thomas D. Matte[1], Zev Ross[2], Iyad Kheirbek[1], Holger Eisl[3], Sarah Johnson[1], John E. Gorczynski[3], Daniel Kass[1], Steven Markowitz[3], Grant Pezeshki[1] and Jane E. Clougherty[4]

Routine air monitoring provides data to assess urban scale temporal variation in pollution concentrations in relation to regulatory standards, but is not well suited to characterizing intraurban spatial variation in pollutant concentrations from local sources. To address these limitations and inform local control strategies, New York City developed a program to track spatial patterns of multiple air pollutants in each season of the year. Monitor locations include 150 distributed street-level sites chosen to represent a range of traffic, land-use and other characteristics. Integrated samples are collected at each distributed site for one 2-week session each season and in every 2-week period at five reference locations to track city-wide temporal variation. Pollutants sampled include $PM_{2.5}$ and constituents, nitrogen oxides, black carbon, ozone (summer only) and sulfur dioxide (winter only). During the first full year of monitoring more than 95% of designed samples were completed. Agreement between colocated samples was good (absolute mean % difference 3.2–8.9%). Street-level pollutant concentrations spanned a much greater range than did concentrations at regulatory monitors, especially for oxides of nitrogen and sulfur dioxide. Monitoring to characterize intraurban spatial gradients in ambient pollution usefully complements regulatory monitoring data to inform local air quality management.

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INTRODUCTION

Over the past two decades, concentrations of criteria pollutants have declined significantly in most urban areas.[1] This progress followed regulatory actions to reduce emissions from industrial sources, motor vehicles, electric power stations, paints and other products. Continued improvements in air quality are expected as provisions of the National Ambient Air Quality Standards (NAAQS), the Transport Rule[2] and other regulations are implemented over time.[3] Despite the improvements, the United States Environmental Protection Agency (EPA) estimated that in 2010, 123.8 million people lived in counties with air pollution concentrations that exceeded one or more of the NAAQS for either short-term or annual average exposure.[1] The new 1-h maximum NAAQS for nitrogen dioxide (NO_2) will likely be exceeded at newly required urban near roadway monitoring sites.[4] In addition, epidemiological studies have demonstrated adverse health effects of criteria pollutants at levels below the NAAQS.[5–7]

While national regulations have played a vital role in compelling states to improve air quality, the NAAQS and associated monitoring networks have significant limitations.[8] Urban monitoring networks developed for regulatory purposes generally have a limited number of rooftop monitors in a metropolitan area and track urban scale trends of air pollutants. These networks are not sufficiently dense to characterize intraurban spatial variation in air quality due to local emission sources, such as traffic. In New York City (NYC), for example, with a land area of nearly 800 km^2 and a population of more than 8 million, there are currently just three regulatory nitrogen oxides (NO_x) monitors, three sulfur dioxide (SO_2) monitors and five O_3 monitors. Of the 23 $PM_{2.5}$ monitor locations (one site per 34 km^2 on average), just two measure $PM_{2.5}$ chemical constituent concentrations, despite these pollutants' spatial heterogeneity within cities.[9] This limited spatial resolution is especially important because intraurban gradients in exposure to combustion pollutants can be greater than between-city differences and these gradients are associated with adverse health outcomes, including cardiovascular and respiratory disease, mortality and the exacerbation of asthma and chronic obstructive pulmonary disease.[10–12]

NYC's first environmental sustainability plan, known as PlaNYC,[13] proposed several local initiatives to reduce combustion emissions from mobile and fixed sources. To address some limitations of available air pollution data, PlaNYC also proposed a local air quality study to: (1) characterize spatial variation in street-level concentrations of combustion-related air pollutants and local emission sources; (2) inform city-led emission reduction initiatives; and (3) provide exposure estimates for epidemiological studies. This paper describes the design and implementation of this monitoring program — the New York City Community Air Survey (NYCCAS) — and summarizes pollutant concentrations and data quality indicators for the first full year of sampling. Further details of the NYCCAS land-use regression (LUR) analysis methods and results for the first winter season of 2008–2009 will be reported elsewhere.[14]

[1]New York City Department of Health and Mental Hygiene, New York, New York, USA; [2]ZevRoss Spatial Analysis, Ithaca, New York, USA; [3]Center for the Biology of Natural Systems, Queens College, Flushing, New York, USA and [4]University of Pittsburgh, Graduate School of Public Health, Department of Environmental and Occupational Health, Pittsburgh, Pennsylvania, USA. Correspondence: Dr. Thomas D. Matte, New York City Department of Health and Mental Hygiene, Bureua of Environmental Surveillance and Policy, 125 Worth Street, CN 34E, Room 326, New York, NY 10013, USA.
Tel.: +1 212 788 1219. Fax: +1 212 788 5380.
E-mail: tmatte@health.nyc.gov
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MATERIALS AND METHODS

Design Overview

The design of NYCCAS borrowed from previous studies of intraurban variation in air quality used for exposure assignment in epidemiological studies.[15–20] These methods were adapted to NYC's emission profile and to assess season-specific pollutant concentration gradients. NYCCAS was also designed to provide data for use in LUR models to estimate air pollutant concentrations at unmonitored locations based on nearby land-use and traffic patterns.

