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Enhancing Environmental Public Health Tracking with Satellite-Driven Particle Exposure Data

By

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Environmental Health

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Erika Rees

B.S.
North Park University, Chicago
2010

Thesis Committee Chair: Jeremy Sarnat, Sc.D.

An abstract of
A thesis submitted to the Faculty of the
Rollins School of Public Health of Emory University
in partial fulfillment of the requirements for the degree of
Master of Public Health
in Environmental Health
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Abstract

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Background: $PM_{2.5}$ poses a threat to human health which demands implementation of emission and quality standards. Unfortunately, current ground-level ambient air monitors lack spatial coverage across rural, suburban, and even urban areas, necessitating the use of remote sensing in air quality monitoring. Moderate Resolution Imaging Spectroradiometer (MODIS) instrumentation estimates an aerosol optical depth (AOD), which is correlated with $PM_{2.5}$ concentrations. MODIS gives one central AOD estimate for 10 km x 10 km pixels across the globe. However, it is not yet understood how well the satellite-driven $PM_{2.5}$ estimate represents such a large pixel. The goal of the current study is to analyze MODIS resolution in its ability to detect $PM_{2.5}$ spatial heterogeneity; the more spatially heterogeneous a pixel, the less likely one central MODIS estimate accurately represents the varying concentrations in that pixel.
Methods: Three ground-level $PM_{2.5}$ samplers were deployed in two separate pixels: one pixel with historically 'average' $PM_{2.5}$ means, and one with historically 'elevated' means. As MODIS estimates AOD from the center of the pixel, one sampler was set at each pixel centroid in order to determine MODIS estimate accuracy. Daily $PM_{2.5}$ concentrations were compared across the three sites in the same pixel in order to explore the level of spatial heterogeneity in concentrations.
Results: Overall, almost all pairwise Spearman's correlation coefficients were indicative of strong correlations between site concentrations. The 'elevated' pixel's centroid was moderately correlated with MODIS estimates (R= 0.52). Correlations between the 'average' centroid and MODIS estimate were very strong (R= 0.75), suggesting MODIS accuracy at the centroid. Concentrations in the 'average' pixel were also found to be heterogeneous across the three sites. This heterogeneity supports the hypothesis that a pixel sized 10 km^2 experiences a large variation in $PM_{2.5}$ concentrations that current spatial resolution of MODIS instrumentation fails to capture.

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BACKGROUND:

Since the publication of the Harvard Six Cities study in 1993, hundreds of analyses have been conducted examining the association between poor air quality and morbidity and mortality. Among the strongest associations between air pollution and adverse health outcomes have been specifically with the air pollutant known as fine particulate matter (Pope, 2000). Collectively, fine particulate matter refers to a class of solid- or semi-volatile air pollutants with an aerodynamic diameter 2.5 microns or smaller ($PM_{2.5}$) (Godish, 2004). $PM_{2.5}$ range in shape and include elemental and organic carbon, sulfate, nitrate, inorganic metal and crustal components.

$PM_{2.5}$ poses a threat to human health both because of its size as well as its composition, which may illicit a toxic response either directly or via indirect biological pathway signaling (Pope, 2000). Particles of this size can be inhaled deep into the lungs, reaching the alveoli. Studies have shown that the elderly, the very young, and those with preexisting cardiopulmonary disease may be most susceptible to acute adverse health effects of $PM_{2.5}$ (Mar, 2005). In contrast, it is generally assumed that healthy, middle aged adults with high socioeconomic statuses do not experience increased acute mortality risk, but may suffer adverse effects of long term exposures later in life (Puett, 2011). Knowledge about the precise biologic mechanisms of these effects is complex, reflecting likely multiple modes of action, but it is generally hypothesized that oxidative lung damage and inflammation play a large role leading to hypoxemia and risking further damage to other body systems (Pope, 2006).

Currently, the U.S. Environmental Protection Agency (EPA), in accordance with the Clean Air Act of 1990, regulates six ubiquitous air pollutants which are considered harmful to human health using a system of National Ambient Air Quality Standards (NAAQS) (Watson, 1998). Current NAAQS require that 24-hour average concentrations of $PM_{2.5}$ do not exceed 35 micrograms per cubic meter ($\mu g/m^3$) and that annual concentrations do not exceed an average of $15\mu g/m^3$. These standard values were lowered in 2007 from the previous $PM_{2.5}$ standard requiring 24-hour averages to remain below $65\mu g/m^3$, and reflect the growing concern and acknowledgement of the potential health effects from exposure to this urban air pollutant.

Atlanta, in particular, is a large metropolis that occasionally experiences exceedances of the $PM_{2.5}$ NAAQS throughout the year. Many of the 31 counties within the metropolitan area of Atlanta can be characterized by high levels of $PM_{2.5}$ during the summer months (May-September) especially (Zimmer-Dauphinee, S., 2012). Indeed, epidemiological studies have linked particle pollution to increased pediatric asthma emergency department visits, increased lung inflammation, and vascular disease progression (Strickland, 2010; Seagrave, 2006; Floyd, 2009).

NAAQS compliance is typically assessed through the use of ground-based ambient pollution monitors. The Georgia Environmental Protection Division (GAEPD) currently maintains seven ambient monitors capable of estimating 24-hour averages of $PM_{2.5}$ in the entire metropolitan Atlanta area (Zimmer-Dauphinee, S., 2012). While individual monitors are capable of providing reliable, quality-assured aerosol concentration data for the communities directly around them, spatial coverage of metro Atlanta is lacking due to sparse monitoring across a large urban and suburban area. As a result, epidemiological studies have traditionally used $PM_{2.5}$ concentration data measured at various monitoring sites with the assumption that these local measurements represent the population exposures of all residents in a geographic area (Mao, 2011). Clearly, use of this method poses a risk of exposure misclassification; variation between widespread ambient monitors exist and point $PM_{2.5}$ measurements made using stationary ambient monitoring may not be accurate estimates of the population exposure to $PM_{2.5}$. Additionally, rural or remote regions often do not have any ground-based monitors nearby, leading to a greater spatial gap for estimated $PM_{2.5}$ exposure information among residents in those areas.

Satellite data can address issues related to sparse geospatial and synaptic data that accompany the sole use of ground-based monitors (Engel-Cox, 2004). Specific satellite instruments have the ability to provide aerosol optical depth (AOD) measurements, which describe the dimensionless measure of light extinction (or scattering) integrated over a vertical column of the atmosphere reaching from satellite to Earth's surface. This measure of reflectance is the key factor in estimating vertically averaged $PM_{2.5}$ concentrations, and is based on the physical relationships between light scattering and particle mass concentration within an atmospheric column (Wong, 2011; Hidy, 2009). Because the value is vertically averaged, AOD does not provide information about the location of aerosols within the column (Alston, 2011). Regardless of this issue, many studies have shown that AOD values are correlated with ground-based $PM_{2.5}$ measures under the conditions of a relatively cloudless sky and a well-mixed boundary layer (Hidy 2009; Wong, 2011; Hutchinson, 2003; Gupta, 2009). A 2004 nationwide study further demonstrated that the relationship between AOD and ground-level $PM_{2.5}$ concentrations varies by region, with the east coast of the United States exhibiting the strongest correlations between AOD and ground-level $PM_{2.5}$ concentrations (Engel-Cox, 2004).

