SPATIAL MODELING AND MONITORING OF RESIDENTIAL WOODSMOKE ACROSS A NON-URBAN UPSTATE NEW YORK REGION

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NEW YORK STATE
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Final Report

Prepared for the
**NEW YORK STATE
ENERGY RESEARCH AND
DEVELOPMENT AUTHORITY**
Albany, NY
www.nyserda.org

Ellen Burkhard, Ph.D.
Senior Project Manager

Submitted by:
**NORTHEAST STATES FOR COORDINATED AIR USE MANAGEMENT
(NESCAUM)**
Boston, MA

Paul J. Miller, Ph.D.
Project Manager

George Allen
Co-investigator

Lisa Rector
Co-investigator

Prof. Michael Brauer, Sc.D.
School of Environmental Health
University of British Columbia, Vancouver
Co-investigator

Jason Su, Ph.D.
University of California, Berkeley
Co-investigator

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ABSTRACT AND KEYWORDS

This study evaluates the effect of wood combustion on local air quality in the Adirondacks of New York. The study approach uses topography, census data, property assessments, and other relevant publicly accessible databases as inputs into a geographic information system model. The model provides a map of predicted woodsmoke fine particulate matter ($PM_{2.5}$) spatial variability across the study region. The study's focus is on woodsmoke $PM_{2.5}$ because it is a key air pollutant affecting public health in New York State for which public exposure assessments are lacking.

The predicted spatial pattern of woodsmoke $PM_{2.5}$ was compared to observed ambient levels. A monitoring field campaign collected ambient data using a method that discriminates woodsmoke from other combustion sources. The monitoring results show that most of the $PM_{2.5}$ measured in the Adirondacks during the study comes from wood combustion.

The model coupled with the monitoring field campaign demonstrates that U.S. census information can be combined with additional survey and property assessment data to provide a broadly applicable estimate of woodsmoke spatial patterns and population exposure in the Adirondacks. This approach is a promising method for screening potential woodsmoke problem areas in complex terrains across the Northeast and elsewhere in the U.S.

Keywords: air monitoring, emissions, fine particulate matter, geographic information system, wood combustion

PREFACE

The New York State Energy Research and Development Authority is pleased to publish "Spatial Modeling and Monitoring of Residential Woodsmoke Across a Non-Urban Upstate New York Region." The report was prepared by the Northeast States for Coordinated Air Use Management (NESCAUM). The Principle Investigator was Paul Miller, Ph.D. with Co-investigators George Allen and Lisa Rector. Spatial modeling was performed by Michael Brauer, Sc.D. of the University of British Columbia and Jason Su, Ph.D. of the University of California, Berkeley

This study evaluates the effect of wood combustion on local air quality in the Adirondacks of New York. It employs both a field monitoring campaign capable of discriminating woodsmoke from other particulate matter and spatial modeling to evaluate the effect of complex terrain on wood smoke patterns. In doing so, this report develops a promising method for near-source emissions estimates for wood smoke using readily available information. Woodsmoke is a major source of organic particulate matter in New York State and as seen in this report woodsmoke can have very high localized concentrations.
NYSERDA's Biomass Heating Program is a joint effort of the Environmental R&D and Building R&D Programs to develop a high-efficiency biomass heating market of technologies with acceptable emissions performance in New York State.

ACKNOWLEDGEMENTS:

This research was supported by the New York State Energy Research and Development Authority. NYSERDA appreciates the input of project advisors: Dirk Felton, New York State Department of Environmental Conservation; Judith Abbott, Ph.D., New York State Department of Health; Judith Schreiber, Ph.D., New York State Office of the Attorney General; Roy Huntley, U.S. Environmental Protection Agency; and Philip Johnson, Heinz Foundation.

The authors would like to thank Richard Lamica, Dr. Utpal Roychowdhury, and Professor Ken Demerjian, Atmospheric Sciences Research Center, University of Albany, State University of New York (SUNY), for support of north loop field operations, Ed Burgher of Magee Scientific Inc., for loan of equipment and support of south loop field operations, and Perry Hystad, UBC School of Population and Public Health, for linkage of the property tax assessment data. We also wish to thank the New York State Department of Health, the New York State Department of Environmental Conservation (NYS DEC), and the New Jersey Department of Environmental Protection for loan of equipment. Finally, we especially thank Bob Gaza, John Kent, Vito Pagnotti, and Greg Playford of NYS DEC for providing forecasting support during the project.

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EXECUTIVE SUMMARY

Background on Woodsmoke in New York State

Woodsmoke may be thought of as natural, hence “benign,” but there is ample evidence that wood burning emits significant quantities of known health damaging pollutants, including fine particulate matter ($PM_{2.5}$), carbon monoxide, nitrogen oxides, and a number of known carcinogens, including benzene and polycyclic aromatic hydrocarbons. According to the U.S. Environmental Protection Agency (U.S. EPA), $PM_{2.5}$ is the largest health threat from woodsmoke. Health damages associated with $PM_{2.5}$ exposure include respiratory and cardiac mortality, lung function decrements, exacerbation of lung disease, lung cancer, and developmental and immunological effects. A large percentage of the general population (upwards of 50%) is susceptible to adverse health impacts as a result of acute and chronic $PM_{2.5}$ exposure, including children, asthmatics, persons with respiratory or heart disease, diabetics, and the elderly.

In a 2008 report prepared for the New York State Energy Research and Development Authority (NYSERDA), the Northeast States for Coordinated Air Use Management (NESCAUM) reviewed the state of knowledge of the carbonaceous component of $PM_{2.5}$ in New York State, of which woodsmoke is an important component. NESCAUM found that carbonaceous aerosols are a sizeable fraction of $PM_{2.5}$ mass in New York State (between a fourth and a third of total $PM_{2.5}$ mass on an annual basis), and much of the aerosol comes from sources within New York State. Residential wood combustion in New York is an important source category for carbonaceous aerosols, especially in rural counties where residential wood combustion is responsible for almost all (>90%) of carbonaceous $PM_{2.5}$ emissions (Figure ES-1). This is important from a public health perspective because even small towns and villages situated in predominately rural areas of New York can have relatively high population densities that are exposed to woodsmoke.

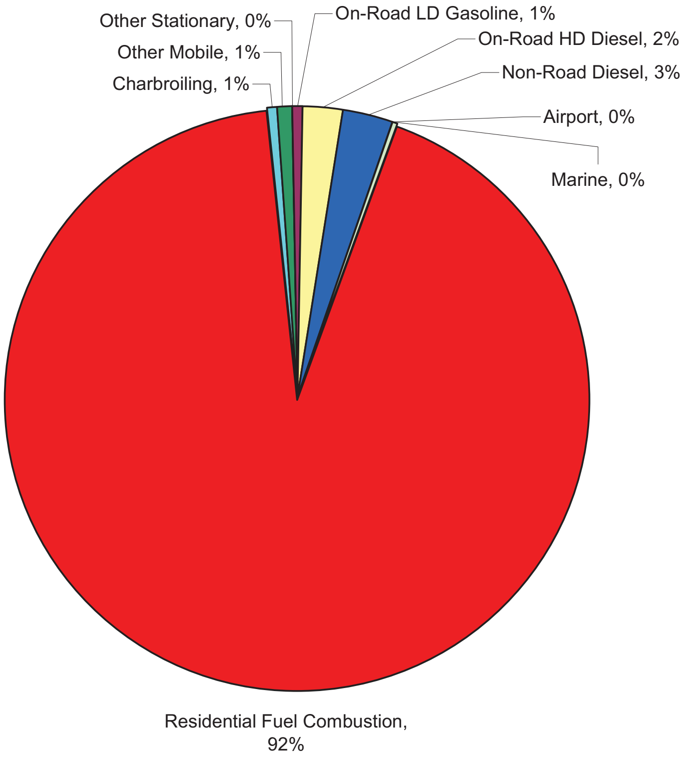

Figure ES-1. Relative contribution of source sectors to total carbonaceous $PM_{2.5}$ in three rural counties of New York State. "Residential Fuel Combustion" is primarily wood use.

Adding to the concern over health impacts from wood combustion is the increasing popularity of wood-fired heating appliances in New York State, both in rural areas as well as in more suburban and urban areas. Relative to oil and gas-fired furnaces, most conventional wood burning devices (e.g., conventional and EPA-certified wood stoves, outdoor wood boilers) used in residential settings are gross emitters of $PM_{2.5}$ pollution. Higher performing wood burning devices are feasible and used in Europe, but are not yet commonplace in New York State.

Volatile fuel prices may have a significant influence on home space heating choices and the level of woodsmoke emissions. Heating oil prices in the Northeast doubled from 2006 to 2008, going from about $2.00 per gallon in 2006 to a peak of just over $4.00 per gallon during 2008, before returning to about $2.00 per gallon in November 2009. Such large swings in heating oil prices could potentially lead to fuel choice shifts towards relatively higher polluting wood combustion devices. Of special note is the rising prevalence of outdoor wood boilers (OWBs) used to provide residential heat in New York State. According to a 2008 report by the New York State Office of the Attorney General (OAG), OWB sales in New York have tripled since 1999, with an estimated 14,500 OWBs sold in the state from 1999 to 2007.

Based on $PM_{2.5}$ emissions testing on a grams per hour basis, unregulated OWBs emit almost four times more $PM_{2.5}$ air pollution than conventional wood stoves, 12 times more than EPA-certified wood stoves, 1000 times more than oil furnaces, and 1800 times more than natural gas furnaces. With the increasing popularity of OWBs and their higher emissions, the OAG has received as of January 2008 over 50 complaints from individuals affected by pollution from the units, and over 60 New York communities have moved to regulate or ban OWBs.

While there is a large body of health studies indicating woodsmoke exposure is a health risk, studies specific to New York State and the Northeast are limited. In light of its relative importance to overall carbonaceous $PM_{2.5}$ emissions in New York, residential wood combustion may pose a seasonal exposure risk during wintertime in areas where terrain and meteorology contribute to poor dispersion of pollutants. Therefore, a key recommendation from the 2008 NYSERDA report is a call for exposure assessment of populations in proximity to residential wood combustion emissions in densely populated villages, towns, and small cities, and areas where meteorology and terrain are conducive to high pollutant concentrations.

Challenges in Assessing Woodsmoke Impacts

A key problem in assessing woodsmoke conditions in non-urban New York State is that the location of wood burning sources is compounded by landscape features (e.g., Adirondack valleys). These features can create significant $PM_{2.5}$ spatial variability, including “hotspots,” on top of regional $PM_{2.5}$ contributions. State ambient air pollution monitoring networks are typically not dense enough, particularly outside of urban areas, to capture fully spatial variability. In addition, the air monitors only measure total $PM_{2.5}$ mass, thus do not distinguish woodsmoke from other components making up the total $PM_{2.5}$ burden in the air.

In addition to the sparse air monitoring network, there is an accompanying lack of sufficiently detailed information on the location and activity levels of wood burning appliances. This is true not only for New York State, but for the larger northeast region and nation as well.

Building a Foundation for Improved Woodsmoke Assessments

The study described in this report seeks to develop a relatively easy-to-use modeling tool for health and environmental agencies that can screen spatially large non-urban regions in New York State (and elsewhere) to assess the potential impacts of residential wood burning on local air quality. With this in mind, the study set out to address four objectives:

1. **Develop a modeling tool that provides a reasonable representation of woodsmoke spatial variability in a non-urban setting in light of relatively sparse air monitoring data and incomplete emissions source information.**

2. **Apply the modeling tool to a complex topographical region to test its capabilities in providing useful information for air quality and health planning needs.**
3. **Explore the limitations of the modeling tool, and recommend possible improvements in the approach.**
4. **Identify potential applications of the monitoring and modeling techniques used in this study that can help address air quality and public health planning needs.**

The approach described in this report applied an innovative geographic woodsmoke model that exploits topography, census data, and other relevant publicly accessible databases to map woodsmoke emissions in the Adirondacks of New York. This modeling technique was developed in the Pacific Northwest/British Columbia, and has been adapted for the non-urban upstate New York region that includes the counties of Essex, Fulton, Hamilton, Warren, Herkimer, Saratoga, Franklin, and Montgomery. The modeling results are compared and refined with ambient air quality data collected during a special-purpose field campaign using an air monitoring technique shown to discriminate woodsmoke from other combustion sources.

The study proceeded in four steps:

1. An initial woodsmoke emissions surface map was developed using publicly available data sources (e.g., U.S. Census data, property assessment data, wood heating appliance manufacturer shipment records, published surveys of wood combustion activity).
2. Candidate fixed monitoring sites and mobile monitoring routes were identified using a location-allocation algorithm applied to the initial woodsmoke emissions map. The intent was to monitor across the region in a manner that captures to the fullest extent possible a wide range of predicted spatial variability in woodsmoke emissions.
3. Fixed and mobile monitoring at sites and along routes identified from the location-allocation algorithm applied in step 2 were conducted using an ambient monitoring technique capable of discriminating woodsmoke from other $PM_{2.5}$ components in the ambient air.
4. Using the collected monitoring data (mobile monitoring in particular) of step 3, the initial woodsmoke emissions surface map of step 1 was refined by temporally correcting for between-day differences, and applying a hydrological catchment technique to estimate upslope distances influencing woodsmoke levels at downwind locations. Three spatial model options were mapped using predictor variables (e.g., median household income, elevation, wood heating appliance density) to determine their relative power in predicting woodsmoke spatial variability compared to the monitoring results.

Overview of Woodsmoke Monitoring Results

This study collected ambient woodsmoke monitoring data using a combination of fixed monitoring sites operated continuously throughout the study period and a mobile monitoring method conducted on 10 evenings forecasted to be favorable for woodsmoke accumulation in the Adirondacks. Figure ES-2 displays the northern portion of the study region along with a trace of the vehicle route taken during 10 selected evenings to collect mobile monitoring data.

Figure ES-2. North loop mobile monitoring route.

Analyses of the collected woodsmoke monitoring data revealed the following:

- Woodsmoke was the primary source of $PM_{2.5}$ observed during this study, and it was also the primary source of the spatial variability of $PM_{2.5}$ concentrations.
- The highest woodsmoke levels typically occur around midnight, and the lowest levels usually occur around noon.
- The highest woodsmoke concentrations are present mainly in towns, although there are examples of woodsmoke between towns (e.g., Elizabethtown to Port Henry). (Figure ES-3 displays the results from a typical mobile monitoring run obtained during this study.)
- In high elevation areas between towns, $PM_{2.5}$ levels (including woodsmoke) go to essentially zero; this represents regional background concentrations.

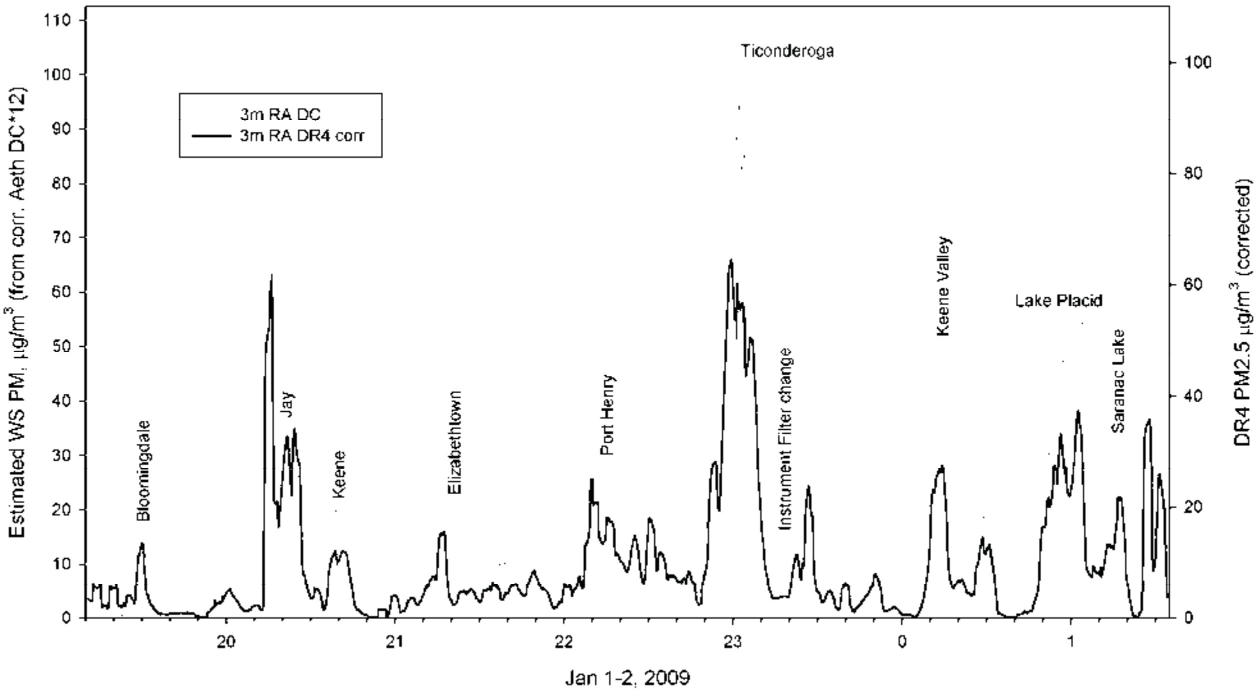

Figure ES-3. Plot of 3-minute running averages of estimated woodsmoke levels obtained during the January 1-2, 2009 north loop run.

- Very high spikes in woodsmoke concentrations (>100 micrograms per cubic meter over the course of several minutes) were seen at times during the nighttime mobile monitoring. These spikes suggest that the nearby presence of wood burning emits a significant amount of $PM_{2.5}$ locally.
- From a public health perspective, high spikes in woodsmoke $PM_{2.5}$ may be cause for concern. Research studies have found associations between short period $PM_{2.5}$ peaks (minutes to hours) and acute cardiovascular and respiratory events, including myocardial infarction in older adults and asthma symptoms in children.
- Short-term spikes in woodsmoke $PM_{2.5}$ may be associated with individual residential wood burning devices, such as outdoor wood fired boilers. The potential role of these wood burning devices in producing such high short-term spikes in $PM_{2.5}$ warrants further investigation.
- Wood burning devices often are operated in close proximity to residential areas so that a large fraction of emissions can result in concentrations to which people are actually exposed. This is borne out in the mobile monitoring data where the highest woodsmoke levels are often recorded within the villages and towns of the study region.

Overview of Woodsmoke Modeling Results

In conjunction with the woodsmoke monitoring, a woodsmoke modeling methodology was applied following the approach outlined below:

- The modeling method used topography, census data, property assessments, and other relevant publicly accessible databases as inputs into a geographic information system (GIS) model. The GIS model provides a map of predicted woodsmoke $PM_{2.5}$ spatial variability across the study region.
- In estimating the spatial extent of woodsmoke, the model applies the concept of hydrological catchment areas. This procedure assumes that under conditions of elevated woodsmoke $PM_{2.5}$ concentrations, downhill ("downstream") drainage flow is the dominant pollutant transport mode. These conditions would exist under calm, cold, nighttime meteorological conditions when woodsmoke $PM_{2.5}$ levels are expected to be highest. Figure ES-4 illustrates the concept of catchments to represent this effect.

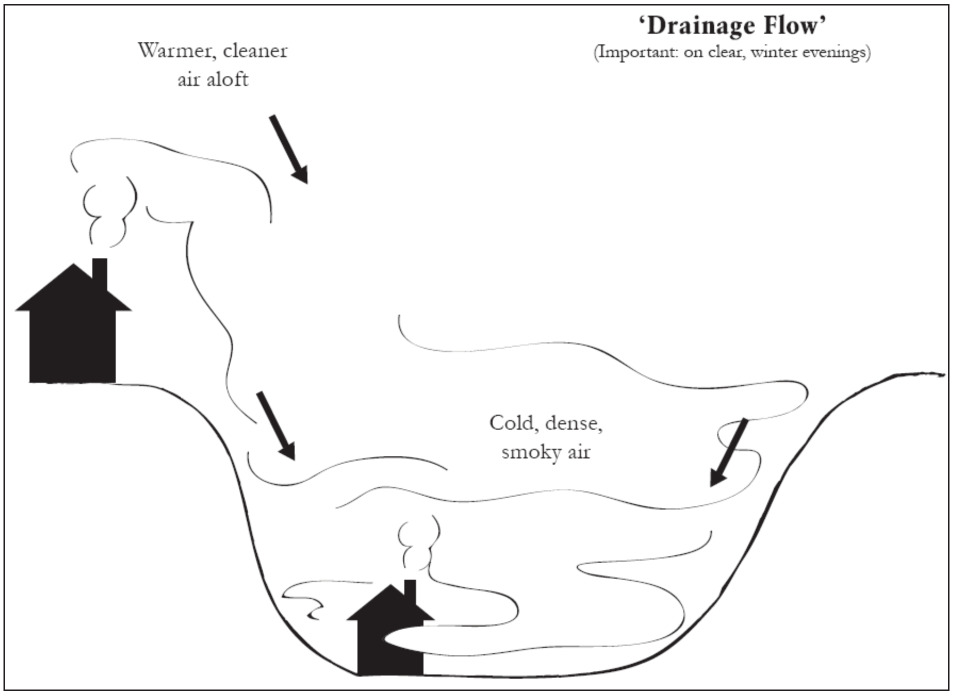

Figure ES-4. Illustration of catchment concept for modeling woodsmoke 'drainage flow.'

- Once the catchments are defined, adjacent upslope catchments are then searched for up to a specified distance to investigate the influence of upslope areas on downslope woodsmoke levels. For example, under relatively stagnant conditions conducive to woodsmoke buildup in catchments, a typical drainage wind speed of 1 m/s maintained over a 3 hour period would correspond to an upslope influence of approximately 10 km.
- A series of candidate predictors in upslope areas are identified and various combinations of these are tested against the measurements in each downslope catchment area of interest to find a best model. These candidate predictors for upslope catchment areas are listed in Table ES-1, and include

considerations of population, building age, economic status, physical properties, and the presence and emissions of wood burning devices.