Targeted Air Pollutants

NYCCAS is focused on several criteria pollutants and other combustion pollutants associated with respiratory and/or cardiovascular health effects. The selected pollutants and their local emission profiles are briefly summarized here:

- *Fine particulate matter ($PM_{2.5}$)*: A significant proportion of $PM_{2.5}$ originates outside the city,[21] but most local spatial variability in $PM_{2.5}$ is likely due to local emissions.[22] Although the National Emissions Inventory[23] attributes only 7% of local primary $PM_{2.5}$ emissions to traffic, it may account for 36% to 39% of ambient $PM_{2.5}$ in high traffic NYC locations.[24] Other important local sources include commercial cooking, heating fuel, electric power generation, construction equipment and other off-road mobile sources.[23]
- *Particle elemental composition:* Disaggregating $PM_{2.5}$ into its constituents has been useful for identifying sources and differential health effects.[25] Of particular interest in NYC is the high concentration of nickel (Ni) and vanadium (V) found in $PM_{2.5}$ samples, indicators of residual oil burning for heating, marine vessels and power generation.[26,27]
- *Black carbon (BC)*: Although BC generally only makes up a small proportion of overall $PM_{2.5}$ (just 4% to 11% selected US cities), it makes up 75% of $PM_{2.5}$ from diesel exhaust[28] and BC has been used as a marker of diesel exhaust particles.[29,30]
- *Nitrogen oxides:* NO_2 is a common marker of vehicular traffic in LUR studies;[31,32] on-road mobile sources account for 38% of NO_x emissions nationally and 30% in New York City. In New York City, however, the residential and commercial fuel combustion sector produces 25% of NO_x emissions compared with 3% nationally.[23] The primary pollutant nitric oxide (NO) is an indicator of fresh combustion emissions[33] and has a steeper concentration gradient than NO_2 near busy roadways.
- *Ozone (O_3)*: As a secondary pollutant, ozone tends to have higher concentrations in more suburban neighborhoods outside Manhattan, as NO_x scavenging may predominate in the high NO_x environment of the urban core.[34] NYCCAS measures O_3 only during the summer to capture the seasonal peak in New York City.
- *Sulfur dioxide (SO_2)*: Nationally approximately 80% of SO_2 emissions are estimated to be from electric power plants and large industrial facilities.[23] An important source within New York City is high-sulfur residual heating fuel use in large commercial and residential buildings.[26,27] NYCCAS SO_2 measurements are performed during the winter season only.

Spatial and Temporal Allocation of Monitors

Overall approach. Our principal aim was to estimate spatial variation in annual and seasonal average concentrations of the target pollutants at street level. Some previous studies have assessed spatial patterns in annual average concentrations by monitoring all study locations simultaneously at a time when pollutants were expected to be near their annual mean.[18] We collect one 2-week integrated sample at all sites used to model spatial variation, referred to as distributed sites, in each of the four seasons. To assess season-specific spatial variation, these 2-week averages can be adjusted for city-wide temporal variation using the mean concentration at five central, reference sites that are monitored year round.

Number of distributed sites. No standard methods have been established for assessing power or sample size requirements for air sampling networks for LUR studies. As a guideline, a minimum of 40 sites has been proposed.[35] Sample size considerations include the size of the modeling area, the anticipated variability in pollutant concentrations and available resources.

To relate sample size to the anticipated relative precision of spatial estimates, we developed statistical simulations based on existing pollutant data. Using a regular 300 m × 300 m grid of 7595 points as candidate monitoring locations, we calculated the $PM_{2.5}$ and NO_2 kriging variance associated with randomly generated monitoring networks ranging from 10 to 400 locations (in increments of 10). The theoretical variogram models used in the simulation were based on regulatory monitoring data for $PM_{2.5}$ (Dr. Michael Jerrett, personal communication, based on analyses conducted for Ross *et al.*[22]) and NO_2 concentrations measured for a study exposure to traffic pollutants (Drs. Bart Ostro and Janice Kim, personal communication, based on Ostro and Kim[36]). We also developed simulations (using the same grid of candidate monitoring locations) that estimated $PM_{2.5}$ prediction accuracy (based on mean-squared error) using kriging and nearest monitor models under different network density scenarios. Predictions based on randomly selected sets of candidate locations ranging in size from 10 to 400 (in increments of 10) were compared against "true" $PM_{2.5}$ values represented by an LUR smooth surface (Dr. Michael Jerrett, personal communication, based on analyses conducted for Ross *et al.*[22]).

The relationships between monitor number and kriging variance/mean-squared error from the simulations were fit with non-linear decay functions. These simulations indicated that, for both NO_2 and $PM_{2.5}$, the kriging variance declined dramatically as the number of monitors in a network increased from 20 to 60. Although kriging variance continued to improve through 400 monitor locations, incremental improvements were considerably smaller for scenarios above 150 monitors. Thus, a network of 150 sites appeared to provide a reasonable compromise between spatial coverage and sampling cost and was used as the target network size.