The National Aeronautics and Space Administration (NASA) launched the first instrument capable of estimating AOD, the Moderate Resolution Imaging Spectroradiometer (MODIS), aboard the Terra satellite platform in 1999 (Hidy, 2009). Three years later, the Aqua platform was launched with an additional MODIS instrument to double the AOD observation frequency over any region (Wong, 2011). The Terra platform transects the Atlanta area daily at 10:15 am local sun time and the Aqua platform passes this same area three hours later, providing two AOD estimations of daytime $PM_{2.5}$ concentrations. MODIS instrumentation acquires AOD data in 36 spectral bands, or groups of wavelengths; AOD information is read in 10 km x 10 km grid cells or pixels, estimating reflectance information at the pixel's direct center or centroid. This 10 km spatial resolution, while offering improvements in spatial resolution over sparsely sited ambient monitoring, may still be limited in sufficiently modeling $PM_{2.5}$ spatial distributions. It is likely that urban and suburban areas may require more spatial and spectral detail to pinpoint local pollution sources and fully characterize $PM_{2.5}$ spatial heterogeneity (Wong, 2011).

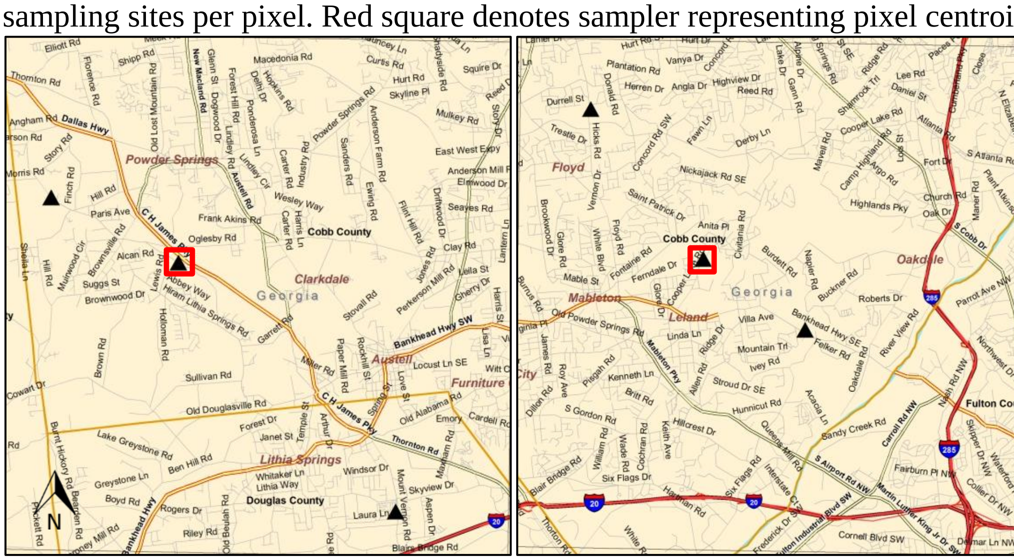
As noted, MODIS retrieves AOD estimates from the center of a standard sized 10 km x 10 km pixel. In the current study, we examined the accuracy of MODIS by comparing concentrations between a ground-level monitor located at the pixel centroid and corresponding MODIS centroid estimates. To further examine the ability of MODIS to capture $PM_{2.5}$ spatial variability within a pixel, we also measured $PM_{2.5}$ concentrations across the 10 km x 10 km pixel. This objective was met by comparing multiple ground-level readings in a single pixel to the MODIS estimate; the more spatially heterogeneous a pixel, the less likely one central MODIS estimate accurately represents the varying concentrations across that pixel. Exploring the ability of MODIS to accurately estimate $PM_{2.5}$ concentrations and the limits of its capabilities for reflecting spatial variability trends is a critical task for evaluating the usefulness of satellite remote sensing in communities lacking ground-based monitoring.

METHODS:

Monitoring Program Overview

Ground-level monitoring was conducted at six different locations in the western suburbs of Atlanta, Georgia. Pixels which do not currently include any Georgia EPD ambient air monitors were selected as locations for this study. In total, twenty, 24-hour integrated samples were collected on relatively cloudless days. $PM_{2.5}$ sampling began on August 30, 2011 and ran through November 30, 2011. Figure 1 shows the location of the six monitoring sites (three sites per pixel).

Figure 1: Sampling Site Selections: Douglas, Cobb, and Fulton County
Two adjacent pixels selected for analysis. Triangle symbols represent the three sampling sites per pixel. Red square denotes sampler representing pixel centroid.



Site Selection

MODIS $PM_{2.5}$ data from the year 2007 was used to identify one pixel with a MODIS-driven estimated $PM_{2.5}$ concentration consistent with estimated average values in surrounding pixels ('average pixel') and one with an elevated MODIS-driven estimated $PM_{2.5}$ concentration ('elevated pixel') relative to its adjacent pixels. These two pixels were selected in order to explore the accuracy of their significantly different MODIS-driven $PM_{2.5}$ estimations. The two pixels are similar in setting and land usage; both cover areas in suburban Atlanta and do not contain any large point sources of pollution. Interstate-20 runs through the southernmost portion of both pixels, subjecting each pixel to presumably equivalent amounts of vehicular air pollution. It is possible, however, that the observed differences in the MODIS-driven $PM_{2.5}$ estimations exist due to a higher degree of spatial heterogeneity in the elevated pixel; a local pollution source at the centroid of the elevated pixel, for example, would give a higher MODIS-driven $PM_{2.5}$ estimation than what may be considered an accurate estimate for the rest of the pixel, while the average pixel may reflect more homogenous $PM_{2.5}$ concentrations throughout the entire pixel. Therefore, it is expected that the elevated pixel will have more heterogeneity among the three sites potentially due to a local point source near the centroid.

Ground-level Sampling Protocol

$PM_{2.5}$ samples were collected using personal environmental monitors (PEMs, SKC Inc.), 37mm Teflon filters, battery run pumps (SKC Inc., OEM), and gas flow meters. For protection, the pumps and gas meters were placed inside 13 x 9.5 x 8.75 inch coolers, and were connected to the PEMs via rubber tubing running to the outside of the coolers. The sampling platform elevated the PEMs one foot above the cooler lid. All sampling locations were sited in accordance with EPA's ambient monitoring siting criteria; all PEM inlets were placed between two and seven meters above the ground with 180° of unrestricted air flow (Watson, 1998). Samplers were set at least ten meters from the drip line of trees and at least two meters away from walls, buildings, and other structures. A sampler's distance to the nearest traffic lane was dependent upon a spatial scale and a daily average traffic count (Figure 2). The three sites within each of the 10 km^2 pixels were located at least 3 km apart in a pattern consistent with the direction of the prevailing winds: one in the southeastern corner, one at the centroid of the pixel, and one in the northwestern corner.

Figure 2: Sampler Placement Relative to Streets
Sampler distance to nearest traffic lane is dependent upon spatial scale and average daily traffic count (ADT); all samplers were placed to sample on the EPA 'urban scale' seen below (Watson, 1998).