Table ES-1. Candidate predictors used to model residential woodsmoke concentrations.

Population	Building age	Economic	Physical property
Total	<1950	Average dwelling value	Elevation
White	1951-60	Average household income	Green vegetation index
Non-white	1961-70	Median household income	Soil brightness
Black	1971-80	Median family income	**Emissions**
Asian	1981-90	Average family income	Wood heater appliance density
Immigrants	1991-00	Average income	Centralized wood heater density
Households	Total buildings	Education less than grade nine (pop.)	Woodsmoke emissions
Families	Median year built	Population in poverty	
		Unemployment population (age over 25)	

- The best model explains about 58% of the variability in measured woodsmoke $PM_{2.5}$ and includes an emissions variable (e.g., wood heater appliance density) as well as other socioeconomic and geographic variables.
- The model performance improves slightly as the upstream search distance increases from 1 km to approximately 4 km, suggesting that 4 km (2.48mi) is the distance of maximum influence for woodsmoke during this study.

The best model was then used to develop a predicted woodsmoke $PM_{2.5}$ concentration map for the full study area. Figure ES-5 shows the predicted woodsmoke $PM_{2.5}$ concentration map (gray scale) along with the values measured from mobile monitoring (yellow-orange-red colored line) conducted in Essex County, New York. Figure ES-6 expands the application of the best model to the entire seven county study region, demonstrating the method's power in identifying potential woodsmoke "hot spots" in areas without pollution monitors. Analyzing the results of the best model leads to the following observations:

- There is reasonable agreement between the modeled woodsmoke spatial distribution and the mobile monitoring results of Figure ES-5, with the highest mobile monitoring values (red color) generally located in areas that also have the highest predicted woodsmoke $PM_{2.5}$ levels (dark gray shade).
- If the population residing in areas with the upper third of modeled woodsmoke concentrations is considered to be exposed, then more than 50% of the population in the north loop and Essex County areas during the study period was exposed to elevated residential woodsmoke ('exposed' population = 28,800 people).
- Across the entire study region (seven counties), 26% of the population was exposed to elevated residential woodsmoke ('exposed' population = 127,670 people).

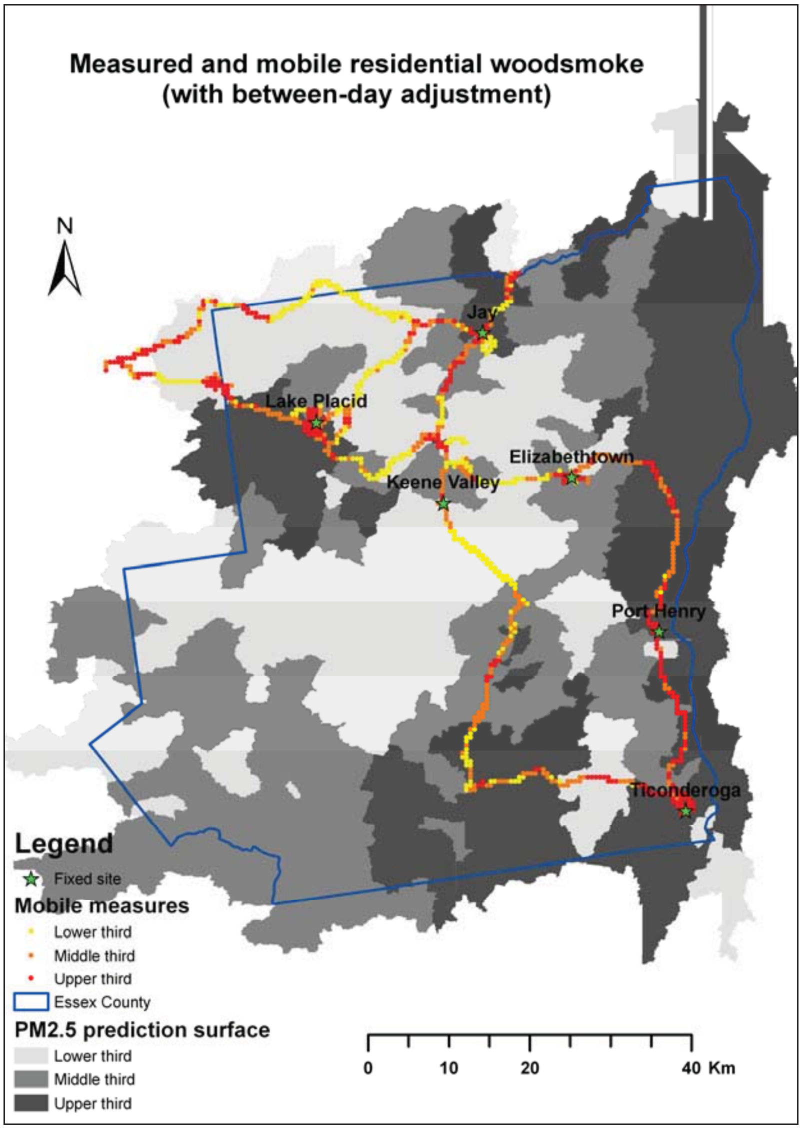

Figure ES-5. Mobile measurements and modeled residential woodsmoke in Essex County, New York. The highest mobile monitoring values (red color portion of line) are generally located in areas that also have the highest predicted woodsmoke levels (dark gray shade).

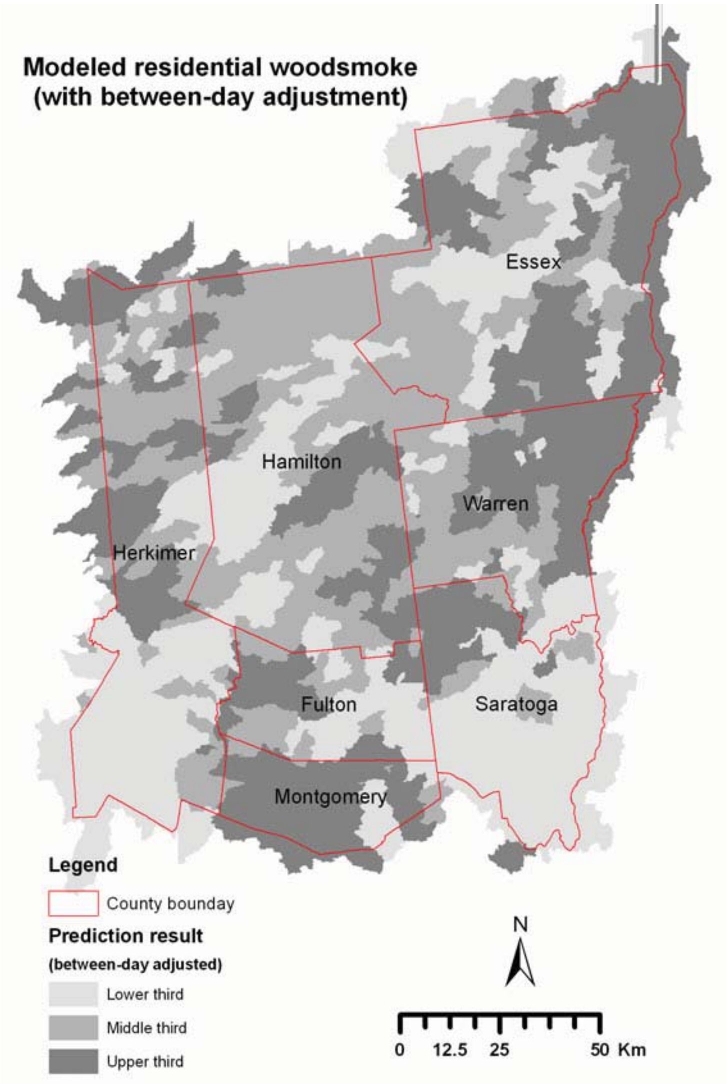

Figure ES-6. Modeled residential woodsmoke spatial pattern for the seven county study area in the Adirondacks region. Darker gray shades indicate higher modeled woodsmoke levels.

Conclusions and Recommendations

Based on the experience and results obtained in this study, the following conclusions and recommendations can be made that respond to the four objectives the study set out to address.

1. **Develop a modeling tool that provides a reasonable representation of woodsmoke spatial variability in a non-urban setting in light of relatively sparse air monitoring data and incomplete emissions source information.**

- The mapping results indicate that it is feasible to use readily accessible public information (e.g., census and survey data) in conjunction with a GIS-based mapping technique to produce a “screening” assessment of woodsmoke spatial patterns in complex terrains.
- Low elevation, increased wood heater density, increased dwelling value, increased number of families and increased non-white population all were associated with higher downslope woodsmoke $PM_{2.5}$.
- The model performance improved slightly as the upstream search distance increased from 1km to approximately 4 km, suggesting that 4 km is the distance of maximum influence for woodsmoke sources in the study area.

2. Apply the modeling tool to a complex topographical region to test its capabilities in providing useful information for air quality and health planning needs.

- In all models tested, the most important predictor variable was the wood heater (density) emissions variable. Including this variable alone explained 44% of the variability in the measured woodsmoke concentration. Addition of other spatial variables only improves the models marginally.
- The best model explained 58% of the variability in measured woodsmoke $PM_{2.5}$ and included both an emissions variable (e.g., wood heater appliance density) as well as other socioeconomic and geographic variables.
- Considering the population residing in areas with the upper third of modeled woodsmoke $PM_{2.5}$ as exposed, more than 50% of the population in the north loop and Essex county areas was exposed to elevated woodsmoke concentrations.
- For the whole study region (7 counties), 26% of the population (equivalent to approximately 128,000 people) was exposed to residential woodsmoke.

3. Explore the limitations of the modeling tool, and recommend possible improvements in the approach.

- While the modeling technique provides reasonable spatial representation of woodsmoke variability across the region, the model does not identify the very high, short-term woodsmoke concentration peaks observed during the mobile monitoring. These peaks can be a public health concern.
- Permitting requirements, locally specific sales data (e.g., county level), or other public reporting options for wood burning appliances would help fill knowledge gaps. Spatially resolved emissions data are particularly important for wood combustion sources given their location in residential areas and the fact that their impact on air quality is more localized than many other sources (e.g., power plants).
- The modeling technique had to make simple, and perhaps incorrect, assumptions about trends in residential wood combustion activity in response to changes in home heating oil prices and other factors in the absence of any specific information on wood-burning proportions by year. Given the

simple assumptions, the methodology used in this study is not appropriate to estimate the magnitude of woodsmoke emissions.

- If this modeling approach is to be applied to other areas to estimate the potential impact of woodsmoke $PM_{2.5}$ without any measurements for evaluation, improvements in the emissions data will be useful. Two specific areas for improvement include updating the proportion of homes using wood as a main heating fuel and better identification of locations and numbers of potentially high emitting sources, such as outdoor wood boilers.

4. Identify potential applications of the monitoring and modeling techniques that can help address air quality and public health planning needs

- The fixed-site monitoring approach is a relatively low maintenance technique for continuously tracking woodsmoke levels in communities during the course of a winter that can help identify conditions leading to high woodsmoke concentrations, thus help in pollution forecasting and public outreach efforts in locally-specific areas.
- The ability of the mobile monitoring method to detect short term spikes in woodsmoke may have application in developing better information on the locations of OWBs and other high emitting wood combustion sources. Because it can be conducted fairly quickly and easily along roadways in a local area, it may provide some ability to identify specific OWBs or other wood combustion sources that pose public health concerns at the local level.
- A mobile monitoring field campaign to gauge the prevalence of high woodsmoke spikes in a local region may provide emission inventory developers with a better sense of the prevalence of OWBs and other high emitting woodsmoke sources compared to assumptions made in inventory models.
- The modeling technique provides a monitoring network analysis tool that can help prioritize where to locate fixed monitoring sites and mobile monitoring routes for targeted field campaigns that best reflect where public exposure and woodsmoke levels may be highest.
- The modeling approach is readily transferable across regions because it uses publicly available information (e.g., census and survey data) that is common across the country. As such, it has potentially broad application for public exposure assessments to woodsmoke where extensive ambient monitoring networks are lacking (although regionally specific woodsmoke emissions and monitoring information can help improve the modeled woodsmoke spatial patterns).
- The modeling technique can be a screening tool to help identify high woodsmoke locations for targeted woodstove change-out programs or other strategies aimed at reducing woodsmoke emissions and public exposure.

Section 1

INTRODUCTION

Woodsmoke may be thought of as natural, hence “benign,” but there is ample evidence that wood burning emits significant quantities of known health damaging pollutants, including particulate matter, carbon monoxide, nitrogen oxides, and a number of known carcinogens, including benzene and polycyclic aromatic hydrocarbons (Naeher et al. 2007). According to the U.S. Environmental Protection Agency (U.S. EPA), fine particulate matter ($PM_{2.5}$) is a major health threat from exposure to woodsmoke (U.S. EPA 2009a).

Emissions Performance of Wood Burning Devices

Relative to oil and gas-fired furnaces, most conventional wood burning devices used for residential space and water heating are gross emitters of $PM_{2.5}$ pollution. In terms of total $PM_{2.5}$ mass emitted over time (e.g., grams per hour), EPA-certified woodstoves emit over 85 times more $PM_{2.5}$ than an oil or gas furnace, while conventional woodstoves emit over 250 times more $PM_{2.5}$, and uncertified outdoor wood boilers (OWBs) emit over 1000 times more $PM_{2.5}$ (NYS OAG 2008). Higher performing wood burning devices are feasible and used in Europe, but are not yet commonplace in New York State (NYSERDA 2008a). The U.S. EPA currently has a voluntary certification program for manufacturers of OWBs to promote the production and sale of cleaner, more efficient models (U.S. EPA 2009b). At U.S. EPA’s most stringent certification level (“Phase 2”), certified OWBs are about 90% cleaner than uncertified models. Testing of OWBs qualifying for Phase 2 certification indicate that the cleaner units still emit one to two orders of magnitude more $PM_{2.5}$ on an annual average emission rate basis (grams per hour) than residential oil or gas furnaces.

Volatile fuel prices may have a significant influence on home space heating choices, hence the level of woodsmoke emissions. Heating oil prices in the Northeast doubled from 2006 to 2008, going from about \$2.00 per gallon in 2006 to a peak of just over \$4.00 per gallon during 2008, before returning to about \$2.00 per gallon in November 2009 (EIA 2009). Such large swings in heating oil prices could potentially lead to fuel choice shifts towards relatively higher polluting wood combustion devices. Of special note is the rising prevalence of OWBs in New York State. According to a 2008 report by the New York State Office of the Attorney General (OAG), OWB sales in New York have tripled since 1999, with an estimated 14,500 OWBs sold in the state from 1999 to 2007. Based on $PM_{2.5}$ emissions testing on a grams per hour basis, uncertified OWBs emit almost 4 times more $PM_{2.5}$ air pollution than conventional wood stoves, 12 times more than EPA-certified wood stoves, 1000 times more than oil furnaces, and 1800 times more than natural gas furnaces. With the increasing popularity of OWBs and their higher emissions, the OAG has received as of January 2008 over 50 complaints from individuals affected by pollution from the units, and over 60 New York communities have moved to regulate or ban OWBs (NYS OAG 2008).

The U.S EPA is currently considering whether to revise and expand the application of New Source Performance Standard (NSPS) provisions of the Clean Air Act to a broader suite of residential wood heating devices in order to reduce their $PM_{2.5}$ pollution (Wood 2009). If EPA moves forward, it will likely take five to seven years to implement a final rule. The U.S. EPA is also under court order to propose an area source rule under the Clean Air Act for smaller institutional/commercial boilers by April 2010. The standards would likely cover wood boilers less than 20 million Btus per hour and set limits on the amount of hazardous air pollutants ("HAP" or "air toxics") that may be emitted by these sources (EPA 2009c). While a new institutional/commercial area source rule for wood boilers would cover sources at schools, hospitals, prisons, farms and other commercial settings, it would not cover OWBs used for residential heating.

Health Impacts of $PM_{2.5}$ and Woodsmoke

In setting national ambient air quality standards for $PM_{2.5}$, the U.S. EPA has summarized numerous studies finding associations between short- and long-term exposure to $PM_{2.5}$ and adverse health outcomes. These include lung function decrements, exacerbation of lung disease, respiratory and cardiac mortality, lung cancer, and developmental and immunological effects (U.S. EPA 2005). A large percentage of the general population (upwards of 50%) is susceptible to adverse health impacts as a result of acute and chronic $PM_{2.5}$ exposure, including children, asthmatics, persons with respiratory or heart disease, diabetics, and the elderly (Johnson and Graham 2005). A review by Naeher et al. (2007) summarized the evidence relating exposure to woodsmoke particulate matter with adverse health impacts and the importance of woodsmoke as a contributor to $PM_{2.5}$ in many locations. Therefore, strategies aimed at reducing woodsmoke exposure can be effective at lowering $PM_{2.5}$ exposures overall.

In a 2008 report prepared for the New York State Energy Research and Development Authority (NYSERDA), the Northeast States for Coordinated Air Use Management (NESCAUM) reviewed the state of knowledge of carbonaceous component of $PM_{2.5}$ in New York State, of which woodsmoke is an important component (NYSERDA 2008b). NESCAUM found that carbonaceous aerosols are a sizeable fraction of $PM_{2.5}$ mass in New York State (between a fourth and a third of total $PM_{2.5}$ mass), and much of the aerosol comes from sources within New York State. Residential wood combustion in New York is an important source category for carbonaceous aerosols, especially in rural counties where residential wood combustion is responsible for almost all (>90%) of carbonaceous $PM_{2.5}$ emissions (Figure 1-1). This is important from a public health perspective because even small towns and villages situated in predominately rural areas of New York can have relatively high population densities that are exposed to woodsmoke.

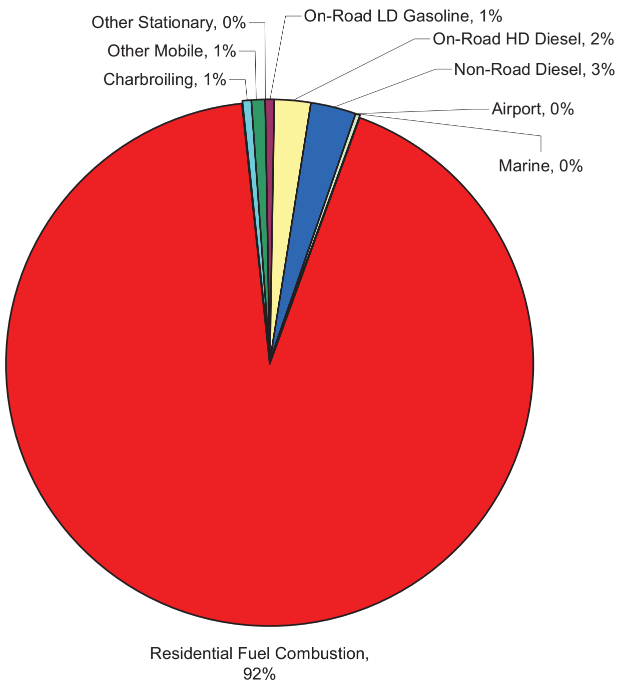

Figure 1-1. Relative contribution of source sectors to total carbonaceous PM2.5 in three rural counties of New York State. "Residential Fuel Combustion" is primarily wood use.

The U.S. EPA has set national $PM_{2.5}$ ambient air quality standards based on annual and daily (24-hour) averaging times, but shorter time period $PM_{2.5}$ "spikes" (minutes to hours) can also be of concern. Studies have found associations between short period PM peaks and acute cardiovascular and respiratory events, including myocardial infarction in older adults and asthma symptoms in children (Adamkiewicz et al. 2004; Delfino et al. 1998, 2002; Gold et al. 2000; Henneberger et al. 2005; Larsson et al. 2007; Mar et al. 2005; McCreanor et al. 2007; Morgan et al. 1998; Peters et al. 2001; Svartengren et al. 2000).

Recent work has also identified adverse respiratory impacts specifically from short term (4-hour) exposures to woodsmoke (Barregard et al. 2006, 2008; Danielsen et al. 2008). Short-term spikes in woodsmoke $PM_{2.5}$ can be associated with individual residential wood burning devices, such as outdoor wood fired boilers (Johnson 2006). Wood burning appliances often are operated in close proximity to residential areas so a large fraction of emissions can result in concentrations to which people are actually exposed (Ries et al. 2009; Bennett et al. 2002).

While there is a large body of health literature indicating woodsmoke exposure is a health risk, studies specific to New York State and the Northeast are limited. In light of its relative importance to overall carbonaceous $PM_{2.5}$ emissions in New York, residential wood combustion may pose a seasonal exposure risk during wintertime in areas where terrain and meteorology contribute to poor dispersion of pollutants. Therefore, a key recommendation in the 2008 NYSERDA report was a call for exposure assessments of populations in proximity to residential wood combustion emissions in densely populated villages, towns, and small cities, and areas where meteorology and terrain are conducive to high pollutant concentrations (NYSERDA 2008b).

Challenges in Assessing Woodsmoke Impacts

A key problem in assessing woodsmoke conditions in non-urban New York State and other rural areas of the Northeast is the location of wood burning sources, compounded by landscape features (e.g., Adirondack valleys). These features can create significant $PM_{2.5}$ spatial variability, including “hotspots” of elevated concentrations on top of regional $PM_{2.5}$ contributions. State ambient air pollution monitoring networks are typically not dense enough, particularly outside of urban areas, to capture fully this spatial variability. In New York State, there were a total of 29 ambient air monitoring stations reporting $PM_{2.5}$ measurements to the U.S. EPA’s Air Quality System database as of 2008. For New York’s land area of 47,214 square miles, this equates to one monitor per 1,628 square miles. The monitors, however, are generally concentrated in urban and suburban settings, thus their coverage is sparser across large parts of New York. Of the 29 sites, EPA classified only four as being located in a rural setting, with 16 identified as being in an urban or center city location and nine as suburban. Seventeen of the 29 monitors are located in the New York City metropolitan area, with 12 located in the remainder of the state. Only one $PM_{2.5}$ monitor is located in the Adirondacks region, and is at the base of Whiteface Mountain (classified as rural). In addition, the ambient air monitoring data in the EPA database are for total $PM_{2.5}$ mass, and are not speciated for woodsmoke $PM_{2.5}$ and other constituents (U.S. EPA 2009d).