Spatial allocation of distributed sites. A number of previous LUR air pollution studies have used a 'location–allocation' to achieve optimum monitor spacing, placing more monitors where expected spatial variation in air quality is greatest.[19] We did not use this approach given the limited regulatory monitoring data available to estimate demand surfaces for multiple target pollutants. Instead, we aimed to capture the range of variation in key local emission sources using a two-step approach of stratified random sampling followed by purposeful site selection.

Stratified random sampling was implemented on the 300 m × 300 m grid used in the sample size simulations. Grid resolution reflected the anticipated spatial extent of important source impacts on pollution concentrations from prior LUR studies.[37] Grid cells were stratified on traffic and building density as indicators of important local emissions sources. Building density is more suitable than population density for both residential and commercial areas of the city. For each cell, we calculated traffic density using data from the New York Metropolitan Transportation Council Best Practice Model[38] and total density of interior building space based on the Primary Land Use Tax Lot Output data files from the New York City Department of City Planning.[39] These variables have highly skewed distributions and are moderately correlated with one another (Spearman's $\rho = 0.32$). We stratified lattice cells into upper ('high') and lower three ('norm') quartiles by traffic and building density, cross-classifying cells into four strata. Lattice cells were randomly selected without replacement, with equal probability of selection from each stratum to oversample locations with high traffic and building density. After selecting a cell, its eight abutting cells were excluded from subsequent sampling. In total, 120 sites (80%) of the overall total of 150 monitoring locations were selected using stratified random sampling.

After stratified random sampling, the distribution of assigned sites was evaluated and 30 additional "purposeful" sampling locations were identified to: (1) place at least one location in each of 59 populated New York City Community Districts (subareas of the city with populations ranging from 34,000 to 243,000 and areas ranging from 3.5 to 56.3 km^2); (2) reduce major geographic gaps (areas of the city >3000 m from a monitor); (3) sample on both sides of at least one north–south and one east–west street canyon; (4) provide at least two public park sites per borough; and (5) monitor near a subset of point and area sources of special concern (e.g., major truck routes, highway interchanges, ongoing construction, wholesale markets, traffic congestion points and transportation facilities) that were identified through discussions with local stakeholder groups including national and local environmental groups and the NYC Department of Transportation.

For each approximate sample location identified by the site allocation process, field teams identified a street-side light pole or other mounting structure. For stratified random sample sites, a suitable mounting pole nearest to the sampled lattice cell's centroid was chosen. Where sampled cells fell within a property that could not be accessed by field teams or lacked light or utility poles, a nearby street-side location was identified. For

purposeful sites, a mounting location near the facility, intersection or other point of interest was identified. Field teams documented site characteristics using digital photographs and standardized forms, recording monitor locations on orthophotos for later GIS coordinate assignment.

Reference monitoring sites. In addition to the 150 distributed sites, which would be monitored for one 2-week session per season, we selected five additional continuously monitored locations, referred to as reference sites. Reference sites provide 2-week averages for all 2-week sessions year round to adjust distributed site values for temporal variation associated primarily with meteorology.[40] We chose one central location in each of the five boroughs (counties) that comprise New York City, colocated with regulatory monitors where possible, and away from major roadways, significant industry or high building density.

Final reference sites colocated with Department of Environmental Conservation (DEC) sites included Queens College (Queens; 7096-15; AIRS no. 36-081-0124; Corresponding pollutants: NO_x; $PM_{2.5}$, $PM_{2.5}$ speciation; ozone, SO_2), New York Botanical Garden (Bronx; DEC 7094-06; AQS 36-005-0133; Corresponding pollutants: NO_x; $PM_{2.5}$, ozone; SO_2); and La Tourette Golf Course (Staten Island; DEC no. 7097-20; AIRS no. 36-085-0132; Corresponding pollutants: none). Because no suitable DEC sites in Brooklyn or Manhattan were identified, sites were identified in two large public parks: Central Park in Manhattan and Prospect Park in Brooklyn.

Temporal allocation of distributed sites. Sampling campaigns are divided into four seasons: winter, December–February; spring, March–May; summer: June–August; and fall: September–November and each season is partitioned into six 2-week sampling periods for a total of 48 weeks of distributed site monitoring each year. For logistical reasons, deployment of monitors for each session occurs on Tuesdays. If possible, failed samples at a site in a season are re-sampled in a subsequent 2-week period in the same season. Additional 2-week sessions of monitoring only at reference locations are added between some seasons to continually track temporal variation and maintain roughly comparable seasonal schedules across years. The first monitoring session began on 16 December 2008 and during year 1 a reference site monitoring session was added 25 August 2009.