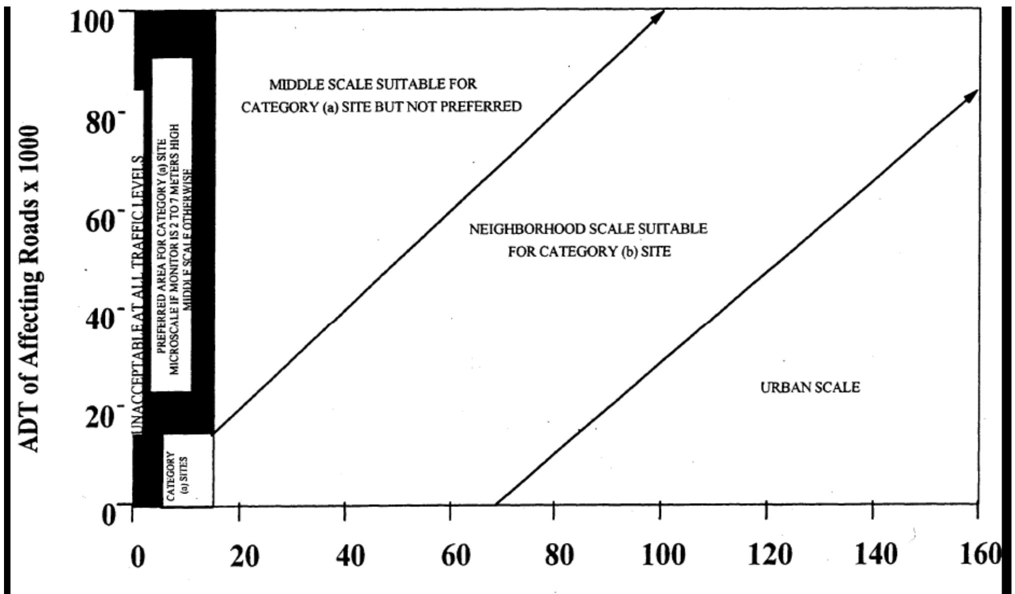


Figure E-1. Distance of PM samplers to nearest traffic lane (meters)

Samplers were deployed on relatively clear days to avoid satellite cloud cover and, thus, unsuccessful AOD retrieval. Samplers were set to start sampling at approximately 3:00 pm Eastern Time and run for 24 hours. BIOS flow calibrators were used to check and reset the flow rate to 4.0 L/min each sampling day. At each monitor, field technicians recorded the site location, filter number, time, meteorology, gas meter beginning and ending volumes, and miscellaneous notes; field notes are presented in the Appendix.

Gravimetric Analysis

Prior to sampling, all filters were dried and pre-weighed in humidity and temperature controlled clean room. Gloves, a face mask, and a full body suit were worn at all times in the particle-free room to avoid filter contamination. Filters were conditioned in glass chambers filled with silica gel, producing an environment with less than 10% relative humidity, for at least 24 hours. Prior to filter weighing, microbalance performance was verified using standard weights. All filters were weighed twice using a microbalance with a precision of ±5 μg. The average of the two weights was used in the analysis; repeated weights were all reproducible within 0.005 mg. The PEM filters were post-weighed in the particle-free room using a similar quality control protocol.

Quality Assurance/Quality Control

Data quality assurance procedures were implemented to ensure minimal contamination and error in both the field and laboratory handling of the samples. A set of 10 field blanks were collected throughout the six sampling sites. A Limit of Detection (LOD) was determined as three times the standard deviation of the mean of the blank filter concentrations. Completeness was calculated as the number of samples collected divided by the target number of samples.

MODIS Data Retrieval

A geographically weighted regression (GWR) model was developed to examine the relationship among concentrations of $PM_{2.5}$, AOD values, meteorological parameters, and land use information. $PM_{2.5}$ concentrations retrieved are 24-hour averaged and downloaded from the EPA's Air Quality System Technology Transfer Network. AOD observations were derived from MODIS on board both Terra and Aqua. Meteorological fields were obtained from North America Land Data Assimilation System (NLDAS). A 2006 Landsat-derived land cover map of the study area (suburban Atlanta) was downloaded from the National Land Cover Database (NLCD) to provide land use information. The results indicated that GWR combined with AOD, meteorological parameters, and land use information as the predictor variables, could generate a better fit than the traditionally utilized Ordinary Least Squares (OLS) method and achieve high accuracy in $PM_{2.5}$ concentration predictions.

Data Analysis

Descriptive statistics and graphical displays were used to characterize concentrations from the two pixels. In order to compare the two pixels, Spearman's correlation coefficients, mean differences from the centroid, and coefficients of divergence were calculated. Spearman's correlation coefficient was specifically used to determine the degree of linear association in $PM_{2.5}$ concentrations between site pairs. Coefficients of Divergence (COD) were used to define spatial heterogeneity. COD allows a degree of uniformity between two sites, *j* and *k*, to be formally calculated using the following equation:

$$\mathrm{COD}_{jk} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{x_{ij} - x_{ik}}{x_{ij} + x_{ik}}\right)^2}$$

where n is the number of observations, x_{ij} is the average concentration of $PM_{2.5}$ (i) at location j. COD approaches zero when the $PM_{2.5}$ concentrations across the two compared sites are relatively homogeneous and approaches one when the concentrations are heterogeneous. For the purposes of this study, CODs greater than 0.20 represent relatively heterogeneous concentrations between sites (Krudysz, 2008). Since a primary objective of this study is to compare concentrations of $PM_{2.5}$ across sites and pixels, descriptive statistics were conducted using data collected on days when results from all six sites were available. Estimates retrieved from MODIS were then compared to the three ground-level sites within corresponding pixels. All ground-level and MODIS data were analyzed using SAS version 9.3 (Cary, N.C.).

RESULTS and DISCUSSION:

Of the twenty sampling days, 95.2% of samples from six sites were successfully collected. Six samples were excluded due either to $PM_{2.5}$ concentrations measuring below the limit of detection (3.4 μg/m^3) (N = 3 samples), suspected filter contamination (N = 1 samples), or pump system failure (N = 2 samples). Descriptive statistics for each site are shown in Table 1.

Table 1: Full Data Descriptive Statistics
Observations with suspected contamination, malfunctioning pumps, or calculated under the limit of detection removed; *ALL other data included.* All concentrations expressed in μg/m^3.

Site	# Obs.	Mean	Std. dev.	Minimum	Maximum
ELEVATED					
Centroid	19	11.5	4.8	4.4	20.2
NW	19	11.9	5.3	4.3	22.5
SE	20	12.0	4.9	5.2	21.1
AVERAGE					
Centroid	19	15.0	6.1	6.1	26.1
NW	18	12.6	5.4	4.8	23.6
SE	19	12.9	6.2	4.4	30.5
MODIS					
Elevated	12	13.1	4.0	6.1	19.0
Average	11	12.4	5.1	5.2	21.9

In order to compare concentrations of $PM_{2.5}$ across sites and pixels, a matched analysis was conducted using only the data collected on days when results from all six sites were available. This resulted in a dataset containing fifteen sampling-days, each with a valid concentration from all six of the sites. Descriptive statistics for concentrations on these 15 days are presented in Table 2. All three elevated pixel sites averaged near 12.7 $\mu g/m^3$ with a standard deviation near 4.6 for the twenty day period. The average pixel exhibited greater variability in measured $PM_{2.5}$ during the twenty day averages across the three sites. The mean difference between the ground-level monitors and the centroid is also provided in Table 2; this statistic provides a simple method of quickly determining how different, on average, the southeast and northwest ground-level concentrations are from the centroid based ground-level concentrations. Both non-centroid locations in the average pixel differed from the centroid far more than they did in the elevated pixel, suggesting that the average pixel contained more spatially variable concentrations than the elevated pixel. Figures 3 and 4 provide an additional overview of the $PM_{2.5}$ concentrations from the six sites during the 15 days with complete results.