The lack of detailed inventory information on the location and emissions of wood burning appliances exists not only in New York State, but regionally and nationally as well. An assessment of North American inventories by NARSTO (2005) identified residential wood combustion as a “first tier” priority area that deserved targeted resources to improve available emissions information. The lack of detailed information on location and emissions of woodsmoke sources complicates the ability of air quality planners to use traditional air quality modeling techniques to estimate $PM_{2.5}$ levels from woodsmoke, and assess public exposure to it. Therefore, there is a need for improved information to identify local areas with potentially high woodsmoke levels that can lead to effective management programs.

Assessing Air Pollution Spatial Variability

A growing number of studies have highlighted the substantial spatial variability of selected air pollutants that exists within urban areas (Cyrys et al. 1998; Fischer et al. 2000; Hoek et al. 2002a). In several epidemiological analyses, it has been demonstrated that such within area variability can be greater than the variability between different urban areas (Miller et al. 2005; Jerrett et al. 2005a). Further a large body of literature indicates that individuals residing in proximity to pollution sources, especially traffic sources, experience greater health impacts (WHO 2005; Hoek et al. 2002b; Brauer et al. 2002; Roemer and Wijnen 2001; Gauderman et al. 2005). These findings have important implications for the design and interpretation of epidemiological analyses and for air quality management. In response to these research findings, there are emerging policy requirements for more targeted assessments of localized public health impacts (Van Atten et al. 2005).

The need for more detailed characterization of air pollution variability within urban areas has also led to new approaches to model long-term average air pollution exposures (Jerrett et al. 2005a). For both traffic-related pollution and woodsmoke, routine ambient monitoring networks have only limited ability to assess impacts and spatial variability throughout populated areas. These new approaches have largely focused on traffic-related air pollutants (Briggs et al. 1997; Hoek et al. 2001; Brauer et al. 2003; Gilbert 2005; Cyrys et al. 2005; Ross et al. 2005; Henderson et al. 2007; Su et al. 2009), with a goal of estimating ambient levels of these pollutants throughout an entire airshed at a high level of resolution such as one city block. Land use regression, one useful approach, combines detailed spatial air pollution measurements with land use variables in a regression model within a geographic information system (GIS) framework (Briggs et al. 1997; Jerrett et al. 2005a). While motor vehicles are important air pollution sources in many areas, to date, there have been few applications of land use regression models to other sources, such as wood combustion (Ross et al. 2007).

Larson et al. (2007) and Su et al. (2007; 2008) developed the first series of catchment-based land-use regression models predicting the spatial variation of woodsmoke levels for three urban areas in the Pacific Northwest. There has been, however, no application of these land use regression models for non-urban areas. Given the potentially important impact of woodsmoke on $PM_{2.5}$ spatial variability and on air quality in non-urban residential areas with high residential woodburning, there is a need to develop tools to improve exposure assessments to woodsmoke $PM_{2.5}$ in these areas. In this study, this step is taken by applying a land-use regression model to predict the spatial variation of residential wintertime woodsmoke in an upstate New York non-urban region.

An Approach for Modeling Spatial Variability of Woodsmoke in a Non-urban Setting

The study described in this report applies an innovative GIS woodsmoke modeling approach that exploits topography, census data, and other relevant publicly accessible databases to map woodsmoke emissions in the Adirondacks of New York. This modeling technique was developed in the Pacific Northwest/British Columbia (Larson et al. 2007; Su et al. 2008), and has been adapted for the non-urban upstate New York region that includes the counties of Essex, Fulton, Hamilton, Warren, Herkimer, Saratoga, Franklin, and Montgomery. The modeling results are compared and refined with ambient air quality data collected during a field campaign using an air monitoring technique shown to discriminate woodsmoke from other combustion sources (Allen et al. 2004).

The study proceeded in four steps:

1. An initial woodsmoke emissions surface map is developed, step 1, using publicly available data sources (e.g., U.S. Census data, property assessment data, wood heating appliance manufacturer shipment records, published surveys of wood combustion activity).
2. Candidate fixed monitoring sites and mobile monitoring routes are identified using a location-allocation algorithm applied to the initial woodsmoke emissions map. The intent is to monitor across the region in a manner that captures to the fullest extent possible a wide range of predicted spatial variability in woodsmoke emissions.
3. Fixed and mobile monitoring at sites and along routes identified from the location-allocation algorithm applied in step 2 are conducted using an ambient monitoring technique capable of discriminating woodsmoke from other $PM_{2.5}$ components in the ambient air.
4. Using the collected monitoring data (mobile monitoring in particular) of step 3, the initial woodsmoke emissions surface map of step 1 is refined by temporally correcting for between-day differences, and applying a hydrological catchment technique to estimate upslope distances influencing woodsmoke levels at downwind locations. Three spatial model options are mapped using predictor variables (e.g., median household income, elevation, wood heating appliance density) to determine their relative power in predicting woodsmoke spatial variability compared to the monitoring results.

The remainder of this report is composed of two parts. The first part describes the monitoring technique, fixed-site locations and mobile routes, and results from the field monitoring campaign. The second part describes the mapping and modeling technique, data sources used to generate the initial and final woodsmoke emissions surface maps and models, and how the results compared to the monitoring data with regard to capturing spatial woodsmoke variability. The sequence given in the following two sections (monitoring followed by modeling) does not follow the chronology of the study approach as outlined in the four steps above, but is done in this manner for ease of presentation.

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Section 2

DESCRIPTION OF AMBIENT WOODSMOKE MONITORING APPROACH AND RESULTS

The ambient air monitoring field campaign described in this section have built upon previous experience by the Northeast States for Coordinated Air Use Management (NESCAUM) in developing and applying a field monitoring method for real-time assessment of woodsmoke (Allen et al. 2004). Available emissions, source location, and topographical data are used to strategically select fixed monitoring sites and mobile monitoring circuits to characterize spatial patterns of woodsmoke. The monitoring approach sought out locations of relatively high and low woodsmoke levels to provide a greater range of woodsmoke levels for comparison with the predicted woodsmoke spatial variability obtained from the GIS modeling technique.

FIXED SITE MEASUREMENTS

Woodsmoke particulate matter (PM) was monitored at eight fixed sites during the winter of 2008-2009 using two channel Aethalometers (Magee Scientific, Berkeley CA). Six of the sites were located in the northern portion of the study region, while an additional two were added for the southern portion (site locations listed below). The Aethalometer measures light absorption at two wavelengths: 880 and 370 nm. The data are reported in micrograms per cubic meter, and are called BC (for absorption by black carbon) and UVC (for ultraviolet (UV) absorption by carbon), respectively. The woodsmoke signal is UVC minus BC, called Delta-C, or "DC." It has been shown that DC is specific to woodsmoke (biomass combustion) even in the presence of mobile sources and oil space heating (Sandradewi et al. 2008; Kirchstetter and Novakov 2004). To convert DC to an estimate of woodsmoke concentration, a factor of 12 is used: woodsmoke PM in micrograms per cubic meter = DC*12. This factor comes from a 2004 study in Rutland, Vermont (Allen et al. 2004).

Fixed site Aethalometer data were collected at 5-minute intervals, and processed into 1-hour means using the "data masher" software. This program also generates and applies a correction factor for filter spot saturation, an essential step for a stable measurement of DC and thus woodsmoke PM (Virkkula et al. 2007; Kirchstetter and Novakov 2007). The resulting 1-hour data were screened for outliers and negative values.

A post-study "as-found" collocation of the fixed site and mobile Aethalometers was performed. The fixed site data were normalized to the response of the mobile Aethalometer based on median values of time-matched hourly collocation data. Finally, the DC to woodsmoke factor of 12 was applied to create a database of fixed site estimated woodsmoke PM concentrations.

Fixed Site Locations

Descriptive information for the fixed monitoring site locations is as follows. All sites were within the town, generally close to downtown.

North Town sites	N. Latitude	W. Longitude	Elevation (feet)
Northern study region			
Lake Placid	44° 16' 58.3"	73° 58' 54.2"	1,870
Jay	44° 22' 46.4"	73° 43' 19.9"	710
Keene Valley	44° 11' 26.8"	73° 47' 12.4"	1,040
Elizabethtown	44° 13' 01.3"	73° 35' 19.2"	570
Port Henry	44° 02' 35.6"	73° 27' 28.6"	130
Ticonderoga	43° 50' 36.3"	73° 25' 18.7"	260
Southern study region			
Saratoga Springs-downtown	43° 05' 09.7"	73° 46' 35.8"	310
Saratoga Springs-rural	43° 05' 31.9"	73° 39' 19.9"	240

One north loop fixed site (Lake Placid) had a DR4 nephelometer along with the Aethalometer. The data from the DR4 was intended to provide a rough check at one site of the DC to woodsmoke conversion factor. Review of the data from the Lake Placid DR4 indicated instrument problems for the first two months of the study. For the south loop, the downtown Saratoga Springs site had both an Aethalometer and a DR4 for $PM_{2.5}$.

Figure 2-1 shows the distribution of fixed site estimated hourly woodsmoke PM for the time period when all six sites in the northern study region were operating. The data shown in this figure have been corrected for between-instrument bias.

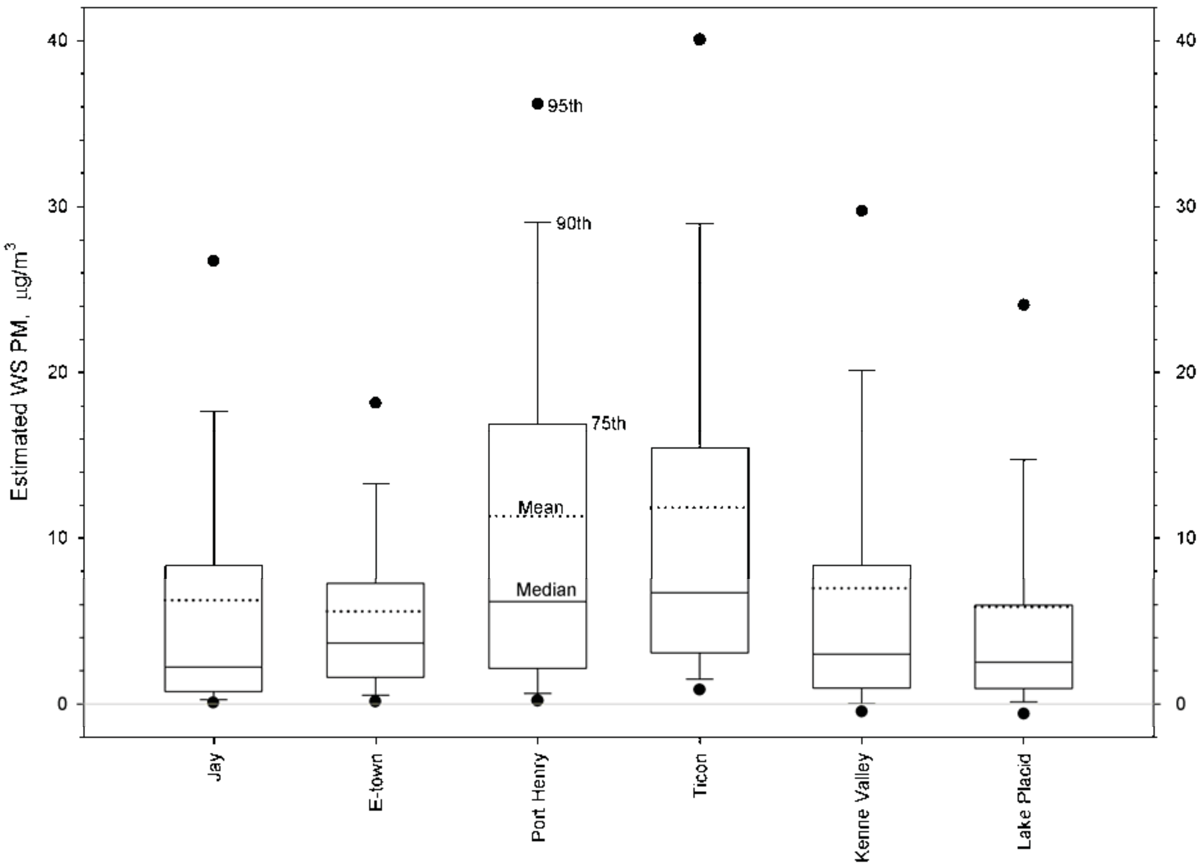

Figure 2-1. Distribution of fixed site estimated hourly woodsmoke PM concentrations for the time period when all six sites in the northern study region were operating.

As seen in Figure 2-1, median and mean levels of woodsmoke PM at the fixed sites in the northern study region during the entire course of the winter monitoring campaign were around 10 µg/m^3 or less. The highest hourly peaks (95th percentile) observed during the entire period were generally between about 20 µg/m^3 and 30 µg/m^3 at four of the sites, while two sites (Port Henry and Ticonderoga) were between 30 µg/m^3 and 40 µg/m^3. For the Saratoga Springs downtown monitor (not shown in Figure 2-1) in the southern study region, the mean and median hourly $PM_{2.5}$ levels were also well under 10 µg/m^3, with the 95th percentile slightly over 20 µg/m^3.

Lake Placid, a large town for this area, appears to have some of the lowest levels of woodsmoke among the fixed sites (but see later discussion for evenings forecasted to be conducive for air pollution buildup). This is likely due to the location of the fixed site, out of the bottom of the valley. Analysis of an intensive spatial mobile run in Lake Placid showed the fixed site location to be much lower in woodsmoke than the downtown area for that point in time. Figure 2-2 is a contour map of Lake Placid, showing the valley and the location of the fixed site, out of the valley bottom and 160 feet higher in elevation.

Figure 2-2. Map of Lake Placid indicating location of fixed site monitor (black square at the top-middle). Elevation lines are 20 feet.

While the Lake Placid monitoring site recorded relatively low woodsmoke levels during the course of the winter monitoring period, it was among the group recording the highest woodsmoke levels on 10 evenings forecasted to be conducive for air pollution buildup during which mobile monitoring was also conducted (described in the following Mobile Monitor Measurements section). Figure 2-3 presents the results from the northern fixed-site monitors during just the 10 forecasted evenings when woodsmoke levels were forecasted to be relatively high. The median and mean levels of woodsmoke PM during these 10 evenings were around 22 $\mu g/m^3$ or less. The highest hourly peaks (95th percentile) were generally above 40 $\mu g/m^3$ at four of the sites (Lake Placid, Ticonderoga, Port Henry, and Keene Valley), while two sites (Jay and Elizabethtown) were between 10 $\mu g/m^3$ and 22 $\mu g/m^3$. For the six towns with fixed monitoring sites, Keene Valley has the lowest population, yet is among the sites with relatively high woodsmoke PM during these 10 evenings. This may be a reflection of its topography (valley location).

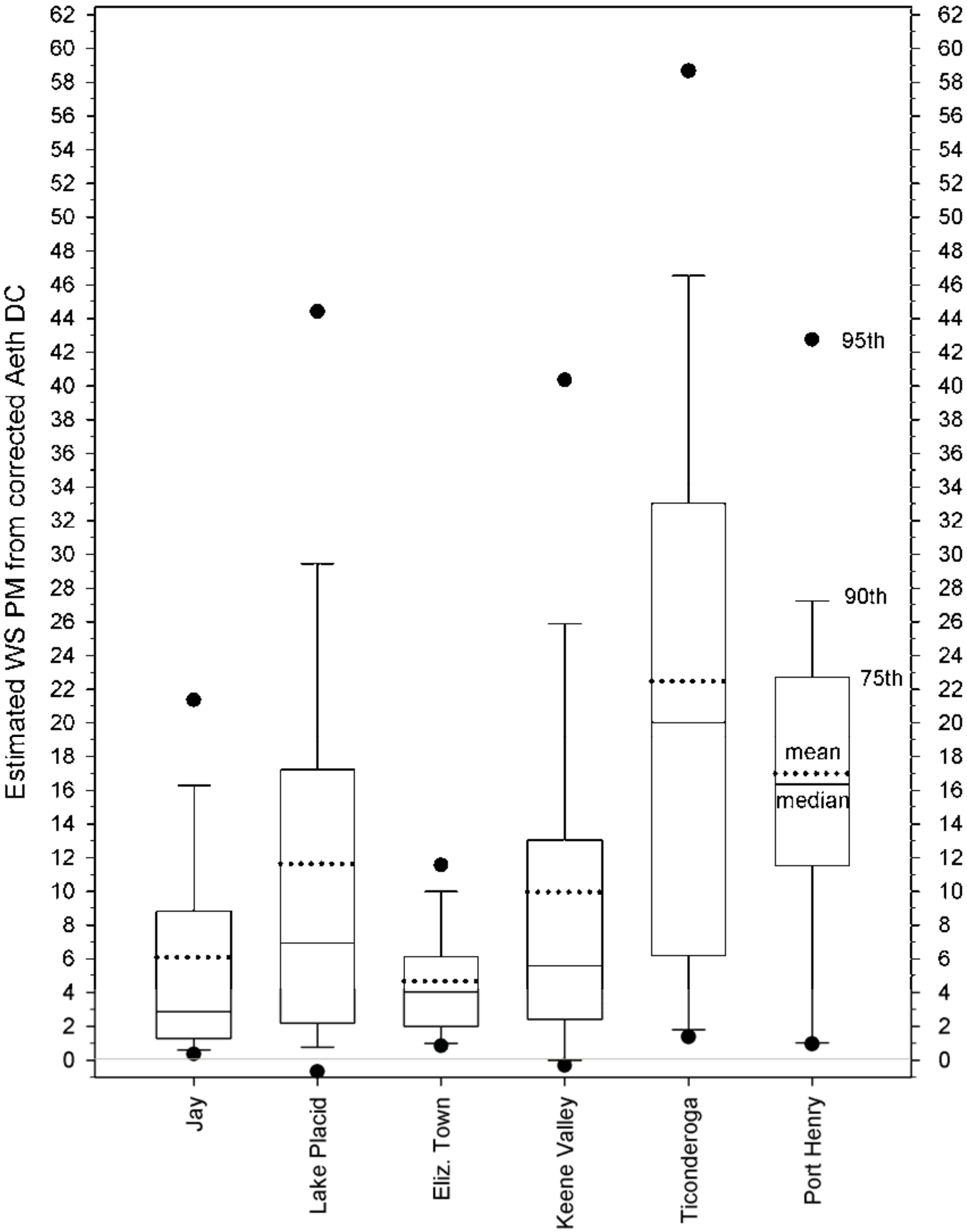

Figure 2-3. Distribution of fixed site estimated hourly woodsmoke PM during 10 evenings when mobile monitoring between fixed sites was conducted.

Quality Control and Data Review

Aethalometers. All fixed site Aethalometers were run on a 5-minute timebase, with either $PM_{1.0}$ or $PM_{2.5}$ µm inlet particle size cuts. All flows and thus Aethalometer data are at standard temperature and pressure (STP) (25C and 1 atmosphere). There is no absolute calibration for the Aethalometer; performance checks, and comparisons with other instruments are the only data quality checks steps that can be done. Flow and leak checks were performed before and after field deployment, with the exception of the Elizabethtown Aethalometer. That instrument failed one week before the end of the study in a way that made a post-study flow check not possible. All Aethalometers were collocated in a test chamber after the study “as found” with the exception of the Elizabethtown instrument, which was repaired and calibrated, and then collocated with the other instruments.

Fixed site Aethalometer data were processed using the “data masher” software with corrections for spot saturation, using 2-spot average and 20-spot smoothing parameters. This software performs many quality checks on the data using internal instrument parameters, and generates valid 1-hour mean Aethalometer data as the output. DC data were then screened for large negative values, and 1-hour DC means less than -0.4 $\mu g/m^3$ (~ -5 $\mu g/m^3$ woodsmoke PM) were removed. Data were then normalized to the response of the mobile loop Aethalometer based on collocated chamber tests. A factor of 12 was then applied to the DC concentration to convert it to estimated woodsmoke PM; this factor comes from previous modeling work (Allen et al. 2004).

The mobile Aethalometer data were processed manually, not using the data masher, because the data sets were very small. A default “k” value of 0.01 was used to correct for spot saturation effects; this is a typical value observed for woodsmoke. Mobile Aethalometers were run on either a 5-second or 1-minute timebase; the majority of the runs used 1-minute.

The two Aethalometers used for the south loop work were compared on-site; no corrections were needed. Data processing for these two instruments was as described above.

Nephelometers. A total of four Thermo DataRams (DR) were used for $PM_{2.5}$ measurements for this project; two for the north loop and two for the south loop. In each case, one DR was used for the mobile work, and one was at a fixed site. All DRs had a $PM_{2.5}$ µm inlet size cut. For the fixed sites, the auto-zero function was enabled and the data recording interval was 10 minutes. For the mobile DRs, the instrument was zeroed prior to each night’s run, and the data interval was 1 second. All DRs were DR-4000 except the south mobile loop, which was a DR-2000 (which is similar to the dual wavelength DR-4000 except it is a single wavelength instrument). All DRs were run with size and relative humidity (RH) correction turned off. No field calibrations are possible with these instruments, and the response to PM is not sensitive to moderate changes in sample flow. A correction factor of 0.7 was used with all DR data, based on earlier comparisons of a DR4 with a federal reference method (FRM) and a Filter Dynamics Measurement System (FDMS) tapered element oscillating microbalance (TEOM) (Allen and Babich 2007).