We schedule distributed sites to be monitored in each 2-week session with a goal of providing relatively similar coverage of the five boroughs, traffic and building density across sessions. To balance spatial coverage across sessions, sites are assigned randomly within sub-borough strata (each borough was subdivided into east and west components) to 2-week sessions within each season. We further constrain the sampling schedule by requiring the number of sites in each of the four traffic–building density strata sampled in each time period to be approximately equal (within ± 25%). Finally, we require more than two and fewer than nine sessions between seasonal sampling sessions at an individual site (e.g., if a site was sampled in spring session six it could not be sampled in either summer session one or summer session two).

SAMPLE COLLECTION AND ANALYSIS

Integrated Sample Collection

Air sampling uses existing methods incorporated into a unit that was specifically designed to meet the unique needs of this study: (1) to sample consistently year round, for unattended 2-week sessions in all weather conditions on internal battery power with minimal risk of pump failure, filter overload or vandalism; (2) to be rapidly deployed and retrieved by field teams who perform 60 site visits in 2 days every 2 weeks; and (3) to synchronize monitoring times across all sites. The sampling unit components include: Harvard Impactors (Air Diagnostics and Engineering, Harrison, ME, USA) with 37 mm Teflon filters (PTFE membrane filters, 2 μm pore size; Pall Life Sciences) for collecting $PM_{2.5}$ samples; a 0.5–5 liters per minute (LPM) SKC pump (Model 224-PCXR4) calibrated to an actual flow rate of 4 LPM at the forecasted average outside temperature; and a custom-designed, programmable smart controller allowing for simultaneous start and stop of deployed units at midnight and continue to operate 15 min each hour, yielding an 84-h sample with a volume of 20.16 m^3, over the 2-week period (avoiding filter overload). The sampling unit also contains relative humidity, temperature and barometric pressure sensors connected to a HOBO micro station data-logging device (Onset Computer Corporation, Pocasset, MA, USA). The sampler is powered by two 6 V 13Ah batteries connected in parallel. The equipment is mounted inside a watertight and crushproof polypropylene case (Pelican Model 1550NF silver case, San Antonio, TX, USA; exterior dimensions 16 in $L \times 13$ in $W \times 6.9$ in D). A weather shelter fixed to the outside of the sampling unit provides space for two passive samplers (Ogawa & Co. USA, Pompano Beach, FL, USA) for gaseous pollutants. The complete unit weighs approximately 35 pounds and is mounted on signal/street light posts or utility poles, 10–12 ft above ground using a permanently installed lockable mounting plate that enables rapid deployment and retrieval (Figure 1).

Laboratory Methods

The analysis of the Ogawa passive samplers is performed by RTI International Laboratories (Research Triangle Park, NC, USA) using water-based extraction techniques, colorimetric analysis for NO_x and NO_2 (NO calculated by the difference of NO_x–NO_2), and Ion Chromatographic analysis for SO_2 and O_3, with calculations to convert assay results to concentrations in ambient air.[41,42] Gravimetric $PM_{2.5}$ analysis is also performed by RTI, including Teflon filter preparation, pre- and post-sampling weighing and quality control/assurance.[43] Reflectance analyses is performed at Queens College, Center for the Biology of Natural Systems (CBNS) (Flushing, NY, USA), using an EEL (Incorporating Evans Electroselenium) smoke stain reflectometer (Model 43D; Diffusion Systems, London, UK). Absorbance is calculated using a modified published method.[44]

Ambient $PM_{2.5}$ samples are analyzed by X-ray fluorescence (PANalytical Epsilon 5 EDXRF spectrophotometer; Almelo, The

Figure 1. New York City Community Air Survey (NYCCAS) integrated filter-based sampling unit with Harvard Impactor inlet (at the bottom) for particulate matter ($PM_{2.5}$) and externally mounted shelter for two passive samplers for gaseous pollutants (NO_2, NO_x, SO_2 and O_3) and Rh/temperature sensors.

Netherlands) for 31 elements by DRI using standard methods.[45] Elemental constituent results will be presented in a future publication.

Quality Assurance/Quality Control

For $PM_{2.5}$ samples, pump flow rates before and after sample collection are compared and the temperature-corrected flow rate is compared with the expected flow rate (4 l/min). Cumulative pump run time and controller data are reviewed sample volume that is computed. Flow rates must be within 10% and volumes and exposure times must be within 5% of targets for data to be considered valid.

Qualtiy assurance/quality control processes include three field and two lab blanks and colocated samples at three distributed and two reference sites during each session. For each pollutant and season, descriptive statistics are computed for reference and distributed sites by session to identify potential outliers for further investigation. For measurements colocated with regulatory monitors for the same pollutants, NYCCAS 2-week integrated sample concentrations are compared with the corresponding 2-week means computed from regulatory monitoring data obtained from the US EPA Air Quality System Data Mart.