Table 2: Elevated and Average Pixel Descriptive Statistics
Observations under the limit of detection removed; *Only 15 sampling days with no missing ground-level data included.* All concentration values expressed in μg/m[3].

Site	# Obs.	Mean	Std. dev.	Minimum	Maximum	Mean Diff w/Centroid
ELEVATED						
Centroid	15	12.7	4.6	4.4	20.2	
NW	15	12.8	4.6	5.6	20.8	0.1
SE	15	12.7	4.5	5.2	20.8	0.0
AVERAGE						
Centroid	15	15.5	6.2	6.1	26.1	
NW	15	13.1	5.6	4.8	23.6	-2.4
SE	15	12.7	4.7	4.4	20.2	-2.8

Figure 3: Integrated 24-Hour $PM_{2.5}$ Concentrations for All 3 Elevated Pixel Sites
Observations under the limit of detection removed; *Only 15 sampling days with no missing ground-level data included.*

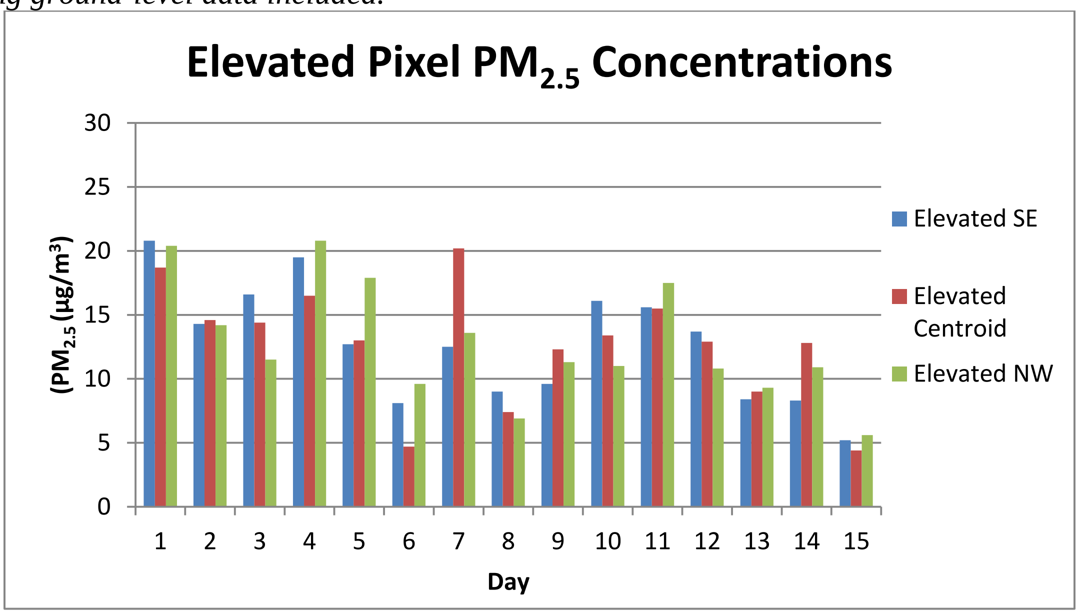
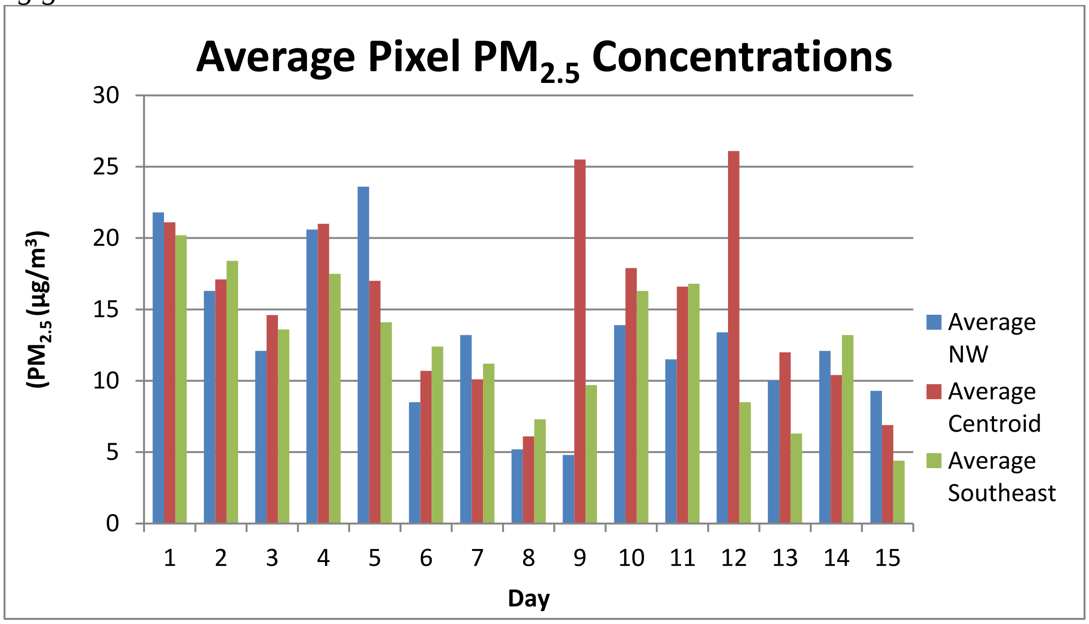


Figure 4: Integrated 24-Hour $PM_{2.5}$ Concentrations for All 3 Average Pixel Sites
Observations under the limit of detection removed; *Only 15 sampling days with no missing ground-level data included.*



Of the 15 matching ground-level sampling days, only 8 had corresponding successful retrieval data from MODIS. Despite efforts to sample on 'relatively cloud-free days', unsuccessful satellite retrieval was most likely due to periodic cloud cover during Terra and Aqua overpass time or high surface reflectivity. However, the 53% retrieval rate seen in the current study is considered quite successful; on average, only 11% of days per month have been shown previously to contain successful MODIS AOD retrieval (Paciorek et al., 2008).

Since MODIS measures AOD at a pixel's centroid, we assessed accuracy by comparing the MODIS estimate with measured centroid values in each of the two selected pixels. Results, presented in Figures 5 and 6 show that there were insignificant differences between the elevated/average centroid $PM_{2.5}$ means and the MODIS means (P = 0.33, 0.21, respectively). Average centroid and MODIS estimates are highly correlated

(Spearman's *R* = 0.75, *P* = 0.007), while the elevated pixel's centroid and MODIS estimates are less correlated (Spearman's *R* = 0.52, *P* = 0.08). The strength of correlation seen in the average pixel is consistent with other studies and is indicative of MODIS accuracy in centroid $PM_{2.5}$ estimations (Alston, 2011; Cox, 2004).