As with the Aethalometers, all four DRs were collocated "as found" in a test chamber after the study to assess their relative response. Three of the four were within acceptable agreement – all within a range of 10%. One DR response was about 40% higher than the mean of the other three. The two DRs used on the north loop were in good agreement and thus those data do not require any normalization. The DR-4000 used at the fixed site in downtown Saratoga Springs read high, and those data were corrected to agree with the other three.

MOBILE MONITOR MEASUREMENTS

Mobile Loop Data Review

The mobile loop had both a DR nephelometer and an Aethalometer. Data from both instruments were visually screened for extreme values and proper operation. The relationship between the Aethalometer DC woodsmoke signal and the DR $PM_{2.5}$ data was highly variable across time and space, as expected. This variability is due to highly heterogeneous woodsmoke composition and the short time-scale (a few minutes or less), compared to the long time-scale (days-weeks) and neighborhood-scale siting of earlier fixed site modeling work. The DC-to-PM ratio is a function of many things, including type of wood burned, how it's burned, and the age of the smoke. Thus, the Aethalometer data are used only as an indicator that woodsmoke was present, not to estimate its concentration. The DR PM data are used for woodsmoke concentrations, with the assumption that at these rural locations in the winter and late at night, there are very few other sources of $PM_{2.5}$ relative to woodsmoke on the stable atmosphere nights when mobile loop runs were done. Data were screened to determine if there were any times when PM (DR) concentrations were elevated with no evidence of woodsmoke from the DC Aethalometer measurements, and there were no such "other PM" events.

Mobile Monitoring Routes

The north mobile monitoring route included all the towns with fixed monitoring sites listed above, as well as Saranac Lake. The loop was driven both clockwise and counter-clockwise to vary the time of night towns were measured in order to remove any bias from taking measurements at the same time in each town across the different mobile runs. Typical departure time from Saranac Lake was 8 p.m. EST, and the loop took six to seven hours to drive. Speeds were approximately 20 mph or less in towns, and at posted road speed limits out of towns. Appendix A provides a fuller description of the protocol followed for the mobile monitoring runs.

The decision on which nights to perform a mobile loop run was based on consultations with NYS DEC weather forecasters. Nights with low wind speed and radiational cooling with valley inversion potential for the domain of interest were targeted as "run nights." The NYS DEC forecasters provided at least one-day advance notice, with an update the afternoon of a potential run night.

A total of ten runs were made; two runs were limited to the northern portion of the loop (the sub-loop that included Lake Placid and Jay), with more intensive in-town circuits. The in-town route always included a drive-by of the fixed monitoring site, as well as other parts of town. Typically 15 to 30 minutes were spent in each town, more in the larger towns and less in the smaller towns.

The south mobile loop route included Saratoga Springs, Glens Falls, and Schuylerville; this took approximately 2.5 hours to drive. Four south loop runs were made starting in mid-January 2009. Figure 2-4 and Figure 2-5 show the route driven for the north and south loops.

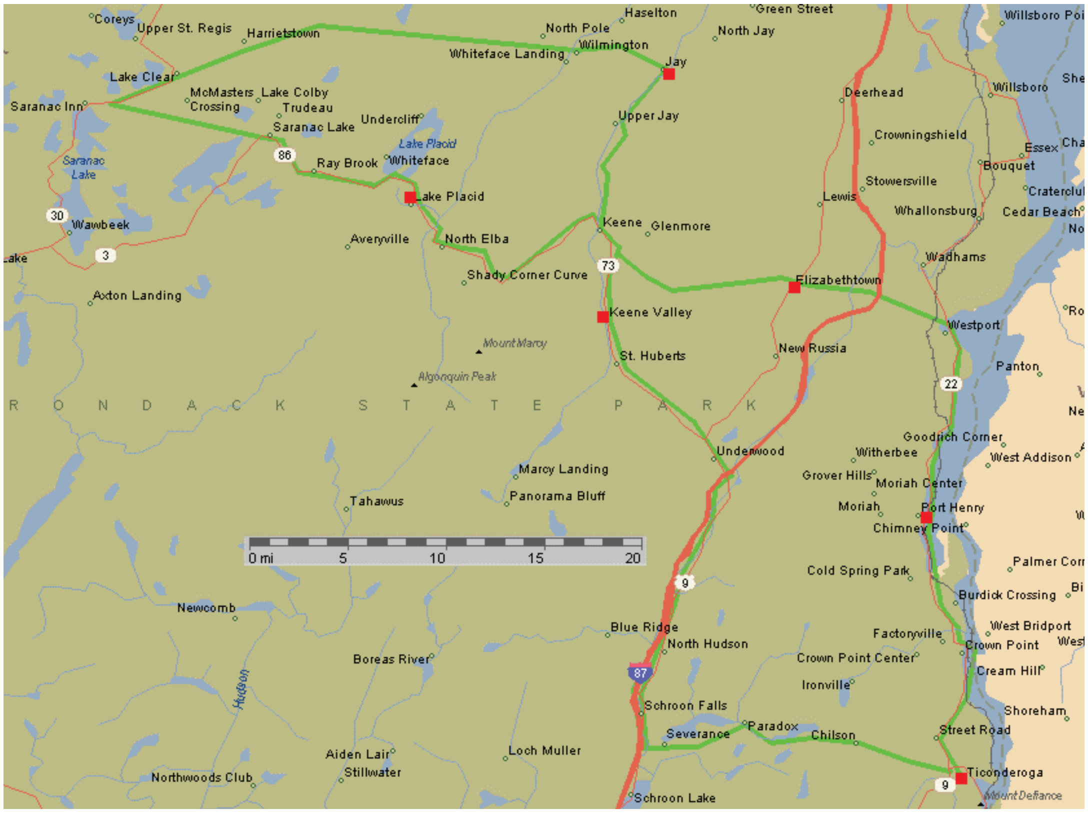

Figure 2-4. North loop mobile monitoring route (green line). Fixed site monitor locations are indicated as red squares.

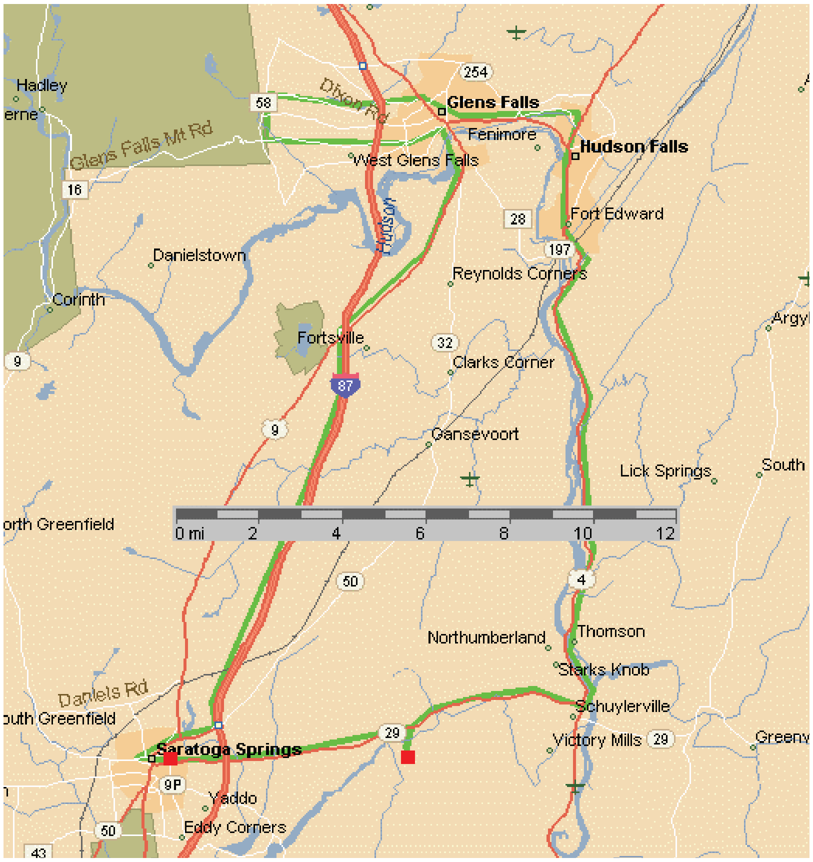

Figure 2-5. South loop mobile monitoring route (green line). Fixed site monitor locations are indicated as red squares.

OVERVIEW OF MONITORING SEASON AND RESULTS

The 2008-09 Adirondacks Winter Weather in Context

The 2008-09 winter was somewhat unusual in that there were fewer classic high pressure weather patterns that persisted for a few days and created strong regional-scale valley stagnation events. In addition, when stagnation did occur during a 24-hour period, it often did not coincide with the preferred "before midnight" time slot (NYS DEC 2009). The weather systems tended to move through the area quickly, making forecasting mobile loop run-nights difficult. On average in the region, winter temperatures (Dec.-Feb.) were slightly colder for 2008-09 compared to the previous four winters. Those years were warmer on average (+2, +2, +3, and 0 °F) than last winter, which was -1 °F from 1971-2000 norms. Winter 2004 was slightly colder, at -2 °F (NRCC 2009).

One indicator of the potential for night-time valley inversions is wind speed. Daily mean and daily 1-hour maximum resultant (vector, not scalar) wind data from the Atmospheric Sciences Research Center at Whiteface Mountain, NY were analyzed for the last five winters. For the daily mean wind speed, last winter was the highest for the 95th percentile, but not for any other distribution metric. For the daily 1-hour maximum wind distribution (Figure 2-6), last winter was distinctly higher than any other year for the 95th percentile value. The arithmetic mean was also the highest of all years, but not by a large amount. These data suggest that last winter may have been somewhat windier than a typical winter, but timing of wind conditions is also important. Light wind speed conditions (< 5 mph) for the last five winters during the mobile run target hours of 9 p.m. to 3 a.m. local time may be a better metric than general daily wind metrics (NYS DEC 2009). This is beyond the scope of this report, but could be an area for future analysis.

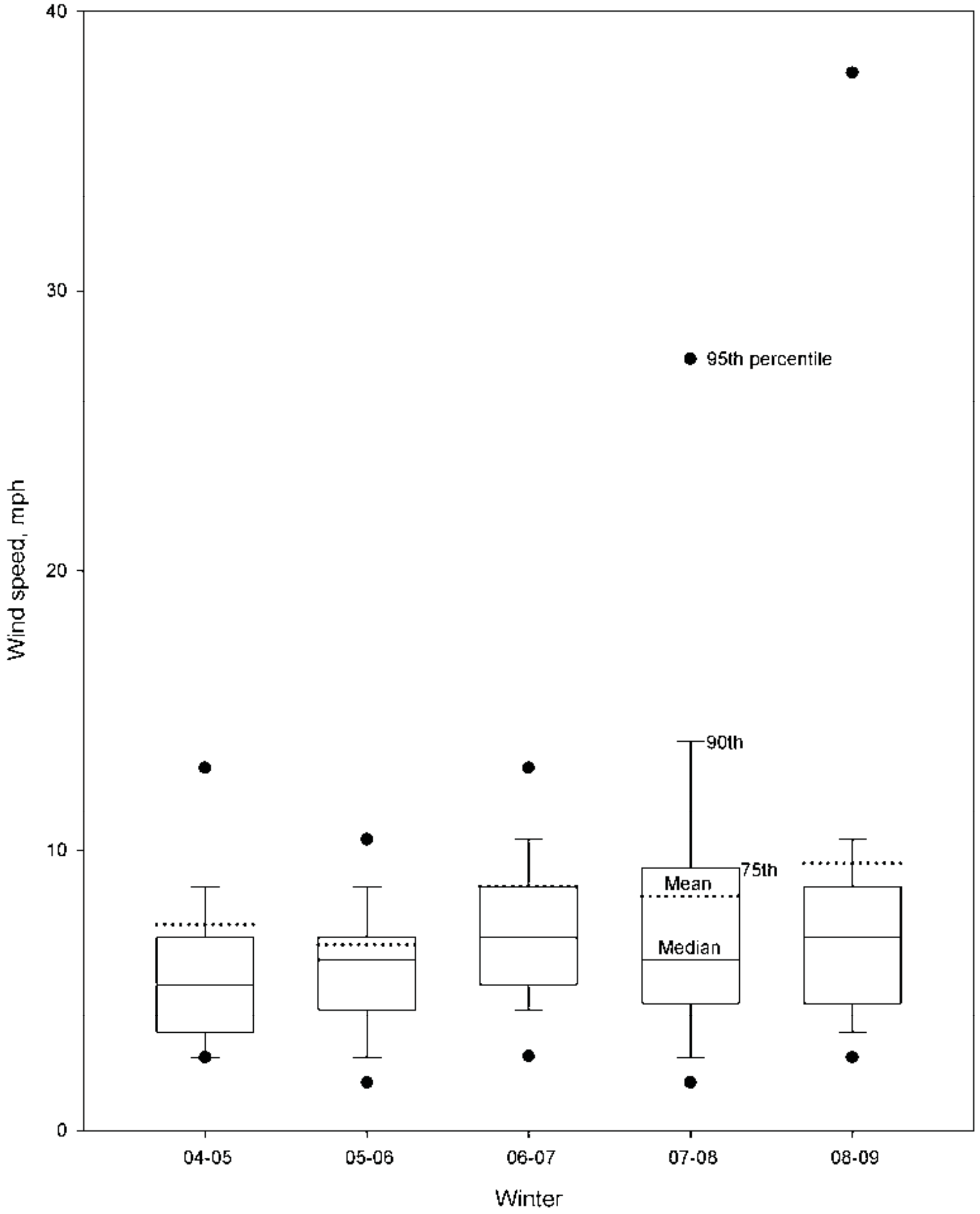

Figure 2-6. Box plot of daily maximum 1-hour resultant wind speed at Whiteface Mountain, NY (December – March).

North Loop Ambient Data Analyses

The following discussion and plots present the results of analyses of the monitoring data to give a better understanding of the temporal and spatial dynamics of woodsmoke $PM_{2.5}$. Two smoothed time-series plots of Aethalometer Delta-C estimated woodsmoke from all six north loop fixed sites are shown in Figure 2-7 and Figure 2-8. The smoothing function is a simple arithmetic running average for a given time interval with no weighting. In the figures, the smoothing times are a running 24-hour and running 3-hour duration respectively. A mobile loop run was done the night of February 5-6. Note that in some of the 24-hour plot cases, the region behaves the same way across all sites (February 6), and in others it appears to be completely decoupled (February 2) between the north and south fixed sites. The decoupling is expected if weather systems are moving through the region during the mobile loop run, which was often the case.

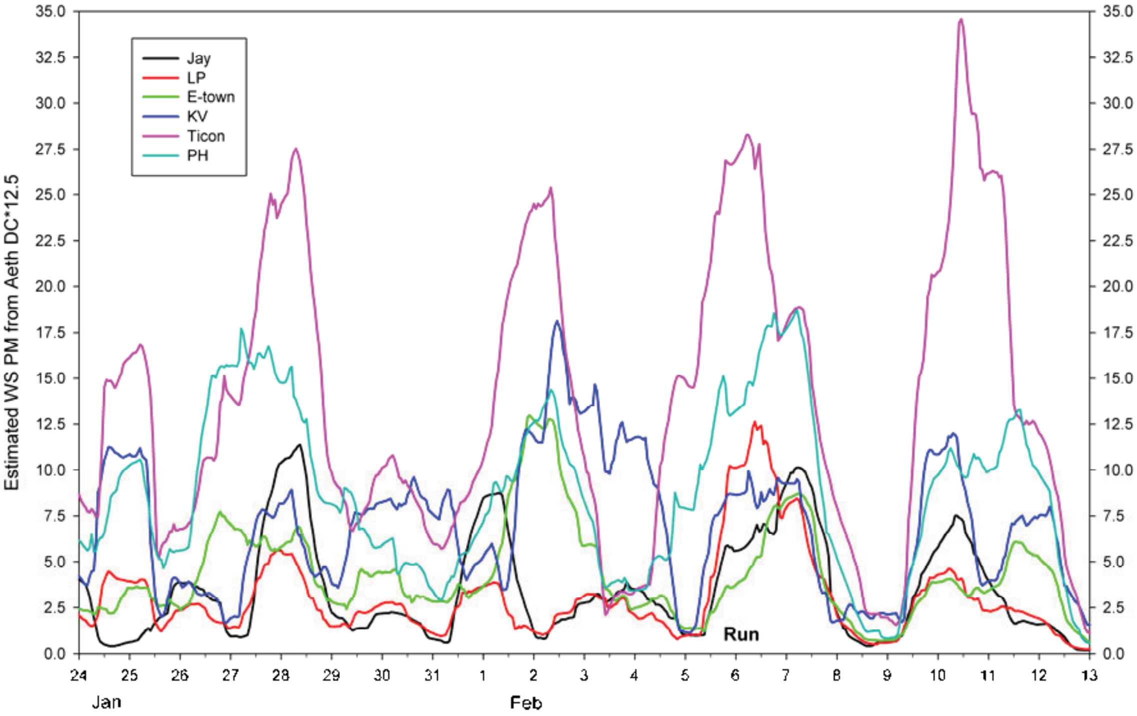

Figure 2-7. Estimated woodsmoke PM 24-hour running mean (μg/m^3) from January 24 to February 12, 2009.

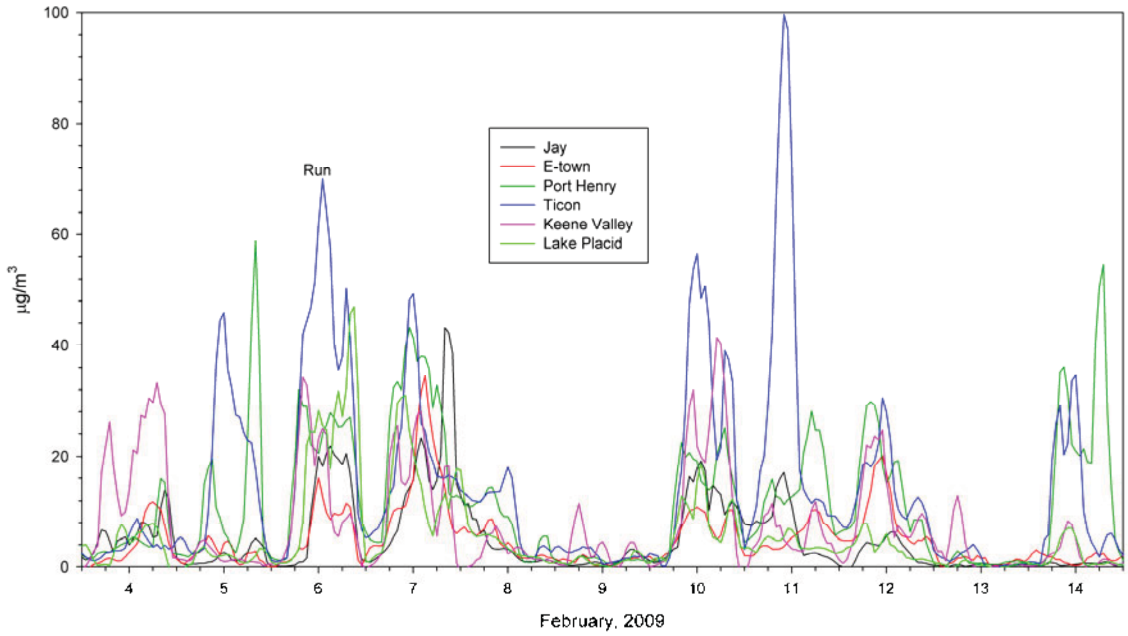

Figure 2-8. Estimated woodsmoke PM 3-hour running average of 1-hour data collected during early February 2009.

The 3-hour smoothed plot shows a larger dynamic range since this duration is short enough to show periods that include only hours with high night-time woodsmoke concentrations. At this time-scale, additional detail shows that even on February 6 there was substantial variation across the region. Periods of low regional concentrations also become more evident, including the brief mid-day example on February 4. It should be noted that at these shorter timescale, the estimate of woodsmoke $PM_{2.5}$ from Aethalometer DC may be more variable compared to longer time periods (days or weeks), because smoke from a single or few sources may dominate short duration concentrations and the DC to woodsmoke relationship can vary depending on the nature of the smoke (e.g., type of wood, combustion conditions, plume age).

The typical mid-day dispersion of valley pollution is clearly shown in Figure 2-9, a diurnal plot of BC, DC, and the BC/DC ratio. Vertical mixing (driven by solar radiation) and wind speed, thus dispersion of local pollution sources, peaks at mid-day. This, along with reduced source emissions from both traffic and woodsmoke, results in a mid-day minimum in $PM_{2.5}$. Local sources of $PM_{2.5}$ in Ticonderoga are from traffic and woodsmoke. DC is only from woodsmoke, while BC is from both traffic and woodsmoke sources. Woodsmoke dominates the BC in this example, although the variation of the ratio of BC to DC (BC lower at night and higher morning and mid-day) suggests some influence by local traffic during daytime hours. It is reasonable to assume that on average, the BC to DC ratio in woodsmoke is constant. Thus, the ratio of BC to DC is the traffic-related signal, while DC is the woodsmoke signal.