Statistical Analysis

We computed the overall range and the interquartile range for characteristics such as traffic, land-use and population density within 300 m of the selected NYCCAS sampling locations. We computed statistics to describe data quality for NYCCAS air pollutant concentration measures during the first full year of sampling, including the proportion of designed samples that were completed, the coefficient of determination (R^2) and mean absolute differences between colocated NYCCAS samples and the associations of NYCCAS measures with 2-week mean concentrations measured at colocated regulatory monitors. To describe and compare variability among pollutants for each pollutant, we computed the coefficient of variation and plotted concentrations by 2-week session for distributed sites and means of reference and regulatory monitor sites, and estimated the shared temporal variation (R^2) explained by session for distributed site measures.

RESULTS

Site Selection

Of 120 candidate monitoring locations selected by stratified random sampling, one location within John F. Kennedy airport was not accessible to field teams and the monitor was re-allocated as a purposeful site. The remaining 119 stratified random sampling sites were included in the final network and they covered 51 out of the 59 populated community districts. In addition to the one re-allocated site, an additional 30 purposefully selected monitoring locations were chosen based on the criteria discussed above. The primary purpose for eight of the selected sites was coverage of community districts without a sampler and three additional sites were included primarily to fill a major spatial gap. The remaining purposeful sites included four sites specifically within street canyons, several sites in high traffic areas and locations near a large wholesale produce market (Hunts Point in the Bronx), a location in Times Square and one near the World Trade Center construction site.

The 150 distributed sites (Figure 2) vary widely in nearby land-use and traffic density; area characteristics within 300 m (corresponding to the resolution of the lattice layer from which potential sites were sampled) of monitoring sites are summarized in Table 1. Total road network length within 300 m of monitors, for example, ranges from 0.7 to 11 km and traffic ranges from 0 to nearly 7000 vehicle-km/h. The estimated population within 300 m of monitors (based on Census 2000) ranged from 0 to more than 16,000, and the building area ranges from 0 to approximately 3.6 mft^2.

Figure 2. Map of New York Community Air Survey (NYCCAS) sample locations in relation to major roads and relative density of buildings within New York City. Major roads are defined as such by the NYC Office of Emergency Management. Building density is estimated as interior square feet of buildings based on New York City Department of City Planning's Primary Land-Use Tax Lot Output (PLUTO) data for each tax lot and displayed as a smooth surface.

Sample Completion and Reliability

During the first year (16 December 2008–2 December 2009), sample loss to instrument failure or other problems was minimal despite temperatures as low as 6°F and as high as 92°F, and 39 days with at least 0.5 in of precipitation (max = 2.3 in). As a result, overall sample completion rates were high: 99% of designed samples for gaseous pollutants (NO_2, NO, SO_2 and O_3) were successfully collected. $PM_{2.5}$ and BC samples were completed at rates of 95% and 94%, respectively (Table 2). Including distributed sites with failed samples that were successfully repeated in a subsequent 2-week period within the season, completion rates among possible quarterly samples at distributed sites were 97% (579/600) for $PM_{2.5}$ and BC and >99% (598/600) for NO_2 and NO. All 150 samples were successfully collected for SO_2 during the winter season and 149 out of the 150 samples were successfully collected for ozone during the summer (Table 2).

Agreement between colocated NYCCAS measures was excellent (Table 3) with R^2 values of 0.95 or higher for all pollutants except ozone ($R^2 = 0.88$). Ozone had one large outlier; with the one outlier removed, the R^2 improved to 0.99. The mean absolute value of percent differences between colocated samples ranged from 2.7% for NO_2 to 8.9% for SO_2.

Correlation between NYCCAS measurements and 2-week averages of measures at colocated regulatory monitors was also strong (Table 4), with R^2 values for the four pollutants (NO, NO_2, $PM_{2.5}$ and O_3) ranging from 0.91 to 0.96. Absolute values for $PM_{2.5}$, NO_2 and O_3 were also similar with slopes near 1 and intercepts near 0. NYCCAS passive methods measured higher NO values and lower SO_2 than did regulatory monitors using federal reference

Table 1. Interquartile ranges of traffic, population and land-use metrics within 300 m of monitor sites, New York Community Air Survey.

	Units	*Reference sites (n = 5)*	*Distributed sites*		*All sites (n = 155)*
			Park sites (n = 12)	*Street-side sites (n = 138)*	
Roadway length	km	1.9–2.5	2.1–3.7	4.3–6	3.8–6
NYMTC traffic density	Veh-km/h	119.4–783.4	301.6–2560	561.4–2801	468.1–2780
NYMTC truck traffic Density	Veh-km/h	5.8–13.5	0.91–24.4	13.4–83.2	10.1–79.4
Census 2000 population	Persons	0–522.7	117–3455	1316–5819	1102–5724
Buildings area	ft^2 (thousands)	0–414.1	0–1753	976.3–4112	863.2–3654
Residential space area	ft^2 (thousands)	0–330.9	0–1331	577.9–2610	449.7–2393
Commercial space area	ft^2 (thousands)	0–200.8	0–312.1	168.1–1134	125.1–1024
Industrial space area	ft^2 (thousands)	0–0	0–50.0	0–77.4	0–62.8

Abbreviations: NYMTC, New York Metropolitan Transportation Council; Veh-km/h, vehicle-kilometers per hour.