Figure 5: Elevated Pixel's Centroid vs. MODIS-driven Estimates
To assess MODIS accuracy, ground-level measurements were taken at the elevated pixel centroid and compared to MODIS estimates here.
Spearman's *R* = 0.52 (*P* = 0.08)

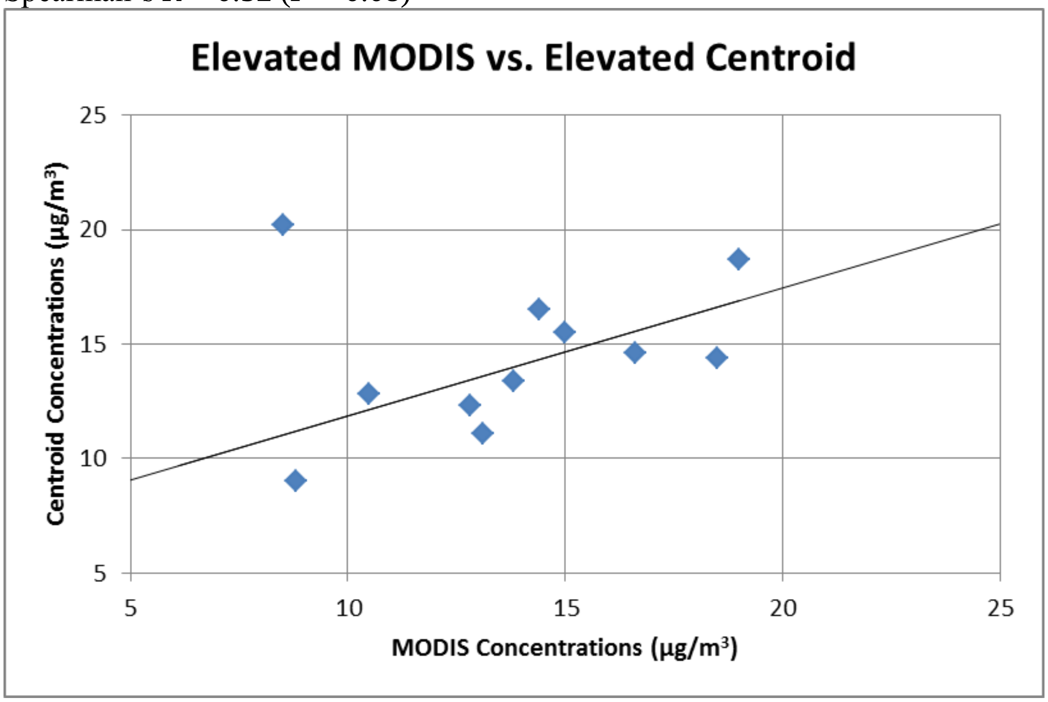


Figure 6: Average Pixel's Centroid vs. MODIS-driven Estimates
To assess MODIS accuracy, ground-level measurements were taken at the average pixel centroid and compared to MODIS estimates here.
Spearman's *R*: 0.75 (*P* = 0.007)

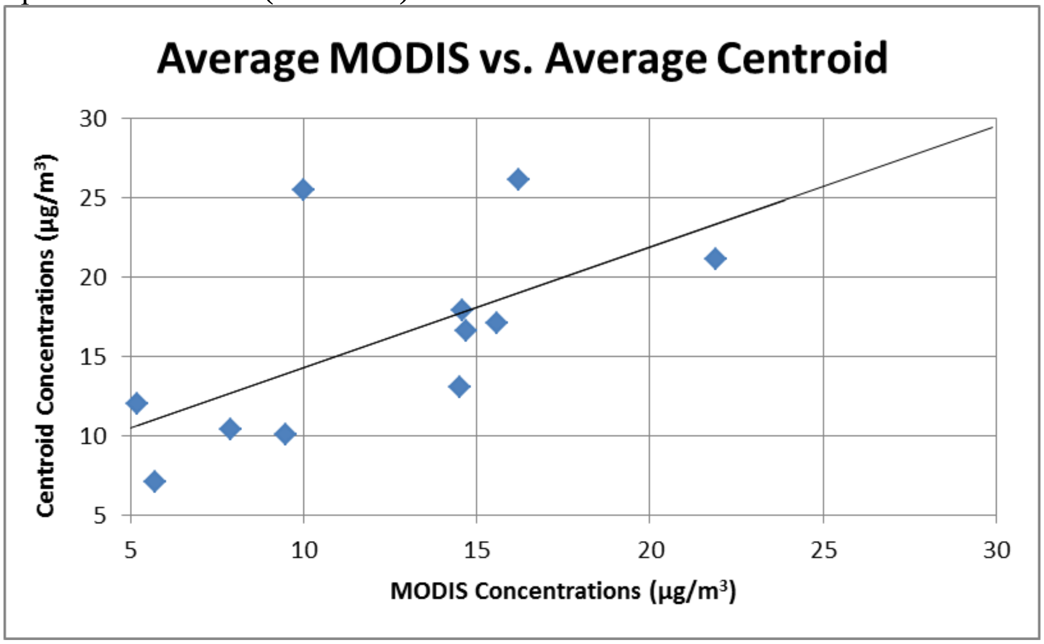


Table 3 presents the descriptive statistics for all 8 days with complete results (ground-level and MODIS). Even with this limited data set, it is apparent that the average pixel contained greater variance in concentration means among sites. MODIS $PM_{2.5}$ estimates are also added into Figures 7 and 8.

Table 3: MODIS, Elevated and Average Pixel Descriptive Statistics
Observations under the limit of detection removed; *Only 8 sampling days with no missing MODIS or ground-level data included.* All concentration values expressed in μg/m^3.

Site	# Obs.	Mean	Std. dev.	Minimum	Maximum
ELEVATED					
Centroid	8	14.6	3.6	9.0	20.2
NW	8	13.5	3.8	9.3	20.4
SE	8	13.2	4.4	8.3	20.8
AVERAGE					
Centroid	8	16.3	5.4	10.1	25.5
NW	8	13.0	4.9	4.8	21.8
SE	8	14.0	4.7	6.3	20.2
MODIS					
Elevated	8	13.1	3.7	8.5	19.0
Average	8	12.4	5.3	5.2	21.9

Figure 7: Elevated MODIS and Ground-Level 24-hour $PM_{2.5}$ Concentrations
Observations under the limit of detection removed; *Only 8 sampling days with no missing elevated pixel MODIS or ground-level data included.*