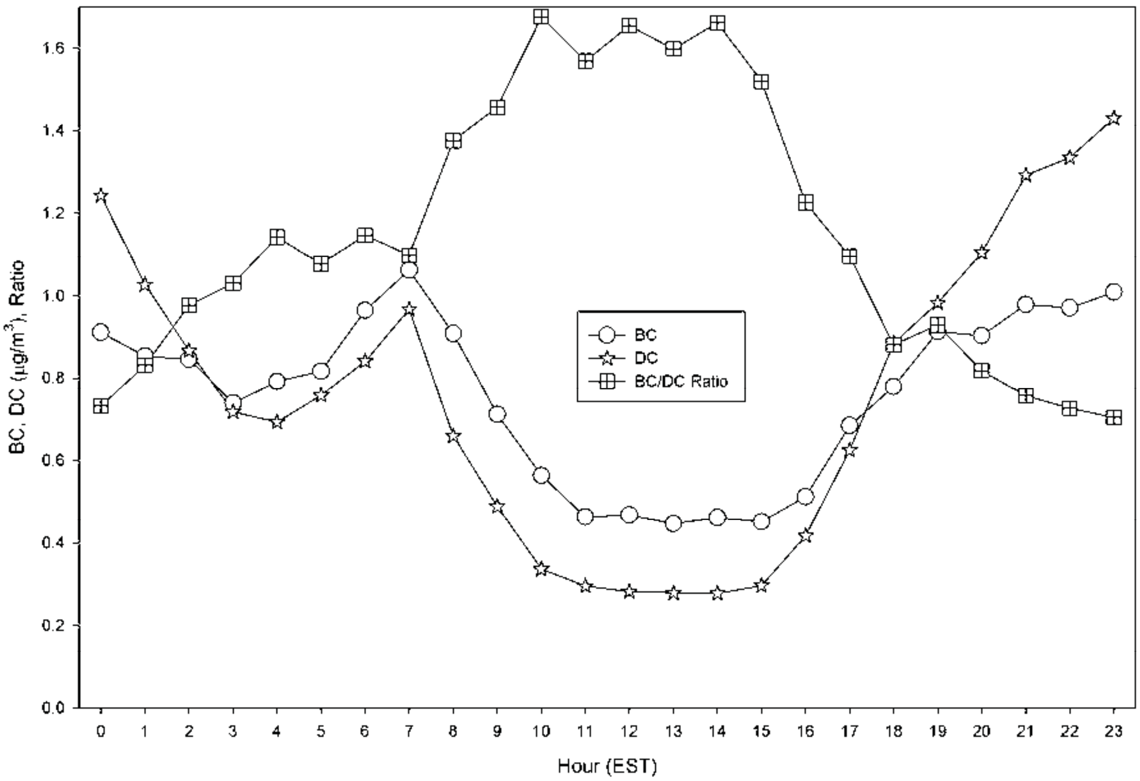

Figure 2-9. Diurnal plot of $PM_{2.5}$ and woodsmoke pollution at the Ticonderoga monitoring site (see accompanying text for explanation of profiles).

An example of DR4 $PM_{2.5}$ and Aethalometer estimated woodsmoke $PM_{2.5}$ from the mobile loop run of January 1-2 is shown in Figure 2-10. The data from both instruments is smoothed with a 3-minute running average, and towns are labeled. It is clear from this time-series plot that the highest woodsmoke concentrations are present mainly in towns, although there are examples of woodsmoke between towns (Elizabethtown to Port Henry). In high elevation areas between towns, the $PM_{2.5}$ goes to essentially zero; this represents regional background concentrations.

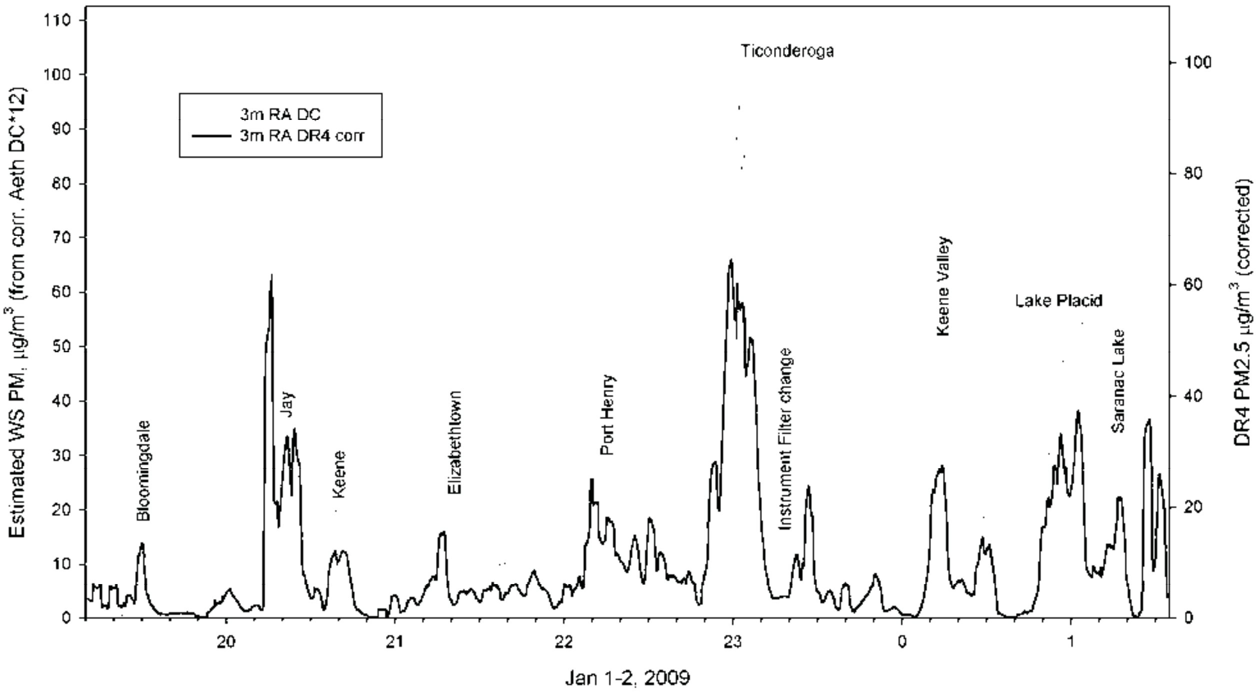

Figure 2-10. Estimated woodsmoke $PM_{2.5}$ 3-minute running averages measured on January 1-2, 2009 during north loop mobile monitoring circuit.

Although woodsmoke is always present when DR4 $PM_{2.5}$ is elevated, the relative relationship can vary by a factor of six or more at this short timescale. As noted above, the shorter the timescale, the larger the variation in this relationship between methods. This is why the DR4 $PM_{2.5}$ data were used in all mobile loop analyses and not the Aethalometer estimated woodsmoke, which is only used to confirm that the observed $PM_{2.5}$ is dominated by woodsmoke.

For two of the north loop runs, the domain was constrained to the northern half of the loop, and additional time was spent doing more detailed runs within towns during the shortened loop drive. A map of the route taken on the night of February 24-25 is shown in Figure 2-11. A quick run east was followed by a slow return; the return route was through Keene (but not Keene Valley). Because substantial woodsmoke had been observed in Saranac Lake on earlier runs, additional time was spent in that area during this run. The northeast run was also extended to Au Sable Forks, northeast of Jay.

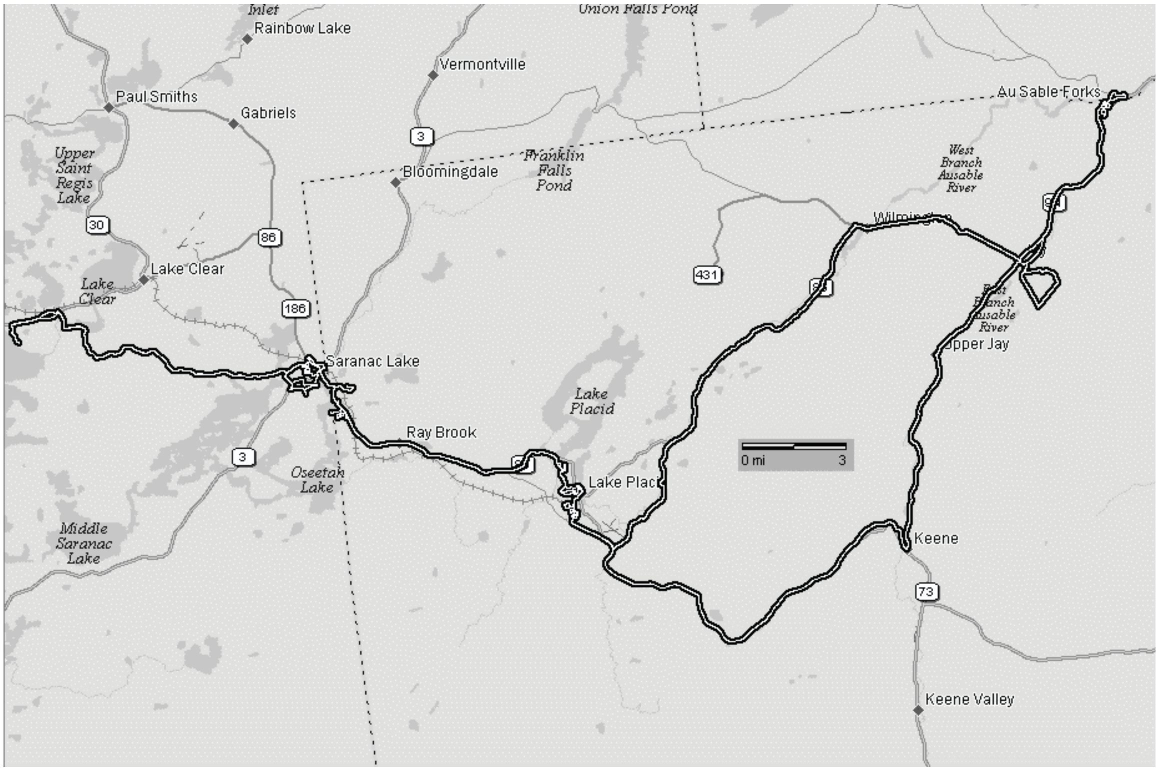

Figure 2-11. **Map of shortened north loop drive during the night of February 24-25, 2009.**

The DR4 $PM_{2.5}$ and the Aethalometer estimated woodsmoke concentrations for this run are shown in Figure 2-12. A 3-minute running average smooth has been applied to these data. The return run (slow) starts at Au Sable Forks. Note that for both Saranac Lake and Lake Placid, the peak concentrations are higher on the return trip, which is later in the evening. This is consistent with woodsmoke PM peaking around the middle of the night, not the early evening.

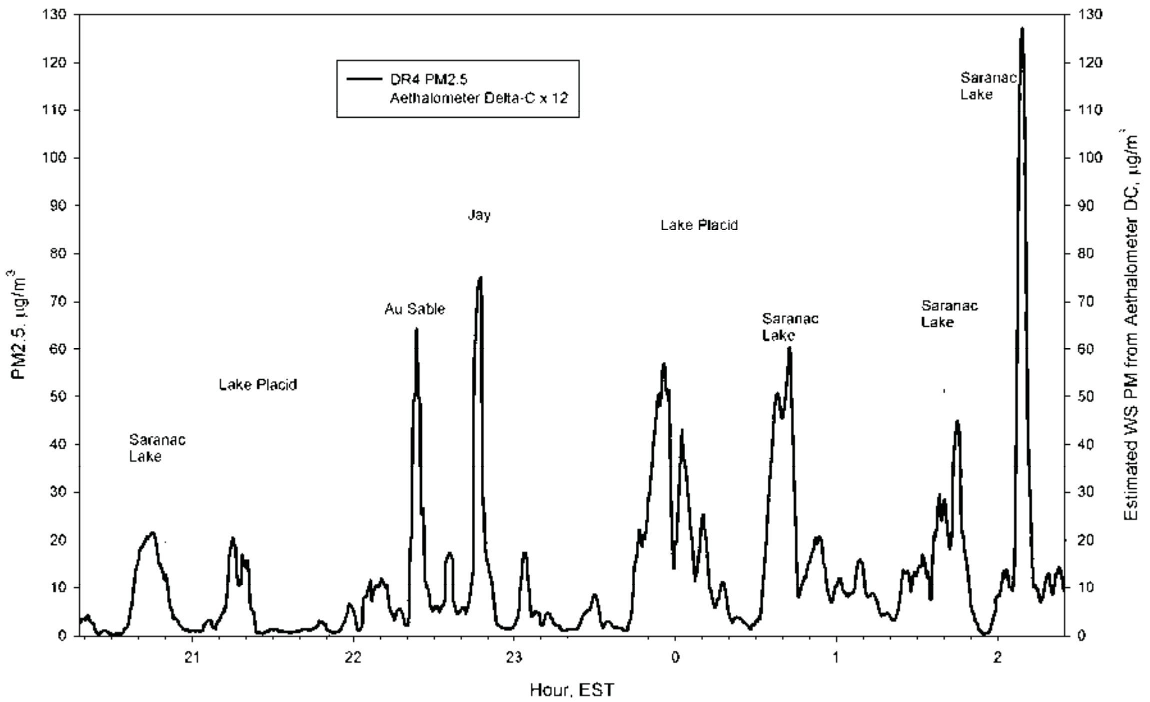

Figure 2-12. Estimated woodsmoke PM 3-minute running averages measured on February 24-25, 2009 during shortened north loop mobile monitoring circuit.

Another way to show concentrations across time and space is a bubble plot, as shown in Figure 2-13. Here, the axes are latitude and longitude, essentially a map of the domain driven that night. The concentration data are 1-minute averaged DR4 $PM_{2.5}$ for the return trip only. The size of the circle (one every minute) represents the concentration. It is very clear from this plot that the highest concentrations are generally in towns, with very low levels between towns. "Home" represents the end point of the evening's trip, a few miles southwest of Lake Clear (see the route map) near the northern tip of Saranac Lake. The highest 1-minute $PM_{2.5}$ concentrations were observed in Jay and on a small side road just north of Highway 30 one mile northeast of the top of Saranac Lake.

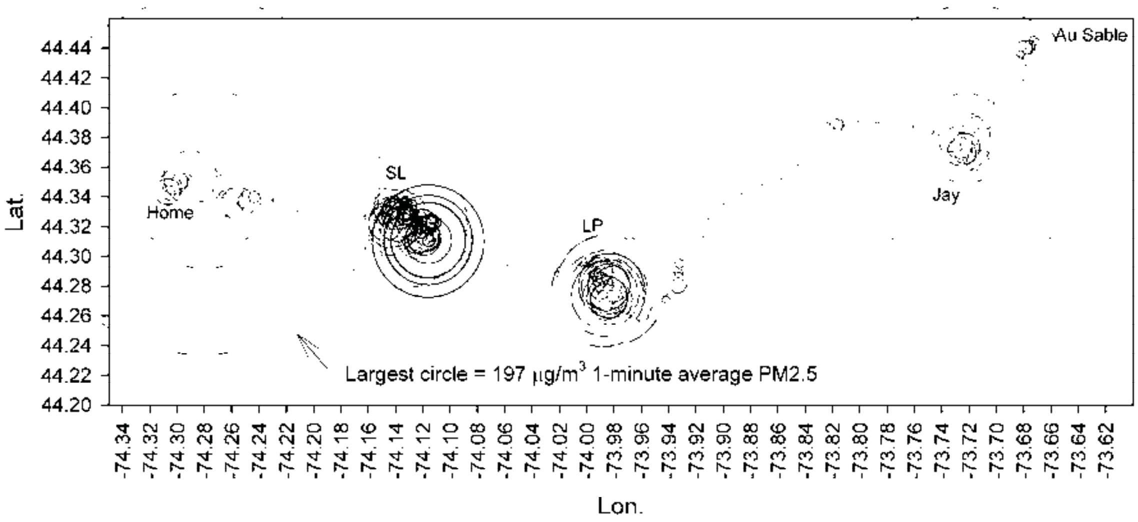

Figure 2-13. Bubble plot of 1-minute averaged $PM_{2.5}$ during return half of shortened north loop drive during the night of February 24-25, 2009.

Using the highly time-resolved $PM_{2.5}$ data from the DR4 nephelometer, it is possible to identify very short term spikes due to what may be individual smoke plumes. Figure 2-14 shows 1-second $PM_{2.5}$ data (actual response time is ~5 seconds) from the Feb. 24-25 north sub-loop return run also shown in the time-series plot of Figure 2-12 and the bubble plot of Figure 2-13. For this type of plot, it is important to also show vehicle speed because that has a strong influence on the duration of a $PM_{2.5}$ spike. The 1-second car speed data shown here are from the on-board diagnostic (OBD) data logger, a more accurate indicator of low speeds than GPS-reported speed.

For this short time scale, the highest $PM_{2.5}$ concentration of 750 $\mu g/m^3$ occurs in Jay at 22:47 (10:47 p.m. local time), but is only present for ~20 seconds at a speed of 15 mph. This represents a distance of about 0.08 miles or 440 feet (134 meters). The largest circle in the bubble plot occurs near the end of the run, at 2:10 a.m. local time. That event is a broader peak of 225 $\mu g/m^3$, and the peak lasts 1 minute 40 seconds. The car was traveling slower, at an average speed of 9 mph; the distance covered during the peak of this event was 0.25 miles. It is not clear if the larger spatial scale of this event was due to local topography or to the plume traveling more parallel to the road.

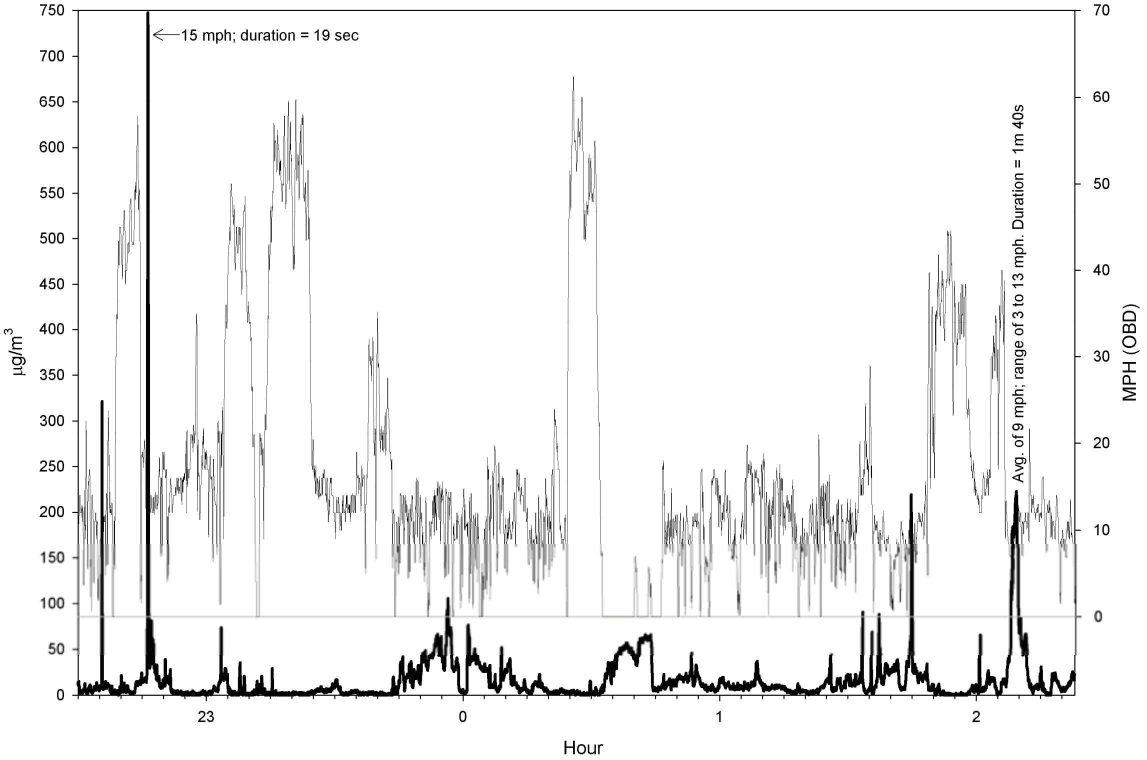

Figure 2-14. Left axis: Plot of PM$_{2.5}$ 1 second data (lower dark line). Right axis: Plot of car speed (upper light line). Data were collected during the return portion of the shortened northern loop drive on the night of February 24-25, 2009.

Finally, a detail of the last 2.5 hours of this trip is shown in Figure 2-15, covering the intensive monitoring in Lake Placid and Saranac Lake. This plot shows 15-second DR4 PM$_{2.5}$ and elevation (in feet). Of particular interest in this figure is the sharp drop in PM at midnight, corresponding to the few minutes when the mobile monitoring was out of the bottom of the Lake Placid valley, and near the Lake Placid fixed site location. This indicates that at least on this night, the fixed site was above the inversion layer, and PM measured there was not representative of the bottom of the valley.

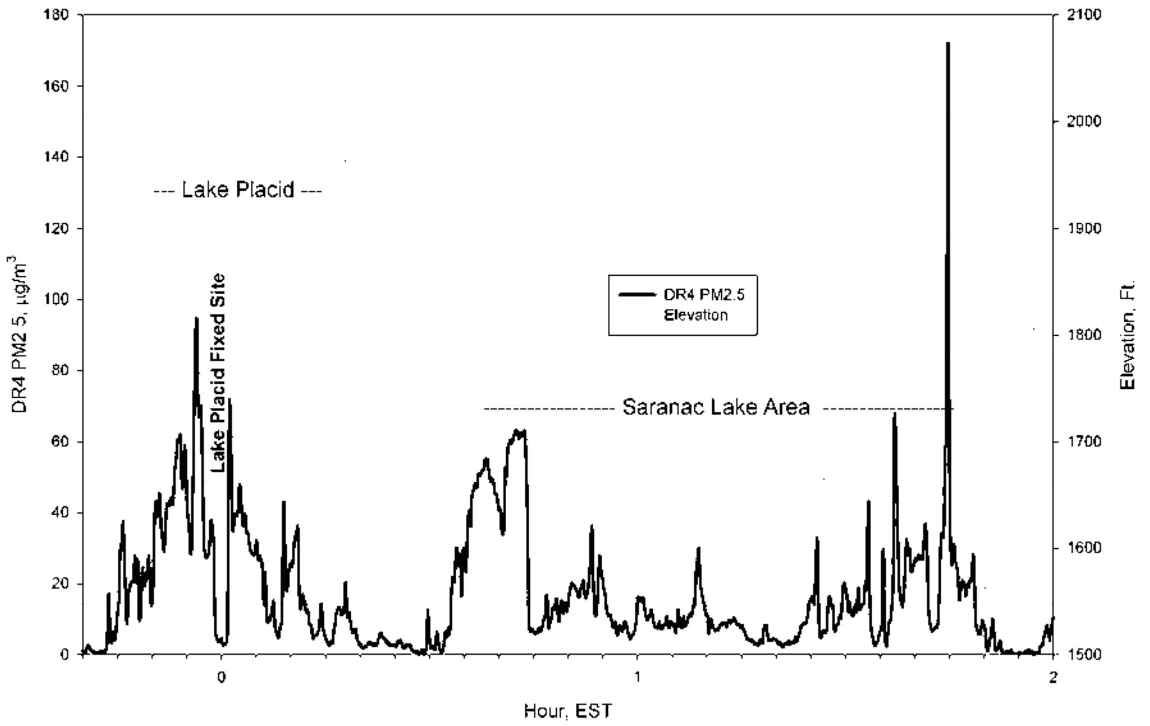

Figure 2-15. Plot of elevation and estimated woodsmoke (15-second running average) on night of February 24-25, 2009 during second half of shortened north loop monitoring drive.