Table 2. Sample completion rates, New York Community Air Survey.

	Sample completion (%)[a]	*Completeness for quarterly sampling (%)*[b]	*Sites with complete set of samples*[c]
$PM_{2.5}$	94	97	129
BC	94	97	129
NO_2	99	100	148
NO	99	100	148
SO_2	99	100	150
O_3	99	99	149

[a]Proportion of all samples attempted that were completed; includes reference sites and colocated samples.
[b]Proportion completed among designed distributed site samples ($n = 600$ for year-round pollutants; $n = 150$ for seasonal pollutants (SO_2, O_3).
[c]Distributed sites with the completion of four seasonal samples for year-round pollutants and one sample for seasonal pollutants (SO_2, O_3).

Table 3. Agreement between colocated samples, New York Community Air Survey.

	Colocated sample pairs (n)	R^2	*Absolute mean % difference*
$PM_{2.5}$	90	0.98	3.2
BC	91	0.97	5.1
NO_2	101	0.99	2.7
NO	101	0.98	7.8
SO_2	13	0.95	8.9
O_3	28	0.88	3.3

Table 4. Comparison of pollutant concentrations measured at colocated NYCCAS samplers and New York DEC Regulatory Monitors.

	Colocated measurements (n)	R^2	*Slope*	*Intercept*
$PM_{2.5}$	25	0.96	1.0	0.12
NO_2	48	0.91	1.03	−0.55
NO	48	0.94	1.09	5.45
SO_2	12	0.92	0.83	−0.67
O_3	12	0.88	1.09	−1.37

Abbreviations: DEC, Department of Environmental Conservation; NYCCAS, New York City Community Air Survey.

methods. Our absorbance-based indicator of BC is not directly comparable to regulatory monitoring of elemental carbon mass concentration.

Pollutant Concentrations: Spatial and Temporal Variation

As anticipated, concentrations of all pollutants at NYCCAS sites spanned a greater range than concentrations at regulatory monitoring sites. Average measurements at street-side sites showed higher concentrations than those measured at the regulatory monitors for all pollutants except SO_2 and O_3. The largest differences were observed for NO, where average street-side concentrations were 2.6 times higher than those observed at the regulatory monitors. Pollutant concentrations were generally higher at street-side sites compared with park sites with street-to-park ratios ranging from 1.7 for NO to 1.0 for ozone (Table 5). The relatively high ratios of NO concentrations at street-side monitoring sites relative to regulatory and reference sites reflects the rapid conversion of NO in fresh vehicle exhaust to NO_2 and is consistent with other studies comparing near roadway to "background" NO concentrations.[46] Mean pollutant concentrations at NYCCAS reference sites were generally similar to concentrations measured at regulatory sites, except for SO_2, which averaged less than half the concentration at reference compared with regulatory sites. Based on the coefficient of variation at street-side sites, SO_2 (0.66) and NO (0.65) were more variable than NO_2 (0.37), BC (0.38), O_3 (0.24) and $PM_{2.5}$ (0.32). The ranges of concentrations measured at NYCCAS street-side locations were greater than at NYCCAS park sites, reference sites and regulatory sites (BC was not measured at the regulatory sites).

The patterns of temporal variation in pollutant concentrations across sessions for NYCCAS sites were generally similar to that for regulatory monitors (Figure 3). $PM_{2.5}$ values at NYCCAS sites were higher during the winter and particularly high values occurred during the sessions beginning 13 January and 27 January when mean values were more than 1.6 times the annual mean and significantly higher than the previous and subsequent sessions. The lower average summer $PM_{2.5}$ concentrations were largely due to the first three sessions (mean = 9.5), which were characterized by below average temperatures compared with the last three summer sessions (mean = 13.7). Minimum values occurred during September and early October. NO_2 concentrations at NYCCAS sites were higher during the winter and early spring, consistent with the trend at regulatory monitors. NO showed the least temporal variability, although concentrations were somewhat higher in winter. Similar to several other pollutants, the highest average values occurred during the session beginning 27 January with mean values 1.9 times higher than the annual average. Winter SO_2 concentrations at regulatory and NYCCAS sites were highest in the

Table 5. Summary statistics for pollutant concentrations at NYCCAS and regulatory monitoring sites.

	Street-side sites			*Non-reference park sites*			*Reference sites*			*Regulatory sites*		
	n	*Mean (range)*	*CV*	n	*Mean (range)*	*CV*		*Mean (range)*	*CV*	n[a]	*Mean (range)*	*CV*
$PM_{2.5}$	138	11.55 (5.17–26.48)	0.32	12	9.85 (4.62–17.53)	0.33	5	9.74 (5.19–17.68)	0.30	10	10.73 (5.66–18.83)	0.30
BC	138	1.27 (0.46–3.31)	0.38	12	0.98 (0.43–1.65)	0.32	5	0.94 (0.50–2.06)	0.26	0	—	—
NO_2	138	27.60 (8.32–87.18)	0.37	12	22.13 (8.10–36.94)	0.32	5	20.21 (9.43–38.16)	0.29	3	22.69 (17.10–34.20)	0.20
NO	138	31.82 (2.69–151.76)	0.65	12	18.88 (4.93–45.15)	0.59	5	15.89 (5.42–54.84)	0.53	3	12.08 (3.30–40.00)	0.69
SO_2	138	5.11 (0.86–18.95)	0.66	12	4.84 (1.14–13.78)	0.79	5	4.98 (0.86–12.71)	0.63	3	10.18 (7.25–13.79)	0.27
O_3	138	24.50 (10.53–36.12)	0.24	12	24.01 (14.62–33.27)	0.26	5	26.48 (16.89–34.31)	0.17	5	26.71 (21.26–31.65)	0.16