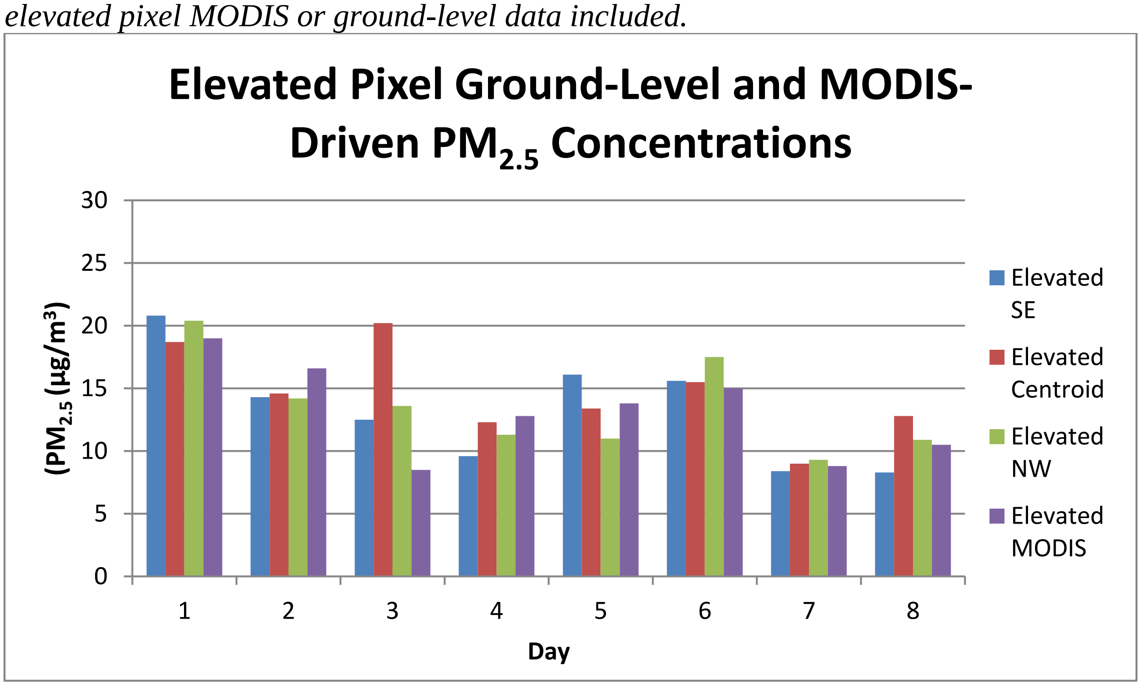
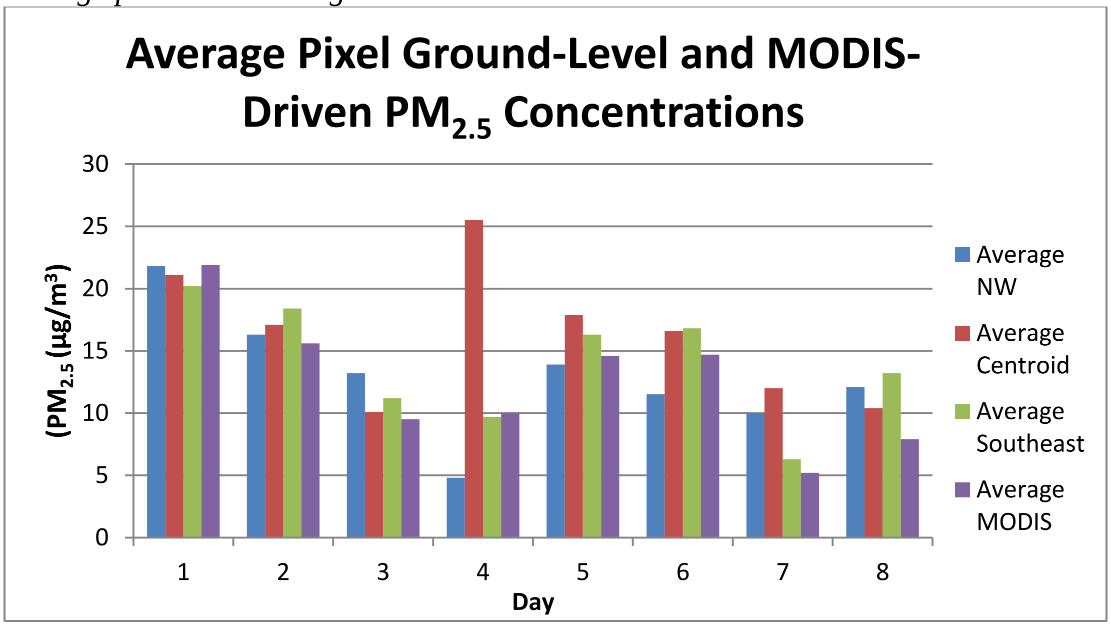


Figure 8: Average MODIS and Ground-Level 24-hour $PM_{2.5}$ Concentrations
Observations under the limit of detection removed; *Only 8 sampling days with no missing average pixel MODIS or ground-level data included.*



There were pronounced between-pixel spatial differences in $PM_{2.5}$ concentrations (Table 4). Within the elevated pixel however, all but one of the pairwise Spearman's correlation coefficients were well above values indicative of strong correlation (>0.60), suggesting that the $PM_{2.5}$ means across MODIS and the three sites were temporally similar. Spatiotemporal homogeneity in $PM_{2.5}$ concentrations across the elevated pixel sites is confirmed as none of the pairwise CODs were found to have values above 0.20, which is indicative of heterogeneity. The average pixel, however, was far more heterogeneous. While all but two of the Spearman's correlation coefficients still imply moderate to strong temporal correlation, the correlations are noticeably weaker than those in the elevated pixel. Similarly, all but two of the CODs are indicative of spatial heterogeneity among the average pairwise ground-level concentration estimates.

Table 4: Coefficient of Divergence (COD) – Spearman's Correlation Coefficient Matrix for All Ground-Level and MODIS Estimates
Pairwise Spearman's Correlation Coefficient (top half) as a predictor of Pairwise Coefficient of Divergence (bottom half). Spearman's $R > 0.60$ indicative of strong correlation between site $PM_{2.5}$ concentrations; COD > 0.20 indicative of heterogeneity in $PM_{2.5}$ concentration.

		ELEVATED				AVERAGE			
		Centroid	NW	SE	MODIS	Centroid	NW	SE	MODIS
ELEVATED	Centroid		0.90	0.86	0.52	0.56	0.73	0.77	0.62
	NW	0.049		0.85	0.70	0.70	0.76	0.88	0.65
	SE	0.039	0.015		0.87	0.74	0.69	0.84	0.87
	MODIS	0.151	0.048	0.009		0.67	0.50	0.84	0.94
AVERAGE	Centroid	0.384	0.329	0.344	0.288		0.49	0.60	0.75
	NW	0.047	0.002	0.008	0.061	0.307		0.74	0.65
	SE	0.001	0.046	0.032	0.059	0.362	0.036		0.70
	MODIS	0.297	0.193	0.136	0.144	0.420	0.074	0.204	

Overall, the results showed that the degree of spatial homogeneity was greater in the 'elevated pixel'. In contrast, there was considerable spatial heterogeneity among the three ground-level sites in the 'average' pixel. This finding suggests that atmospheric remote sensing with a spatial resolution similar to MODIS may be unable to accurately estimate spatiotemporal variability of $PM_{2.5}$ concentrations for a pixel of this size, as $PM_{2.5}$ concentrations can vary greatly across 10 km^2.

Importantly, these data may not be generalizable to all years; spatial patterns between the years 2007 and 2011 may have changed, as is suggested by results that are contrary to our prior hypothesis. GWR values from 2007 displayed much higher average $PM_{2.5}$ concentrations in the 'elevated' pixel compared to the 'average' pixel, despite the pixel similarities in terms of layout, suburban design, and estimated traffic pollution exposures. This initial MODIS data led to the expectation of more spatial heterogeneity among the 'elevated' pixel, giving rise to the possibility that an inaccurately high AOD snapshot was taken from the centroid, while the rest of the pixel had $PM_{2.5}$ concentrations similar to the 'average' pixel. During this field study conducted in 2011, we observed the exact opposite phenomenon.