South Loop Ambient Data Examples

The southern domain for this project was much more limited than the original northern domain. There were only two fixed sites, and only during the second half of the winter (six weeks), with a limited number of mobile runs.

Data from the city of Saratoga Springs (about 1/4 mile from downtown) is shown in Figure 2-16, Figure 2-17, and Figure 2-18, a smoothed time-series, box plot, and diurnal plot respectively. The time series plot of 5-hour running average DR4 PM and Aethalometer DC also shows the time of the four mobile loop runs to put them in a larger temporal context. As with the northern domain, elevated PM is almost always associated with woodsmoke at the fixed site, even though it is near the city center. The box plot of hourly $PM_{2.5}$ shows the mean and median to be well under 10 µg/m^3, with 95th percentile hours slightly over 20 µg/m^3. The diurnal plot shows $PM_{2.5}$, BC, and DC. Here, unlike at Ticonderoga, BC shows a clear morning rush-hour peak relative to the DC woodsmoke signal; this is expected since there is more traffic. DC shows the most dynamic range, again as expected due to the mid-day minimum.

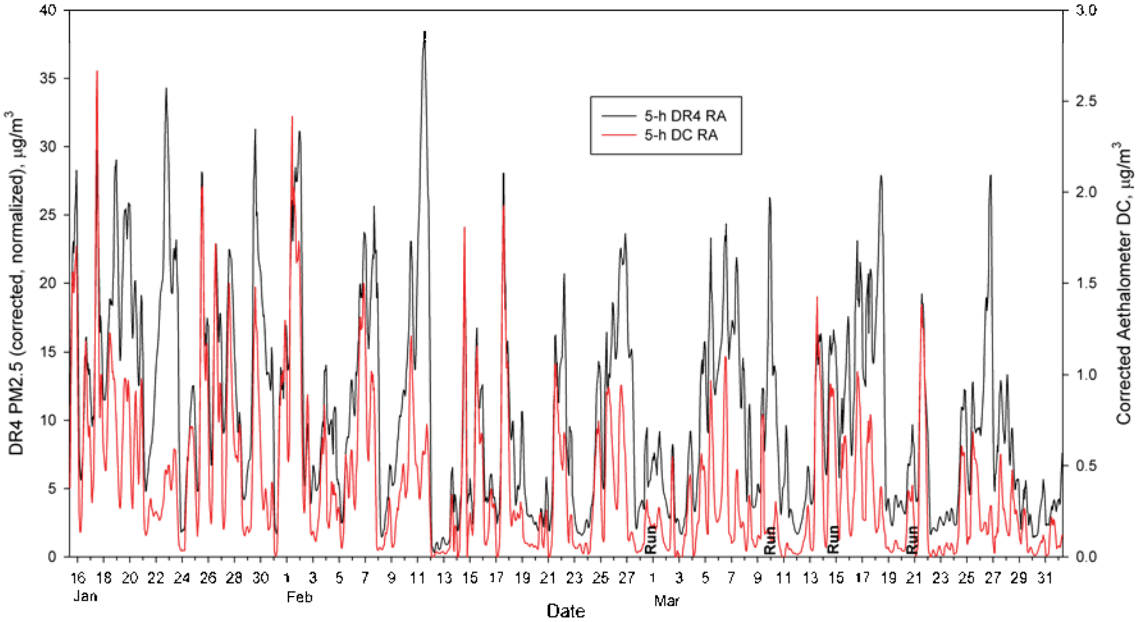

Figure 2-16. Estimated woodsmoke $PM_{2.5}$ (5-hour running average) of at the Saratoga Springs downtown monitoring site from January 16 to March 31, 2009.

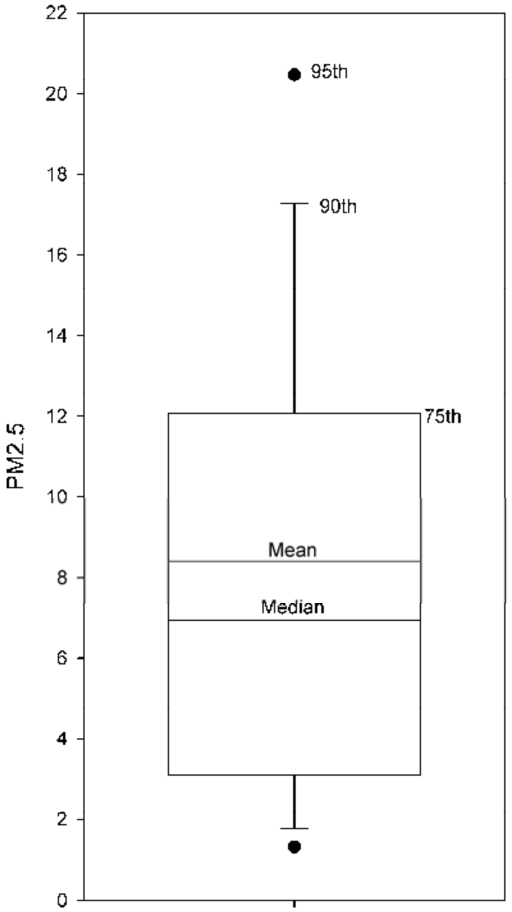

Figure 2-17. Box plot of 1-hour $PM_{2.5}$ concentration distributions from January 16 to March 31, 2009 at downtown Saratoga Springs monitoring site.

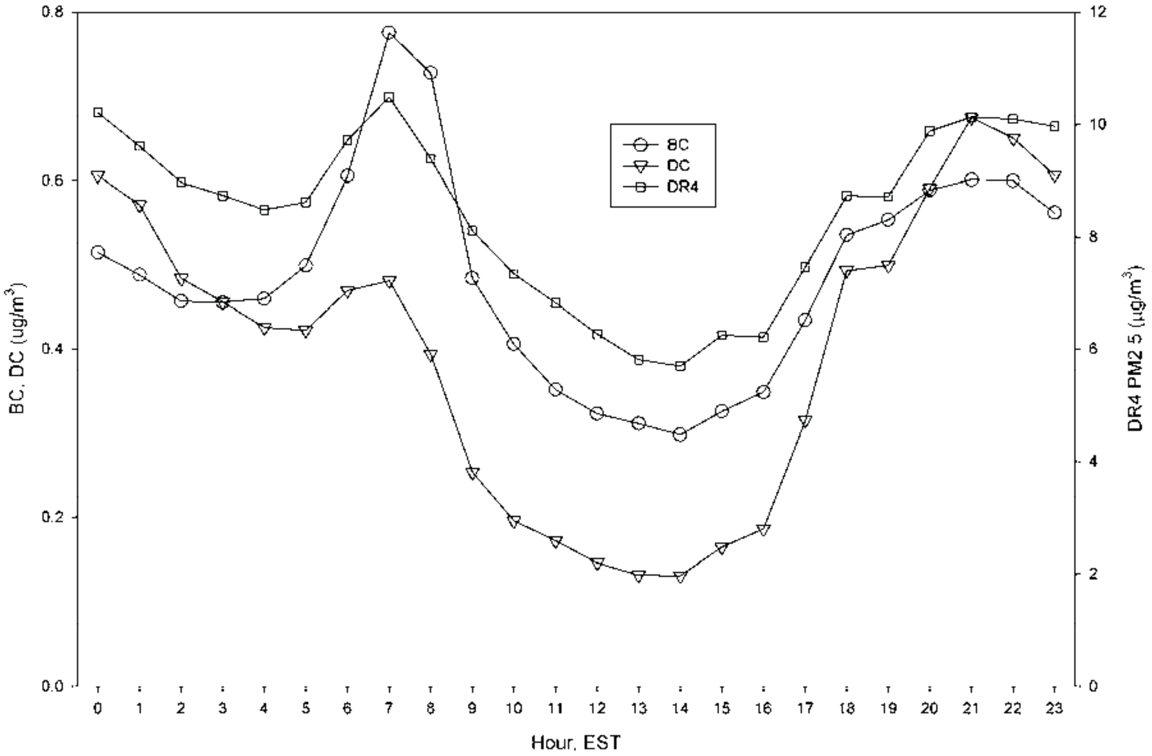

Figure 2-18. Diurnal plot of PM at downtown Saratoga Springs monitoring site.

A similar series of plots across the two Saratoga Springs fixed sites for BC and DC are shown in Figure 2-19, Figure 2-20, and Figure 2-21. The 3-hour smoothed running average of DC shows similar temporal patterns, but with the rural site having generally higher levels of woodsmoke PM. A gradual decline across this time period can also be observed, with the exception of a spike at the rural site on the evening of March 7.

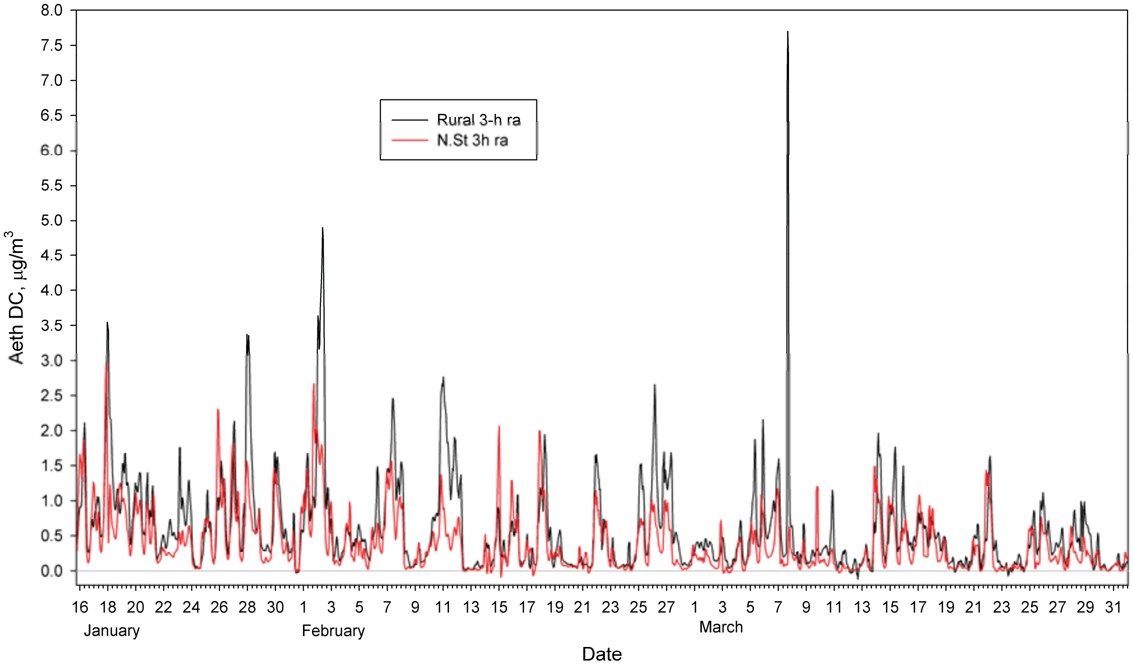

Figure 2-19. Time series plots of estimated woodsmoke $PM_{2.5}$ (3-hour running averages) at Saratoga Springs downtown and rural monitoring sites from January 16 to March 31, 2009.

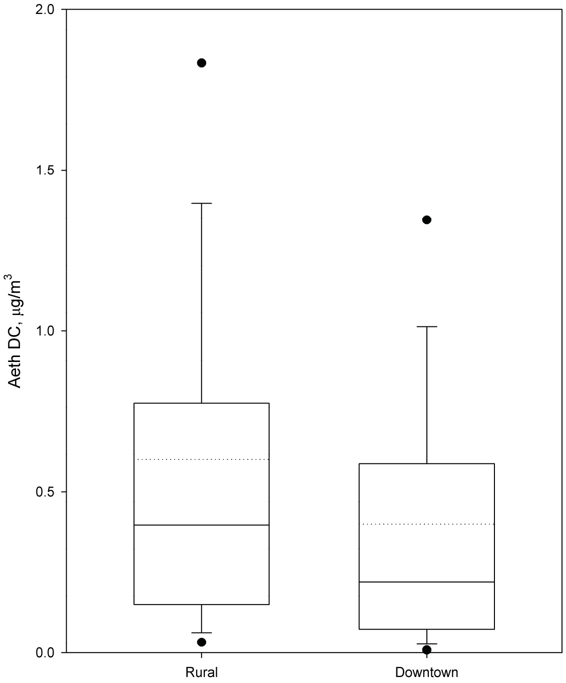

Figure 2-20. Box plots of 1-hour $PM_{2.5}$ concentration distributions from January 16 to March 31, 2009 at Saratoga Springs rural and downtown monitoring sites.

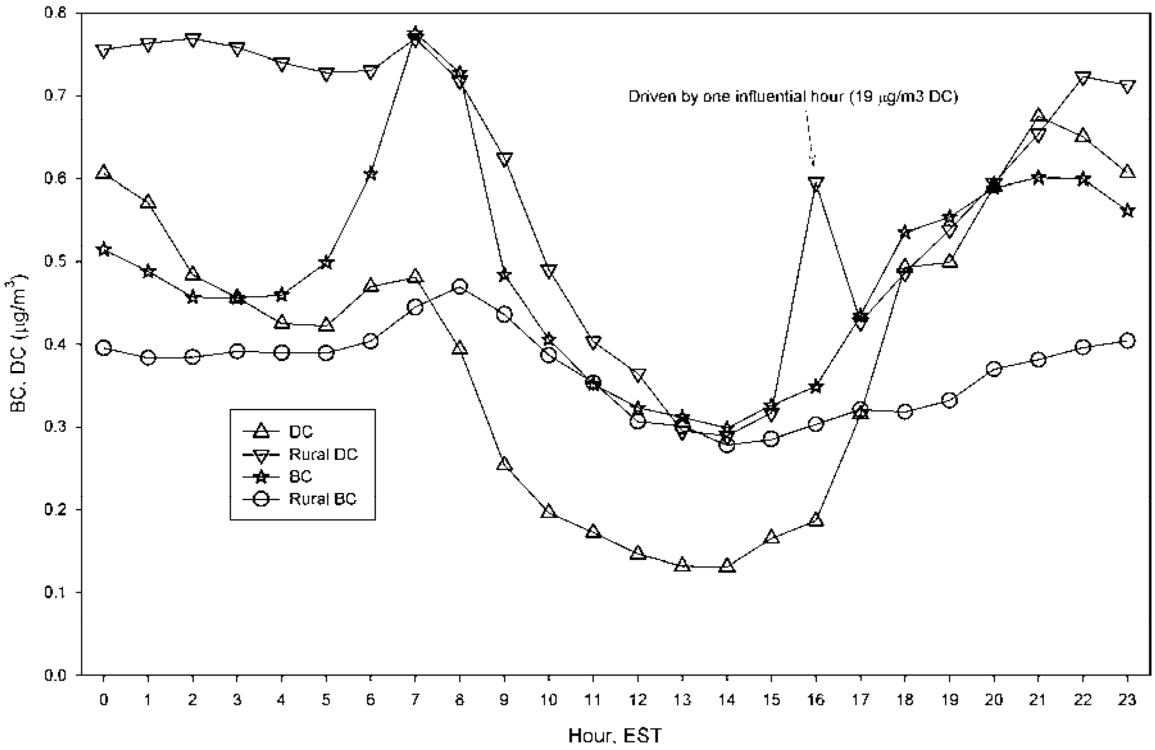

Figure 2-21. Diurnal $PM_{2.5}$ concentration profiles at Saratoga downtown (BC, DC) and rural (Rural BC, Rural DC) monitoring sites.

The diurnal plot shows BC and DC data from both sites. The contrast between BC during morning rush hours is clear, with little to no traffic signal at the rural site. As expected, mid-day BC is on average very similar at both sites. It is interesting to note that DC remains elevated at the rural site even during mid-day; this may be driven by a few local sources being used for heating all the time (such as an outdoor wood boiler or similar large device).

Figure 2-22 shows the DR2 $PM_{2.5}$ data and the Aethalometer DC data for the south loop run of March 14-15. As with the north loop data, periods with elevated $PM_{2.5}$ have a DC woodsmoke signal present. The estimated WS PM from the Aethalometer DC (right axis scale) is generally much higher than the PM from the DR2; at this time we do not have any explanation for this. The highest woodsmoke levels were observed in the urban areas, and also near a large source east of Schuylerville. In general, concentrations for south loop runs were lower than for the north loop; this is expected since the topography of the south loop is much flatter.

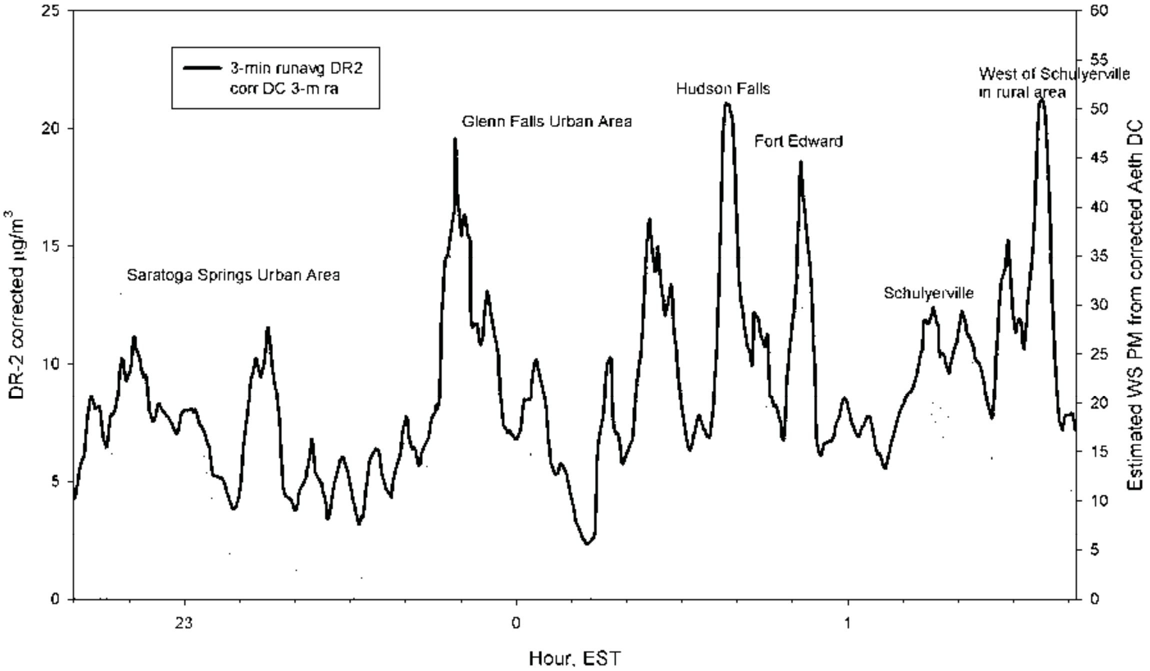

Figure 2-22. Plot of estimated woodsmoke PM (3-minute running averages) from DR2 and Aethalometer (DC) monitoring data for the south loop run of March 14-15, 2009.

OBSERVED LOCATIONS OF OUTDOOR WOOD BOILERS IN A PORTION OF THE STUDY AREA

Currently, New York State does not regulate air pollutant emissions or the proper use of OWBs, but a number of local New York communities do, including placing limits on time of use, and in some cases a complete ban on their installation (NYS OAG 2008). Outside of New York, several states in the Northeast have proposed or adopted state-wide OWB regulations, including Maine, Massachusetts, New Hampshire, and Vermont.[1] In 2007, the U.S. EPA initiated a voluntary certification program with OWB manufacturers to improve their products' emissions performance. The EPA program provides for two levels of certification – a Phase 1 certification level for OWBs that are 70% cleaner than unqualified models, and a Phase 2 certification level for OWBs that are 90% cleaner (U.S. EPA 2009a).

As of November 2009, EPA has already certified 10 OWB models as meeting the more stringent Phase 2 certification level, and 10 year-round models meeting the Phase 1 certification level (U.S. EPA 2009b). The EPA program is voluntary, therefore OWB manufacturers are not mandated to certify their units prior to sale. Uncertified units would be subject only to whatever state or local regulations apply, if any. While much cleaner than uncertified OWBs, the cleanest OWBs certified at the Phase 2 level still emit one to two

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[1] Links to these and other state and local regulations are available at http://www.nescaum.org/topics/outdoor-hydronic-heaters/other-model-regulations.

orders of magnitude more $PM_{2.5}$ on an annual averaged grams per hour basis than residential oil or gas furnaces.

In light of the increasing number of OWBs being sold in New York, an attempt was made to identify OWB locations within a portion of the study region by performing a visual survey of OWBs clearly discernable along a section of the northern loop mobile monitoring route. Figure 2-23 displays a map of 16 identified locations.