Abbreviations: CV, coefficient of variation; NYCCAS, New York City Community Air Survey.
[a]One or more regulatory sites were non-operational for a limited number of 2-week sessions.

13 January and 27 January monitoring sessions, which were 1.3 and 1.7 times greater than the winter averages, respectively. Summer O_3 values at NYCCAS and regulatory monitoring sites were lower during the first two summer sessions, when unseasonably cool weather prevailed. Among pollutants measured year round, the proportion of overall variance at distributed sites explained by time (2-week session) was highest for $PM_{2.5}$ ($R^2 = 0.67$) and lowest for BC ($R^2 = 0.14$).

DISCUSSION

This paper describes the design and implementation of one of the largest urban air monitoring programs of its kind, providing seasonal monitoring of key combustion-related pollutants at 150 sites and year-round monitoring at five reference sites in the five boroughs of NYC. The integrated sampling units performed very well and provided high-quality air pollutant data suitable for LUR and other spatial modeling. All pollutants exhibited significantly more geographic variation at NYCCAS sites than is captured by regulatory monitoring. Temporal variation in 2-week average pollutant concentrations was generally consistent between NYCCAS and regulatory monitoring data.

Within NYC, several prior studies have investigated local sources contributing to air pollution in predominantly low-income neighborhoods, documenting impacts of local truck and bus emissions, especially on concentrations of BC and $PM_{2.5}$.[30,47,48] While useful in linking diesel emissions to pollutants of public health concern, these studies did not provide comparative data on combustion pollutant exposures across other NYC neighborhoods, many of which also have high volumes of truck and overall traffic. Using existing regulatory monitoring data on $PM_{2.5}$ in the NYC metro area, Ross and co-workers[22] showed that spatial variation was associated with local traffic, population density and industrial land-use. That study did not include street-level monitoring, was limited to the geographic coverage of the existing regulatory monitoring network and did not evaluate season-specific spatial patterns. These earlier NYC studies were also not able to provide data on spatial patterns of multiple pollutants and particle composition that may help advance urban air pollution epidemiology. NYCCAS will help to address these limitations by evaluating the fine-scale spatial variation in multiple pollutant concentrations, particle composition and source contributions across the city. NYCCAS data are currently being used to develop exposure data for epidemiological studies of birth outcomes, respiratory illness and cardiovascular morbidity and mortality in NYC.

While the current air quality monitoring and management approaches have accomplished much, limitations pose challenges to future progress in reducing urban air pollution exposures and health impacts. Saturation sampling surveys, such as NYCCAS, using lower cost methods to collect integrated samples is one approach to urban air pollution monitoring that can address some of these limitations by characterizing intraurban exposure gradients at street level, identifying exposure hot spots and supplying the more detailed spatial data needed to improve air quality management decisions and track progress.[8] A local air monitoring program of the scope and size of NYCCAS will not be feasible in many other cities, but a similar approach that is less resource intensive could be a useful complement to existing air quality monitoring. For example, spatial gradients in NO_2 concentrations could be characterized with low-cost passive sampling to help guide placement of newly required regulatory monitors.[4] While NYCCAS is designed to be ongoing, as the major local sources contributing to spatial gradients are characterized, the number of sites monitored may be reduced over time, while maintaining sufficient spatial coverage to track the impacts of local emissions control initiatives.

Improvements are also needed in spatial resolution of air quality models. Those used to support State Implementation Plans currently rely on emissions estimates that are well characterized for large point sources but less so for important area sources such as space heating, which are based on proxy indicators, such as population.[23] The Community Multi-scale Air Quality Model, when used for assessing emission control strategies for criteria pollutants, is generally recommended for use at a spatial resolution of $12\,km \times 12\,km$[49] that cannot capture smaller scale impacts on populations with varying susceptibility profiles. In addition, pollution control strategies focused on standard attainment for single pollutants may not identify the optimal strategies to reduce health risks from multiple harmful pollutants.[8] Promising approaches have been reported that improve model spatial resolution and evaluate emission control strategies for risk reduction from multiple pollutants,[50,51] although improved spatial resolution of emissions estimates and further empirical validation of air quality models are needed. We believe that monitoring studies such as NYCCAS can also support and evaluate such multipollutant, risk-risk–based air quality management approaches, by providing observed data on intraurban air pollution gradients and characterizing local source contributions.