The average pixel displays much more overall spatial heterogeneity between all pairwise sites and MODIS predictions. The spatial heterogeneity between sites just 3 km away may imply that current standard MODIS pixel sizes are too large to assign just one, central $PM_{2.5}$ concentration estimate. The unanticipated degree of variability in concentrations across the average pixel may be due to land use changes or unknown point sources of pollution which were not present prior to 2007. While the findings were opposite from what was hypothesized *a priori*, the results still support the general hypothesis that a pixel sized 10 km^2 experiences a large spatiotemporal variation in $PM_{2.5}$ concentrations that current MODIS instrumentation may fail to capture.

There are a number of limitations of this analysis mostly due to sample size. Due to a rather cloudy fall, only twenty weekdays during the study period were deemed 'relatively cloud-free'. MODIS was also unable to capture nearly half of the data needed for those twenty days, leaving the complete sample size with 64 data points (for each of the 8 days, 6 separate site samples and 2 MODIS estimates).

These results are consistent with previous studies which show that AOD values estimated by MODIS driven-data are correlated with ground-level $PM_{2.5}$ concentrations in Atlanta, GA (Alston, 2011; Engel-Cox, 2004). Many of these studies, however, utilized EPA ambient air monitors from PM data, eliminating the possibility of recreating those studies in remote, rural, or even suburban areas unequipped with EPA monitors. To date, there have not been any studies that analyzed multiple ground-level $PM_{2.5}$ concentrations in a single pixel. With this particular study design, it was possible to determine not only the accuracy of MODIS, but also its ability to capture true heterogeneity among a standard 10 km x 10 km pixel.

CONCLUSION

$PM_{2.5}$ poses a threat to human health which demands implementation of emission and ambient air quality standards. However, current ground-level ambient air monitoring systems only provide $PM_{2.5}$ concentration data for communities near the monitors. Clearly, monitors lack spatial coverage across rural, suburban, and even urban areas, necessitating the use of remote sensing in air quality monitoring. Exploring the MODIS ability to accurately estimate $PM_{2.5}$ concentrations can be extremely helpful for public health scientists assessing air quality in communities lacking ground-based monitors.

The primary research goal was to determine the ability of the NASA MODIS satellite instrument to detect spatial heterogeneity in particulate matter (specifically, $PM_{2.5}$) concentrations across a standard pixel size. Previous studies have shown that AOD is correlated with $PM_{2.5}$ concentrations; however, it is not yet understood how well the satellite-driven $PM_{2.5}$ estimate represents a large pixel.

To date, there have not been studies comparing multiple ground-level $PM_{2.5}$ estimates per pixel to MODIS data. By comparing three ground-level measurements per pixel, it was possible to not only determine the accuracy of MODIS $PM_{2.5}$ estimates, but it was also possible to determine how much $PM_{2.5}$ spatial heterogeneity a 10 km x 10 km pixel likely experiences; the more spatially heterogeneous a pixel, the less likely one central MODIS estimate accurately represents the varying concentrations in that pixel. The current study found that 10 km^2 is certainly a large enough area to find significant heterogeneity in $PM_{2.5}$ concentrations.

The ability to determine average $PM_{2.5}$ concentrations in point-specific communities across the globe with MODIS instrumentation will allow environmental health scientists to more easily estimate personal and population $PM_{2.5}$ exposures. For the first time, exposure scientists may be able to determine average exposures of people in living in rural and suburban areas without the use of additional personal monitoring. This $PM_{2.5}$ data will be valuable for epidemiological studies evaluating associations with morbidity and mortality. It will also allow environmental health scientists and public health regulators to locate specific point sources of pollution, thus alleviating issues associated with standard compliance.

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APPENDIX

1. Letter to Participating Sampling Locations:

EMORY | ROLLINS SCHOOL OF PUBLIC HEALTH

ROLLINS SCHOOL OF PUBLIC HEALTH AT EMORY UNIVERSITY

Title: Satellite-Driven Spatial Model for Tracking: Enhancing Environmental Public Health Tracking with Satellite-Driven Particle Exposure Modeling and Epidemiology

Invitation and Purpose

We would like permission to sample at your facility in a research study. This study validates the accuracy of satellite sensors which can detect ground-level air pollution. The pollutant of focus in this study, particulate matter, is associated with respiratory and cardiovascular disease.

Sponsors

The National Aeronautics and Space Administration (NASA) is the sponsor of this project.

Procedures

We will visit your facility about fifteen days from July through September. It is difficult to determine exactly which days we will visit your site, as sampling procedures are largely depicted by the daily weather.

During a general sampling day, the technician will set up the equipment in the pre-approved location; the sampler will run for the next 24 hours. Upon completion of the sampling duration, the technician may return to change a filter in the sampler or may take the sampler down. The Technician will be present for no more than thirty minutes at a time.

The technician will work with you to place the air pollution sampler in an area that is unobtrusive and safe for both students and staff.

Additional Information for Volunteers

No direct benefit will come to you as a result of participating in this study. If you wish, you may be provided information about the results of the study.

Our collected information about air pollution levels at your facility will be strictly confidential. The investigators will make every effort to keep information identifying your facility private.

Recognize that your participation in this study is completely voluntary and that you are free to withdraw this consent and to discontinue participation in this project at any time.

Questions/Contacts

If you have questions about this study, you may contact Jeremy Sarnat, ScD., 404-712-9725, jsarnat@sph.emory.edu or Erika Rees, erika.rees@emory.edu, in the Department of Environmental Health at the Rollins School of Public Health of Emory University.

Signature

If you agree to participate in this study, please sign below. You will receive a copy of this form.

_________________________________ _____________________________

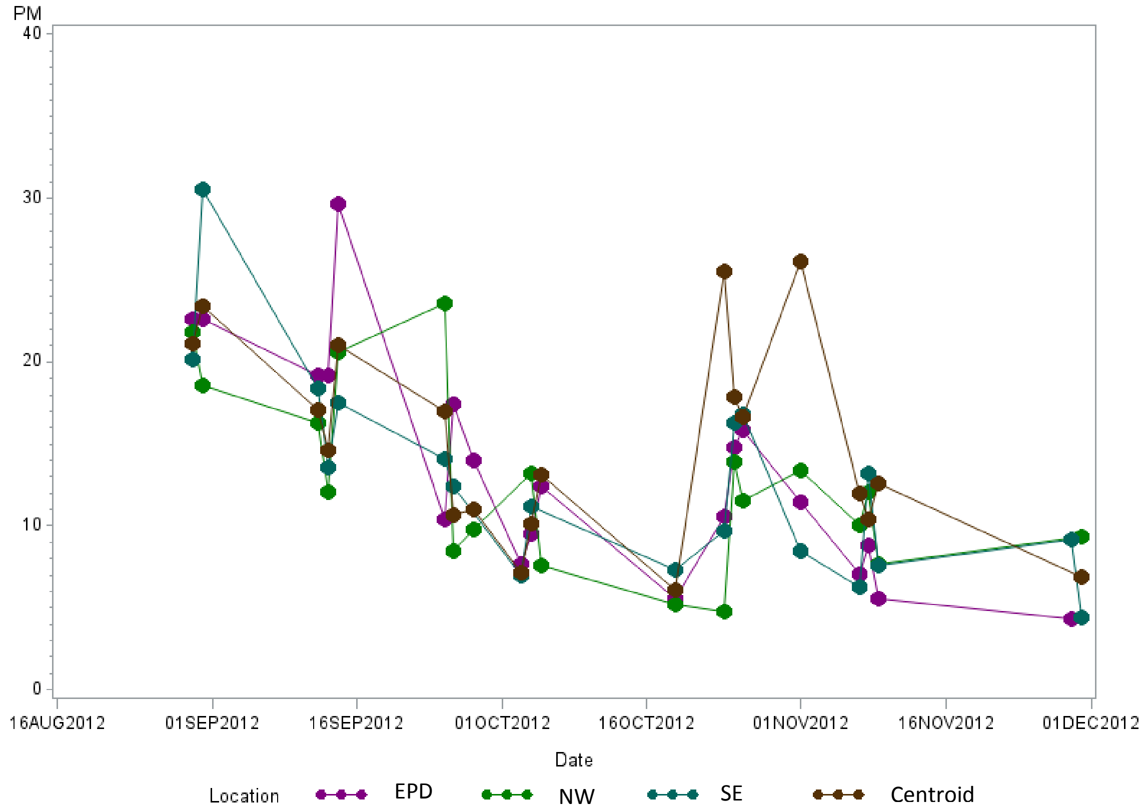
Facility Manager Signature and Date Investigator Signature and Date