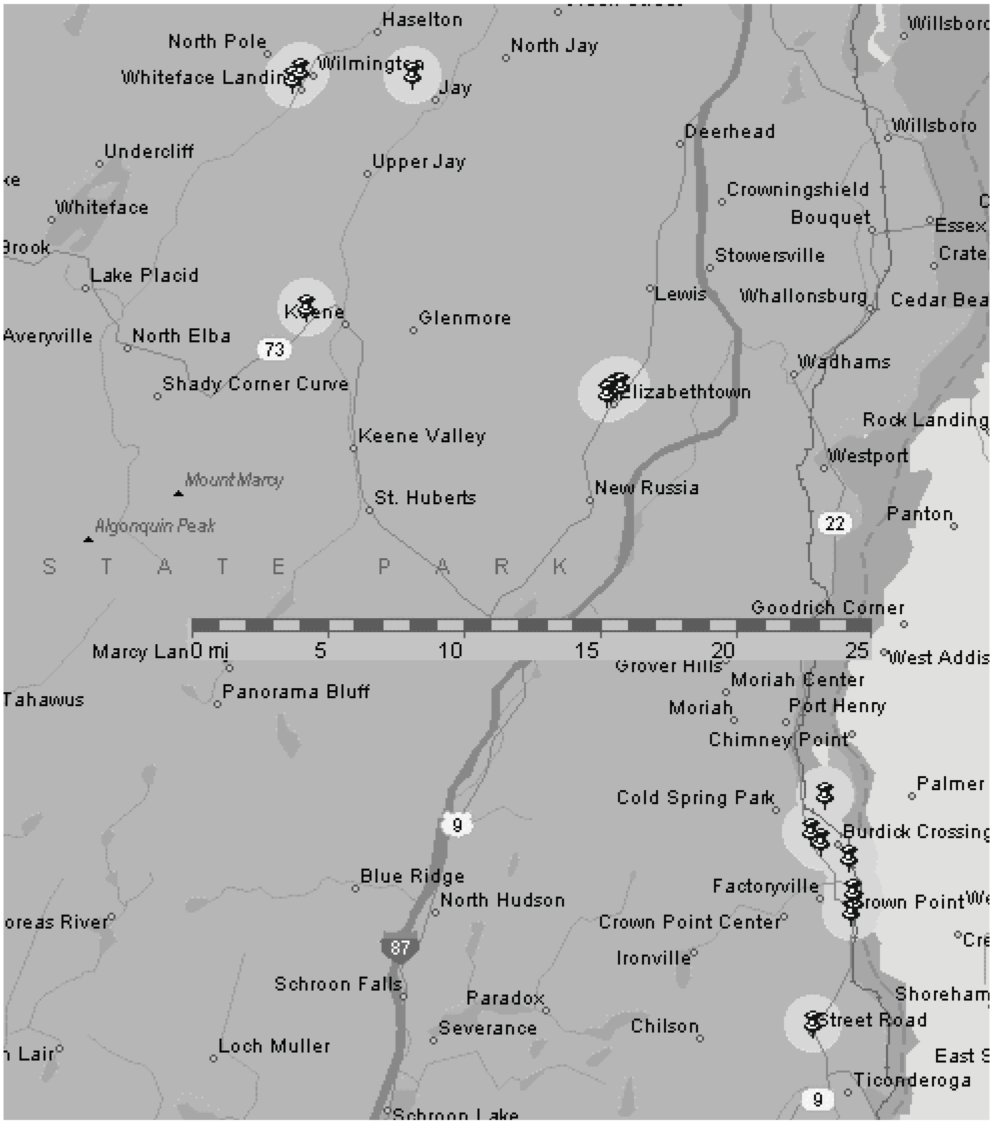

Figure 2-23. Survey of observed outdoor wood boiler locations in a portion of study region.

The OWB survey was not comprehensive, and is highly likely to underestimate OWBs in the surveyed area. An information source containing any detailed OWB location data for New York could not be identified during this study. In the future, it would be useful to seek better information by asking OWB manufacturers to supply data on sales in New York by year and zip code. This could lead to at least a reasonable sense of OWB prevalence at the zip code level. The U.S. EPA might also be in a position to acquire some level of site information for inclusion in future updates of its $PM_{2.5}$ emissions inventory (along with woodstoves, pellet stoves, and fireplaces).

The ability of the mobile monitoring method to detect short term spikes in woodsmoke may also have potential application in developing better information on the locations of OWBs and other high emitting wood combustion sources. Because it can be conducted fairly quickly and easily along roadways in a local area, it may provide some ability to identify specific OWBs or other wood combustion sources that pose acute threats to public health at the local level. The prevalence of high spikes observed during mobile monitoring may also provide emission inventory developers with a better sense of the prevalence of OWBs and other high emitting woodsmoke sources in a region compared to assumptions made in inventory models.

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Section 3

DEVELOPMENT OF AN ESTIMATED RESIDENTIAL WOODSMOKE SURFACE

The overall goal of this project was the development of a spatially-resolved map of estimated woodsmoke particulate matter (PM) concentrations throughout an upstate New York Study area. An assessment of North American emission inventories by NARSTO listed residential wood combustion as a key area consistently identified in a number of reports as being a source of significant uncertainty in emission inventory estimates (NARSTO 2005). The modeling technique described in this section may have general application in New York and other areas in assessing how reasonable estimates are of wood combustion emissions at the local, state, and regional levels, with particular emphasis on their local spatial distribution patterns. Ultimately, improved wood combustion emissions will require improved input data on wood combustion sources, especially potentially high emissions sources such as outdoor wood boilers that are not currently readily captured in routine survey data. Spatial data are important for these local sources given their location in residential areas and the fact that their impact on air quality is more localized than many other sources (e.g., power plants).

The development of the woodsmoke PM concentration map involves the following steps:

1) Estimated woodsmoke PM emissions map at the Census block group level, using readily available datasets and emissions estimates.
2) Enhancement of the map developed in step (1) to incorporate information on individual property heating sources collected from tax assessment data. This step adds resolution by incorporating data at the level of individual homes.

The above two steps result in a map of predicted woodsmoke emissions (not concentrations). Assuming, that emissions are related to concentrations, the emissions map can be used to locate fixed-site samplers and to design a mobile monitoring route along which measurements of woodsmoke PM are made. The location of the fixed sites and the design of the mobile monitoring route follow a specific procedure (steps 3-4 below).

3) Application of a location-allocation algorithm to optimally locate fixed-site samplers. This step uses the predicted emissions map to optimally place a limited number of samplers in the study area in such a way that they will most efficiently provide information on the spatial variability of woodsmoke PM concentrations, while also incorporating additional constraints (e.g., located in populated areas).
4) Application of a network analysis algorithm to design mobile monitoring routes that most efficiently cover the full range of (predicted) spatial variability in woodsmoke PM

concentrations in the study area in a limited amount of time (i.e., by minimizing the distance of the route and therefore the required time spent sampling).

5) Using the designed route(s) from (4), mobile monitoring is conducted by a moving vehicle equipped with a nephelometer, Aethalometer, and logging GPS.
6) From the data collected in (5), all measurements are temporally corrected by a between-day adjustment algorithm and averaged within hydrological catchment areas. The catchment areas are used to relate the measured concentrations to predictor variables in uphill catchment areas. This procedure follows the assumption that under conditions of elevated woodsmoke PM concentrations, drainage flow is the dominant driver for smoke transport.
7) Predictor variables in upslope catchment areas are used to predict the average measured woodsmoke PM concentrations in each catchment area covered by the mobile monitoring.
8) Using the results of the model from (7), the predictor variables are then used to estimate woodsmoke PM concentrations throughout the study area.

The initial phase of the project focused on the development of a map (surface) of estimated residential woodsmoke emissions. Unlike traditional emissions inventories, where total emissions are summed throughout an entire study area, this component was focused on estimating how these emissions are allocated spatially. This map, which characterizes the predicted spatial variability in woodsmoke PM emissions, is used to optimally locate fixed-site samplers and to design mobile monitoring routes for the measurement component of the project.

The study area included the New York counties of Essex, Fulton, Hamilton, Warren, Herkimer, Saratoga, Franklin, and Montgomery.

ESTIMATING THE SPATIAL PATTERN OF RESIDENTIAL WOODSMOKE

The estimation was conducted at the scale of block groups and it included estimation of emissions from four sources: (a) wood heating appliances, including woodstoves and fireplaces with inserts; (b) fireplaces without inserts; (c) pellet heaters, and (d) centralized wood heaters, including outdoor wood boilers.

Estimating the Number of Wood Heating Appliances

Households and wood heater ownership survey data were used to estimate the number of residential wood heaters within each Census block group. The estimation was based on 2006, as this was the most recent Census data that were available.

The number of households in each county during 2006 was obtained from the U.S. Census Bureau (2006 American Community Survey data). The number of households for a block group in 2006 was proportioned based on the 2000 Census Bureau data (using block group and county level data). The fraction of households within each county that own a wood heating appliance (woodstove or wood-burning fireplace insert) was obtained from Simmons Marketing Research (Simmons Market Research Bureau 2003). The fraction of wood stoves owned that were used for heat was obtained from a 2004 Hearth, Patio & Barbecue Association (HPBA) survey (Hearth, Patio & Barbecue Association 2005) (including regional values) and the fraction of fireplace inserts used for heat as compared the total number of fireplace inserts was obtained from the Minnesota state survey (Wu et al. 2005) because no comparable survey was available for this study area.

The number of woodstoves in each block group (2006) was then estimated as:

> *Estimated # of households * stove ownership fraction (adult population) / # of adults per household * usage factor*

The number of fireplace inserts in each block group (2006) was then estimated as:

> *Estimated # of households * fireplace insert ownership fraction (adult population) / # of adults per household * usage factor*

Number of Fireplaces without Inserts

Census Bureau household data and the proportion of households using wood as the main heating fuel were used to estimate the number of fireplaces without inserts at the Census block group level. The fraction of households within each block group that use wood as the main heating fuel was obtained from the 2000 Census. The proportion for a block group is assumed to not change dramatically over time from 2000-2009. This assumption, however, cannot be verified without detailed survey data by year on the fraction of households within each block group using wood as the main heating fuel. If the proportions did change dramatically, for example in response to observed sharp increases in heating oil prices between 2004-2008, it is possible that the methodology described below would underestimate the magnitude of woodsmoke emissions. Even if the wood-burning proportions are assumed to have increased, specific information on the source type breakdown is not available by year so the overall magnitude of emissions may not be accurate.

The ratio of the total number of households that use wood as a heating source (sum of main and other heating source) to those that use it as the main heating source was determined by proportioning the relative wood-burning activity between the rural and urban portions of each block group. This was necessary because the urban and rural ratios differ from each other. (The American Housing Survey has developed these data for a number of categories, including ratios for urban and rural areas inside and outside of metropolitan statistical areas (U.S. Census Bureau 2005). The fraction of urban and rural populations in each block group was determined for all counties from the U.S. Census Bureau data. The number of households that used fireplaces without inserts for heat was then determined by calculating the ratio of the number of households using these appliances for each of the American Housing Survey categories to the total numbers of households in the urban and rural portion of each block group that used wood as a main heating source.

Once the fireplace without inserts number was determined, it was subtracted from the total number of households using wood as heat to obtain the number of households that used wood heating appliances (freestanding stoves and fireplace inserts). The fireplace without insert numbers tabulated by the American Household Survey included gas fueled fireplaces. Consequently, the fireplace without insert numbers had to be adjusted so that only wood-fueled fireplace inserts would be included. This was accomplished by using the HPBA 2004 survey data (DHM Group 2005), which showed the national fraction of fireplaces without inserts that are wood-fueled, and adjusting that fraction to be applicable for each block group. Block group level adjustments were based on the number of households that reported gas (utility, bottled, tank or LP) as their main fuel by county ratioed to the national average (0.577).

1) Urban fireplaces without inserts for each block group were estimated as:

   *Projected # households for year 2006 using wood as main fuel * urban pop % / wood % * (1 - % LGP or NG)*

2) Rural fireplaces without inserts for each block group were estimated as:

   *Projected # households for year 2006 using wood as main fuel * rural pop % / wood % * (1 - % LGP or NG)*

3) Total fireplaces without inserts for each block group were estimated as the sum of the above 1) and 2) estimates.

Even though fireplaces without inserts are estimated as described above, the total number of households with wood heating appliances for each block group could also be estimated by using the total number of households using wood for heat minus the total number of fireplaces without inserts. Given these two approaches, the total number of wood heaters for each block group was calculated by averaging the estimations from the previous section “Estimating the Number of Wood Heating Appliances” and this section.

ESTIMATING THE TOTAL MASS OF WOOD BURNED

Wood Heating Appliances and Fireplaces without Inserts

It is well known that uncertified conventional, certified catalytic and certified non-catalytic cordwood heaters have different characteristic emission factors; consequently the emission factors have been tabulated separately for each of the three types. The proportion of a wood heater type was based on state statistics for year 2000 (MARAMA 2006) with the following proportions: conventional 74.8%, certified catalytic 7.6%, and certified non-catalytic 18.6%. Based upon U.S. EPA's *Emissions Factor Documentation for AP-42*, the dry weight of cords burned per wood heater was assumed to be 3.4 tons, and the dry weight of cords burned per fireplaces without inserts was assumed to be 2.4 tons (U.S. EPA 1992). Total mass of wood burned for each of the three types of heating appliances or fireplaces without inserts for each block group was then estimated as:

> *Total # of appliances of each type * proportion of each appliance type (assumed to be the same for all counties) * total dry weight burned per appliance.*

For fireplaces without inserts, the proportion is 100% and the mass burned is estimated as the total number of fireplaces * the total dry weight burned (2.4 tons).

Pellet Heaters

Pellet heater activity was calculated by using the HPBA and Pellet Fuels Institute (PFI) manufacturer shipment records (Pellet Fuels Institute 2004-2005) to determine the total number of pellet heaters (pellet stoves and pellet inserts) in the U.S. as of 2002 the latest year for which data were available. As there were no sales records, the shipment records were used. Out of business necessity, stove retailers do not maintain a large inventory of pellet heaters, hence stoves shipped to retailers are representative of stoves purchased by consumers. Pellet-fueled centralized heating systems were not included in the calculation because their number is small compared to pellet stoves and pellet inserts and there are no records available for their shipment or sales. Once the total number of pellet heaters in the U.S. as of 2002 was calculated (518,884 units), the fraction of those units present in the MANE-VU region was estimated from PFI pellet shipment records. Once the total number of pellet heaters in the MANE-VU region was estimated, they were proportioned to each block group by the number of households using wood as their main heating fuel as reported by the U.S. Census Bureau for 2000. The final number of pellet heaters for each block group was projected to year 2006 based on the ratio of households between 2000 and 2006.

Total number of pellet heaters was estimated as follows:

*Total # pellet heaters nationwide * fraction in MANE-VU region * block group level fraction of households within the region with wood as main heat*

Total dry pellets burned at a block group for year 2006 was then estimated by multiplying the number of pellet heaters by dry mass burned per appliance. Each pellet heater is assumed to burn 1.25 tons per year (MARAMA 2006).

Centralized Heating Systems (Including Outdoor Wood Boilers)

The activity of centralized cordwood heating systems (the sum of wood-fired furnaces and wood-fired boilers) was estimated using: (1) the fraction of households that reported using wood as their main heating fuel that used centralized heating systems (0.30) as estimated from a Department of Energy, Energy Information Administration 2001 national survey (EIA 2001). (2) The number of households in each block group that used wood as their main heating fuel as projected from the U.S. Census Bureau 2000 data. (3) The average mass of fuel used per appliance, based upon a 2002 MARAMA survey (MARAMA 2002). (4) Multiplication of the amount of wood used per appliance in each block group (both in cords and by mass) based on the heating degree day category in which the county is located. Multiple appliance ownership was not taken into consideration in the calculations.

Centralized cordwood heating systems include outdoor wood boilers (OWBs). Because there are no estimates of the amount of wood burned in OWBs separately from the entire centralized heating unit category, only the number of OWB units, not their activities, were calculated and their activities are included as part of the centralized heater data. The centralized heater category emissions activity is therefore an upper estimate of the OWB emissions.

Calculating Block Group $PM_{2.5}$ Emissions

The AP-42 emission factors from the U.S. Environmental Protection Agency were used to estimate $PM_{2.5}$ emissions for each block group (Table 3-1) (U.S. EPA 1995). This was done by (2) multiplying the total dry mass burned for each heating appliance at a block group level by the corresponding $PM_{2.5}$ emission factor, and (2) summarizing all the $PM_{2.5}$ emissions within each block group. The final estimated block group level total and mean emissions are shown in Figure 3-1.

Table 3-1. U.S. EPA $PM_{2.5}$ emission factors for residential wood combustion devices.

Device	$PM_{2.5}$ (kg per ton)
Uncertified conventional wood heaters	16.9
Certified catalytic wood heaters	8.37
Certified non-catalytic wood heaters	7.51
Pellet heaters	1.53
Fireplaces without inserts	15.27
Centralized cordwood (includes OWBs)	13.82

The above procedure results in estimated $PM_{2.5}$ emissions for each Census block group. To improve the spatial resolution beyond the block group, individual-level property tax assessment data were used to spatially allocate the total emissions within each block group. The main purpose of this component was to allocate the emissions to the residential areas within each block group.

ENHANCING THE WOODSMOKE EMISSIONS SURFACE

Estimated $PM_{2.5}$ emissions at block group level still does not reflect woodsmoke emissions from individual households. The block group level emissions surface was therefore further enhanced by property inventory data from Essex, Hamilton, Herkimer, Fulton, Saratoga and Warren counties. Note that Franklin and Montgomery counties were not included in this step, although they were still part of the final modeling domain.

Fireplace and Woodstove Locations and Density

For the property inventory data, properties with heating sources such as solar, electricity, gas, or none were excluded. In total, 92,991 properties in the six counties with at least one fireplace or wood stove were used in constructing the initial emissions surface (Figure 3-2 left). Housing units without fireplaces or woodstoves were assigned a value of zero. For those with at least one woodburning appliance, each housing unit located inside a block group was assigned the mean emissions estimated for that block group.

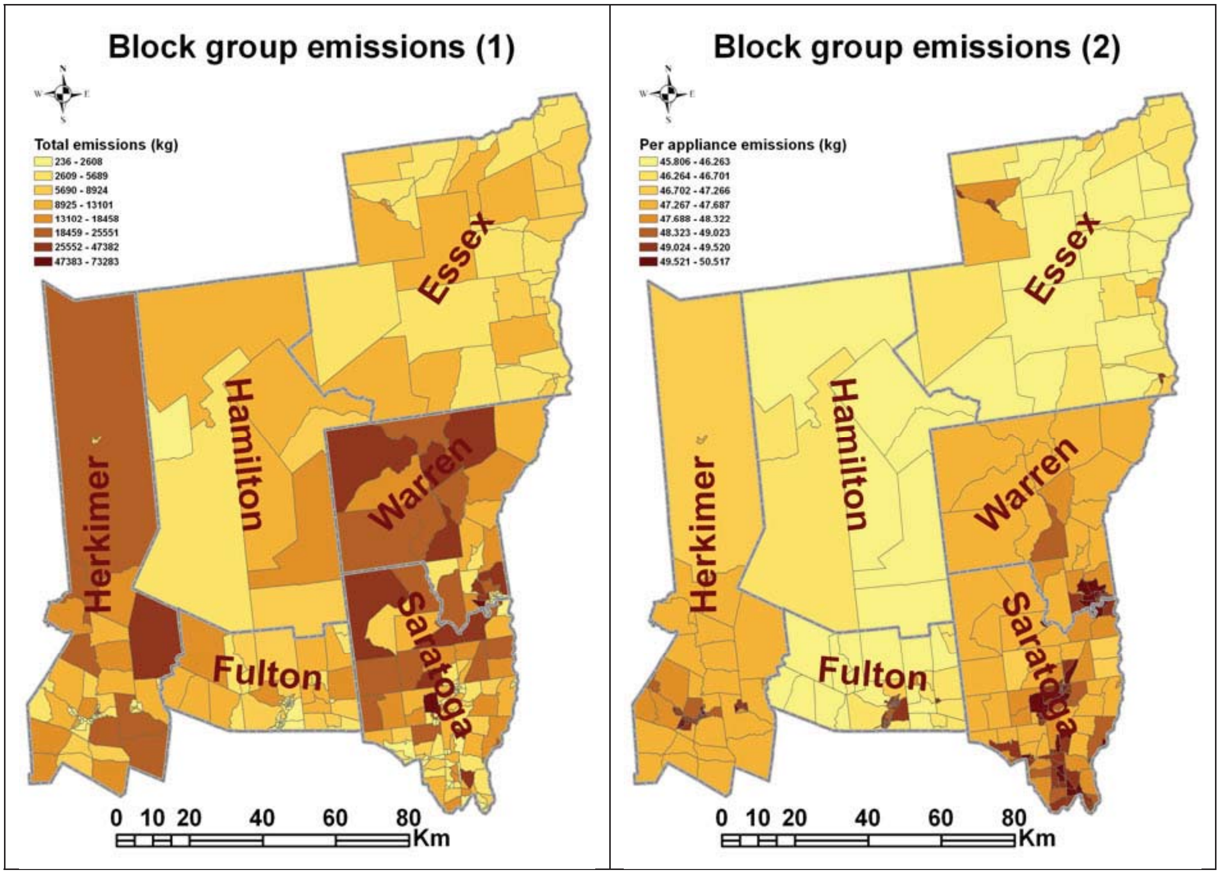


Figure 3-1. Estimated total (1) and mean (2) woodsmoke emissions mapped by Census block group.

A household level $PM_{2.5}$ emission surface was then created using the property assessment data based an inverse distance weighting interpolation algorithm (Appendix B).