Finally, we believe that disseminating findings from local studies such as NYCCAS can enhance local stakeholder engagement in air quality management. After much progress reducing emissions from large point sources and new on-road vehicles, addressing intraurban pollution gradients and local "hot spots" will require more local actions, such as reducing traffic volumes and congestion and heating emissions from buildings. Consequently, better data on local exposures and source impacts are needed to help local residents, commuters and businesses weigh the benefits of such actions against impacts on lifestyles and budgets. For example, results of NYCCAS winter monitoring data, which are detailed elsewhere,[14] were helpful in mobilizing broad

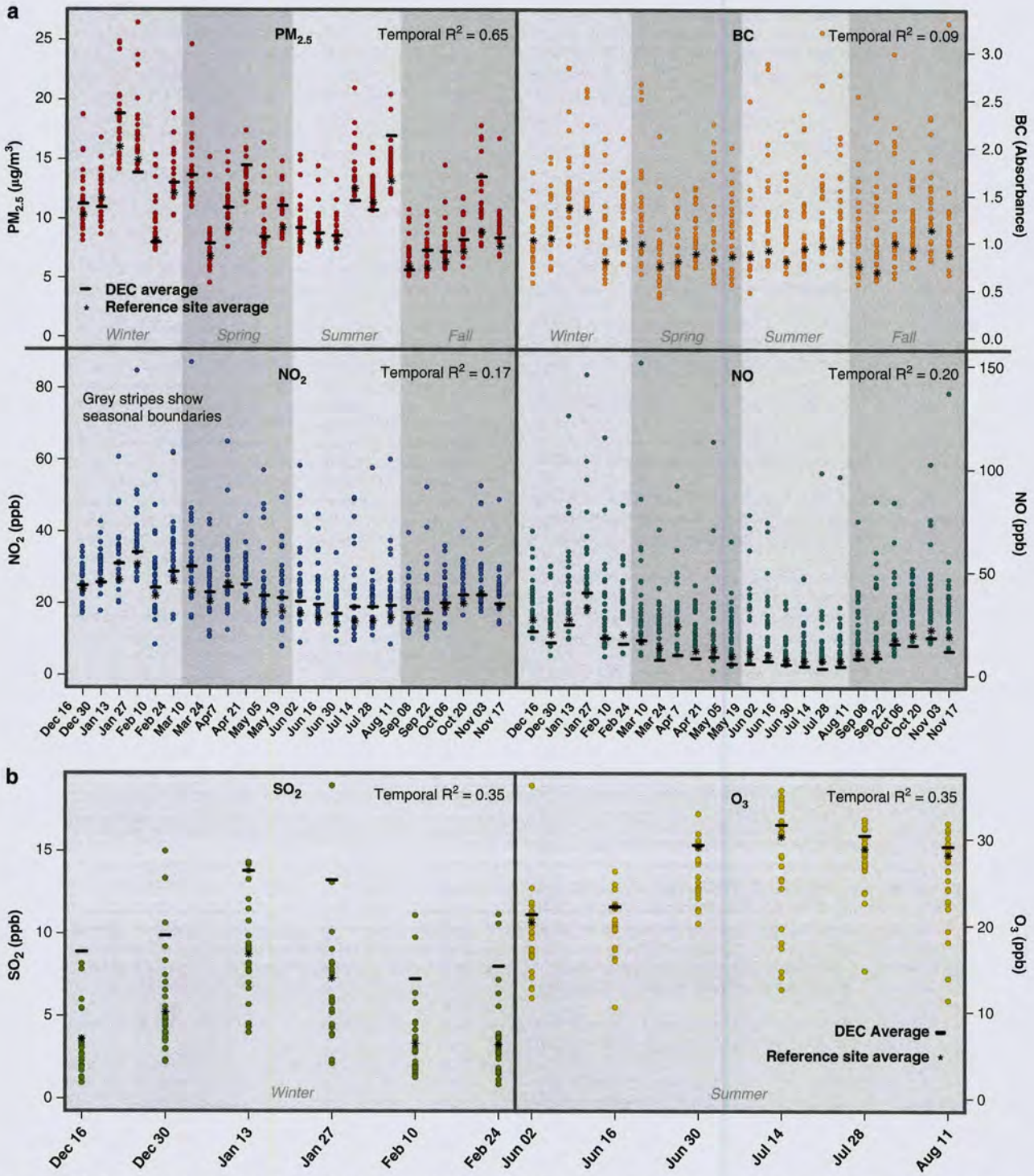

Figure 3. (**a**, **b**) Pollutant concentrations by session measured at New York City Community Air Survey (NYCCAS) distributed sites (solid colored circles), the average of NYCCAS reference sites (black circles) and at New York State Department of Environmental Conservation regulatory monitors (lines). Temporal R^2 is the proportion of variance in pollutant concentrations at distributed sites explained by temporal variation (i.e. the 2-week time period during which the sample was collected).

support for regulations to phase out the use of the most polluting heating fuels in NYC.[52]

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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