2. Sample of NASA ROSES- Atlanta Field Sampling Log Sheet

		START OF SAMPLING					END OF SAMPLING					
Filter ID	Site	Date (mm/dd/yy)	DoW	Time	BIOS flow (LPM)	Gas Meter Reading	Date (mm/dd/yy)	DoW	Time	BIOS flow (LPM)	Gas Meter Reading	Notes (Meteorology, Site/Equipment Status, etc.)
255	Col. Hills	9/13/11	T	AM 2:30PM	4.06	4774.5	9/14/11	W	AM 2:49 PM	4.17	5016.5	
254	Gospel Nation	9/13/11	T	AM 3:00PM	4.02	3798	9/14/11	W	AM 3:20 PM	4.18	4046.4	
261	Praise Acad.	9/13/11	T	AM 3:20PM	4.04	4595.5	9/14/11	W	AM 3:40 PM	4.06	4832.5	
292	Col. Hills	9/14/11	W	AM 2:50 PM	4.00	5017.0	9/15/11	R	AM 2:30PM	4.32	5260.5	Hot/Dry, 90 deg F
290	Gospel Nation	9/14/11	W	AM 3:23 PM	4.04	5803.9	9/15/11	R	AM 2:50PM	4.22	5967.8	' ; Had to replace cooler- battery clip broke
289	Praise Acad.	9/14/11	W	AM 3:44 PM	4.02	4833.2	9/15/11	R	AM 3:05PM	3.99	5057.7	'
242	Milford	9/13/11	T	AM 3:50PM	4.03	6046.5	9/14/11	W	AM 4:14 PM	3.99	6277.4	'
241	Vinings	9/13/11	T	AM 4:10PM	4.04	4598.6	9/14/11	W	AM 4:46 PM	3.85	4825.5	'
256	Primrose	9/13/11	T	AM 4:25PM	4.03	3822.7	9/14/11	W	AM 5:15 PM	3.99	4046.0	'
291	Milford	9/14/11	W	AM 4:18 PM	4.05	6277.9	9/15/11	R	AM 3:35PM	4.11	6505.9	88 deg F, 46% RH
252	Vinings	9/14/11	W	AM 4:50 PM	3.99	4826.1	9/15/11	R	AM 3:50PM	4.04	5046.1	'
288	Primrose	9/14/11	W	AM 5:28PM	4.01	4046.1	9/15/11	R	AM 4:10PM	3.99	4264.1	'

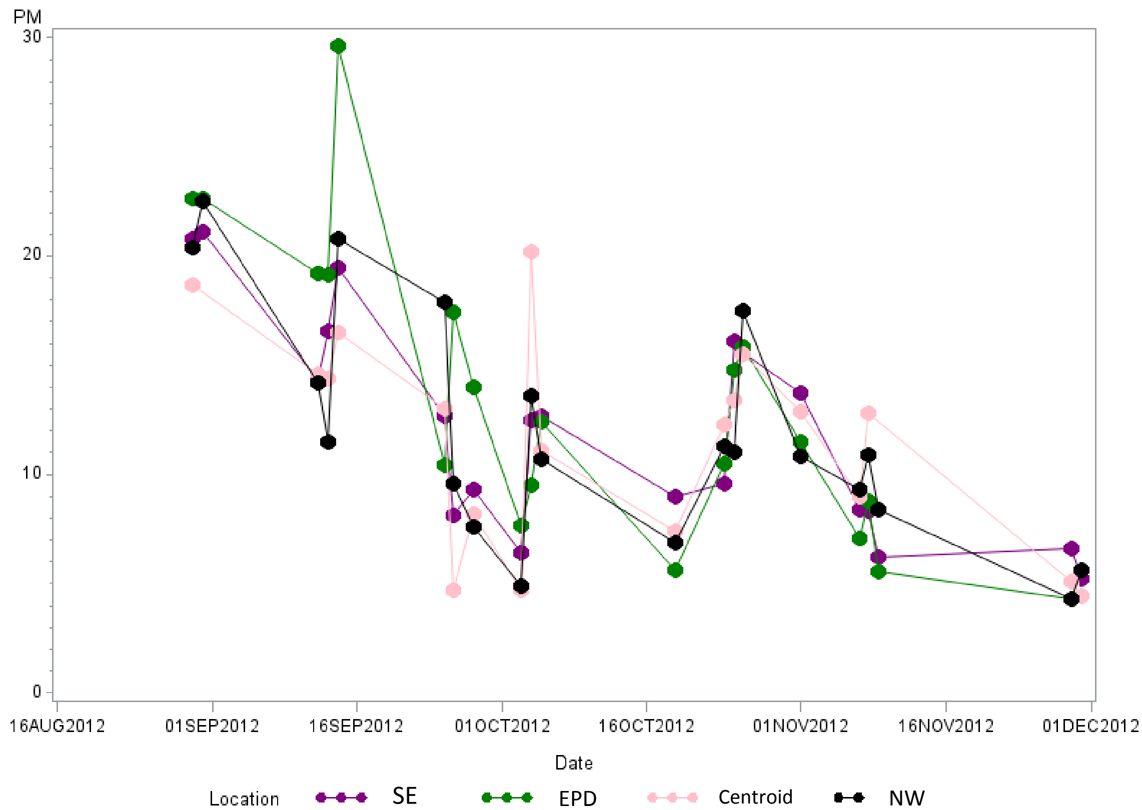
3. Average Pixel Time Series

Time series of all three average pixel sites with the closest Georgia Environmental Department ambient air monitor (CONFDAVE monitor, all QAQC Data).



4. Elevated Pixel Time Series

Time series of all three elevated pixel sites with the closest Georgia Environmental Department ambient air monitor (CONFDAVE monitor, all QAQC Data).



5. Images from the Field and Lab

Sampling equipment (battery-operated pump and gas meter in protective cooler) at a field site

Flow Calibration in the field.

Drying chamber with filters and hygrometer/thermometer