The household level emission surface was further enhanced by taking into account the distribution of fireplaces and woodstoves. The fireplace and woodstove data were resolved at the block group level, the smallest standard geographic area for which all Census data in United States are collected. Areas with a higher density of fireplaces and woodstoves were assumed to generate more woodsmoke emissions. A net residential fireplace/woodstove emissions density was calculated by dividing the block group area into the total number of fireplaces and woodstoves within that block group and then normalizing this value over all the block groups (Appendix B). The adjusted emission surface was computed, with the result shown in Figure 3-2 (right).

The methodology's goal is focused on spatially allocating the estimated emissions, based upon readily available data. Further, for the specifics of this project, the emissions estimates are used to provide a general estimate of the spatial patterns to optimally locate sampling sites and design mobile monitoring routes, as described in the next section. The measurements and the more detailed modeling are then used to determine the spatial patterns. If the emissions estimates, however, are to be applied to other areas to estimate the potential impact of woodsmoke $PM_{2.5}$ without any measurements for evaluation, then any improvements in the emissions data will be useful and important to include. For example, updating the proportion of homes using wood as a main heating fuel is one issue, while the locations and numbers of potentially high emission sources such as outdoor wood boilers is another that users may wish to address for future applications.

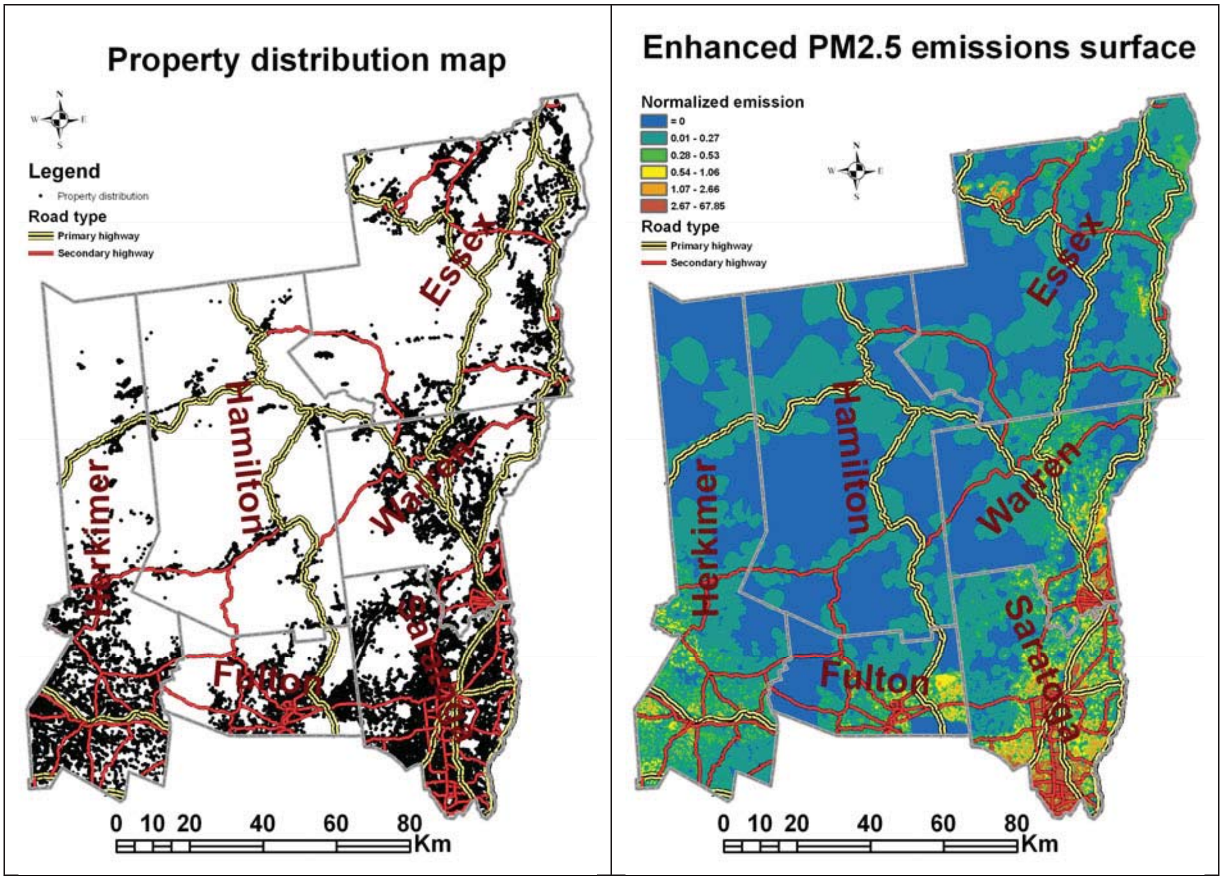


Figure 3-2. Maps of the distribution of properties with at least one fireplace or woodstove (left) and the enhanced $PM_{2.5}$ emissions surface (right).

LOCATION OF FIXED MONITORING SITES AND DESIGN OF THE MOBILE MONITORING ROUTES

The enhanced estimated woodsmoke emissions map of Figure 3-2 (right) is used to optimally locate six fixed-site monitors and to design mobile monitoring routes in a way that maximizes their ability to characterize the spatial variability in woodsmoke PM concentrations within the study region.

Fixed Monitoring Sites

The locations of the fixed site monitoring sites are determined using a location-allocation algorithm (ESRI 2006). Location-allocation models determine the locations for centers (in this case, sampling sites) and the allocation of demands (in this case, the spatial variation of woodsmoke emissions) to centers according to a specific objective. To apply a location-allocation model in this context, a semi-variance surface is first created. This displays the variability (of woodsmoke emissions) as a function of distance. As a semi-variance surface requires identification of a "sufficiently large" distance where any two points on the pollution surface are not spatially correlated (Hewitt 1991; Gilbert et al. 2003), a semivariogram analysis is first used to estimate this distance (shown as the range in Figure 3-3), the distance at which two measurements of woodsmoke would not be expected to be spatially correlated with each other. Calculation details are provided in Appendix C.

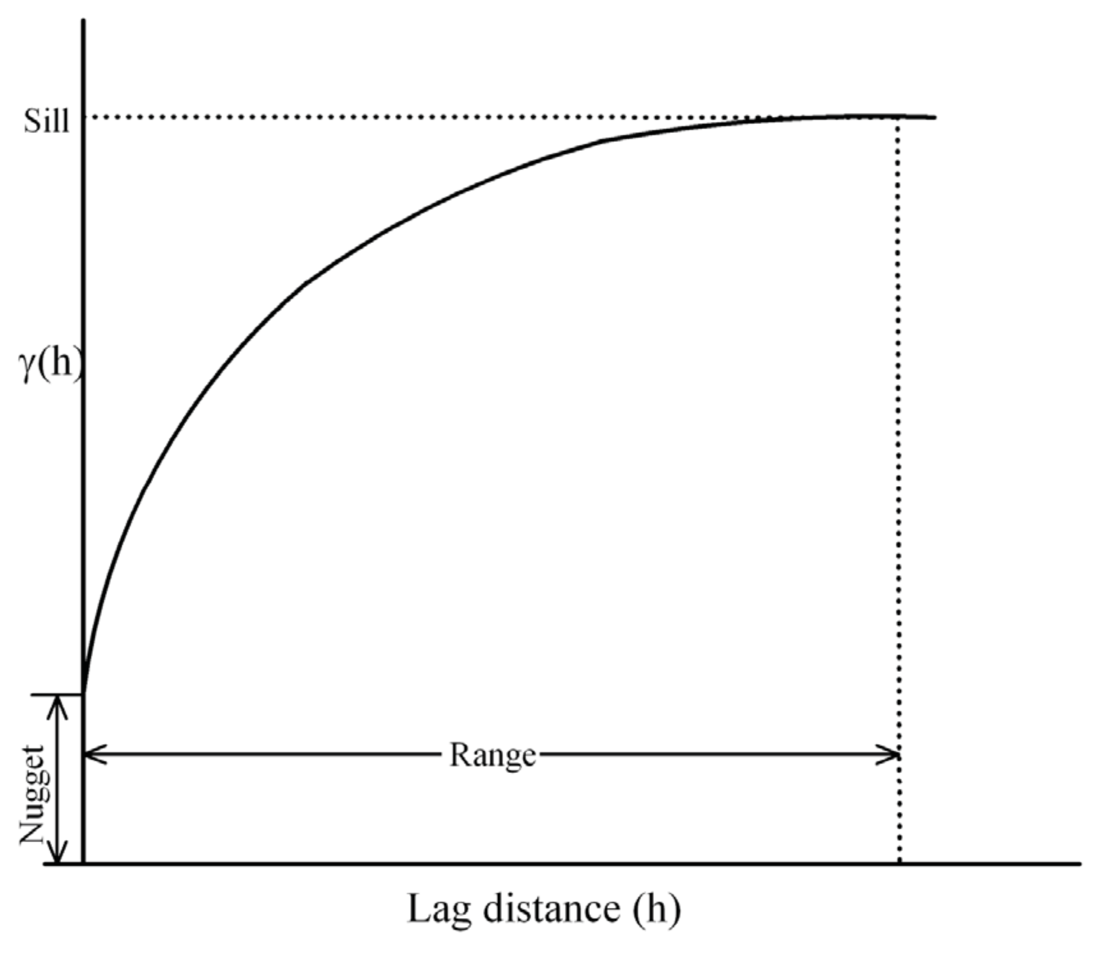


Figure 3-3. A plot displaying a semivariogram.

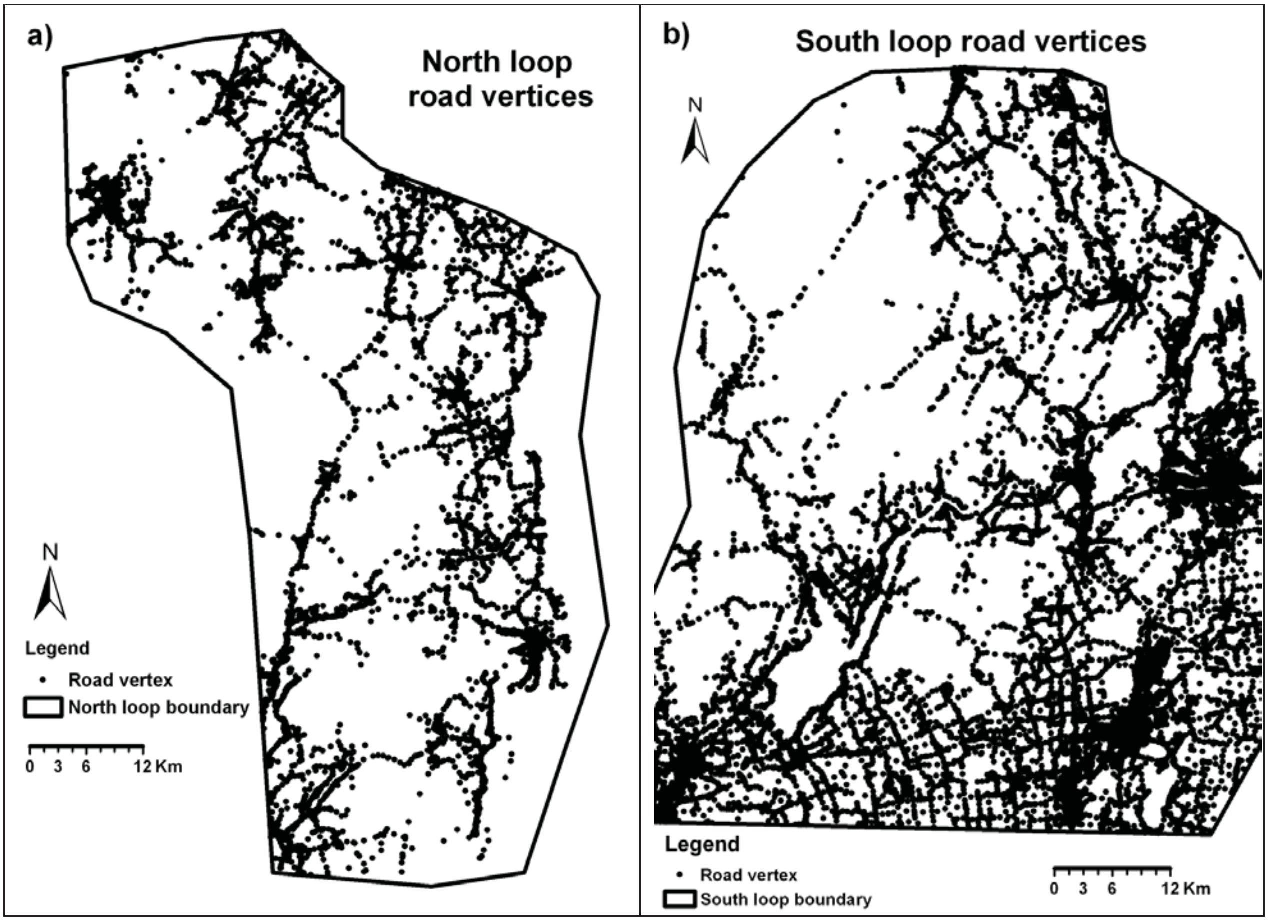


Figure 3-4. North (a) and south (b) loop road vertices converted from the road network of the respective regions. The road network includes primary highways with and without limited access, secondary state and county highways, and local roadways.

Given the study's focus on residential wood combustion, locating fixed-monitoring sites in populated areas is a principal interest. Accordingly, the semivariogram is constrained to use locations close to residences. To accomplish this, locations with higher road network densities, including highway, major, and local roads, are assumed to have a higher proportion of the population. To derive spatial points for estimating the maximum spatial distance of autocorrelation, road networks were converted into points at vertices of each road segment. Based on logistical constraints and knowledge of the study area, two potential mobile monitoring routes were identified, one in the north and another in the southern portion of the study area. The spatial points thus include two parts, one for the north and another for the south loop (Figure 3-4) with, respectively, 7,466 (possible pairs = 27,866,845) and 21,922 (possible pairs = 240,276,081) points. Each lag distance is pinned with an interval of 100 m, and the number of pairs in each lag has an average of 157,940 and is never less than 12,000 to ensure statistical reliability (Burrough and McDonnell 1998).

The results of the semivariograms for the north and south loops are included in Figure 3-5 and suggest a maximum distance of 2000 m. Based on the two figures, the maximum estimated distance of spatial autocorrelation for any two points is 1200 m for both loops, meaning that any sampling sites located more than 1200 m away from each other will not be spatially correlated, based upon the distribution of woodsmoke emissions. Note that this distance is based on the emissions density and does not consider concentrations and transport or dispersion of these emissions.

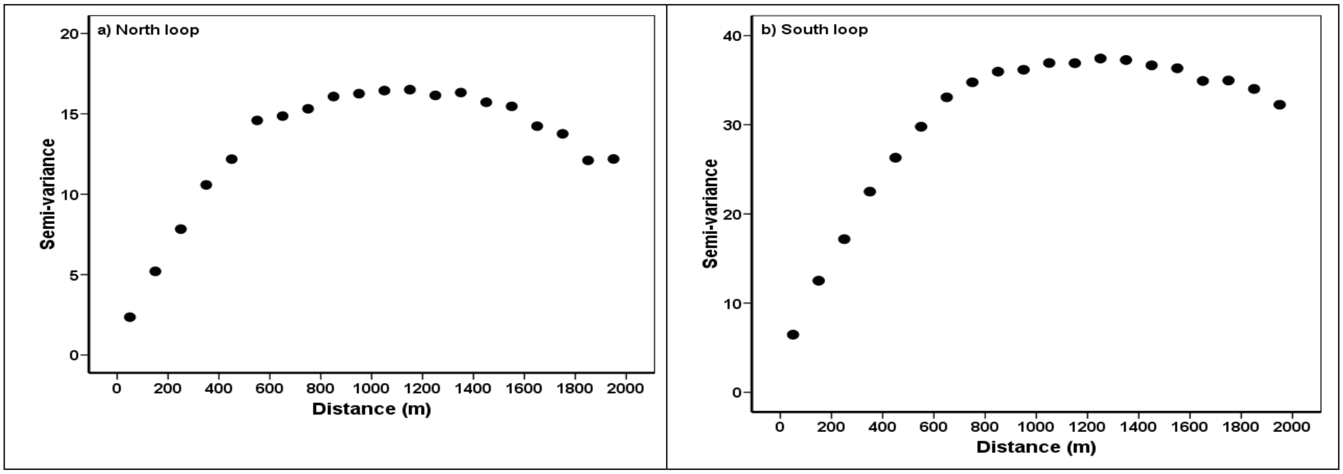


Figure 3-5. Semivariograms of the north (a) and south (b) loops.

Creation of Semi-variance Surfaces

Using the spatial points and considering the range of 1200 m estimated from the semivariogram analysis, estimated semi-variance surfaces were created for the north and south loops (Figure 3-6). Details are provided in Appendix B.

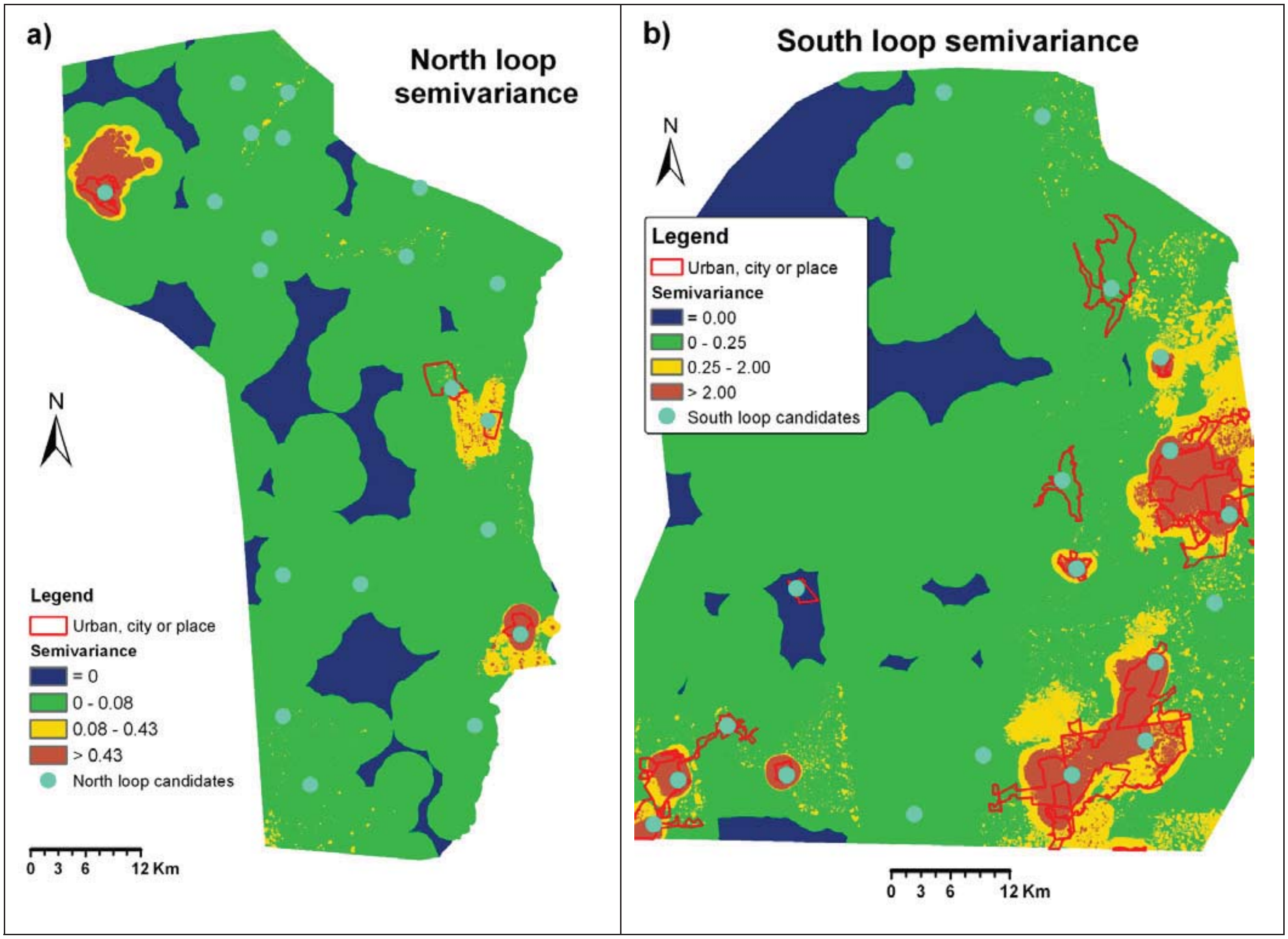


Figure 3-6. Estimated residential woodsmoke semi-variance surfaces and monitoring location candidates for the north (a) and south (b) loops. The redder shades are places of higher population density.

<u>Selection of Candidate Fixed Monitoring Sites</u>

To avoid oversampling only at locations of high spatial variability of residential woodsmoke emissions and to ensure that the minimum distance between two samplers is 1200 m, candidate fixed monitoring sites were located using the following criteria: (1) If possible, they should be located inside the urban areas, (urban, city, or place, as defined by the U.S. Census Bureau), with each urban area having at most one candidate site. These places are displayed in Figure 3-6. (2) If possible, candidate sites should be located at high spatial variability locations (i.e., high semi-variances in Figure 3-6). Again, only one candidate site was located at each high spatial variability cluster to avoid oversampling in a specific location. (3) If possible, monitoring locations should be placed at locations of high road network density (Figure 3-4). Given the study's interest in conducting measurements in populated areas, road network density is used as a surrogate for population density under the assumption that places of higher density road network will also have higher population density. As can be seen in Figure 2-6, urban areas cover only a very small fraction of the residential houses in the study region (see Figure 3-4 and Figure 3-6). Using the above three criteria, each region (i.e., the north and south loops) is separated into multiple clusters and a candidate site is chosen from the highest semi-variance of a corresponding cluster. In total, 40 candidate sites were identified, 20 for the north and 20 for the south loop. Their spatial distributions are displayed in Figure 3-6.

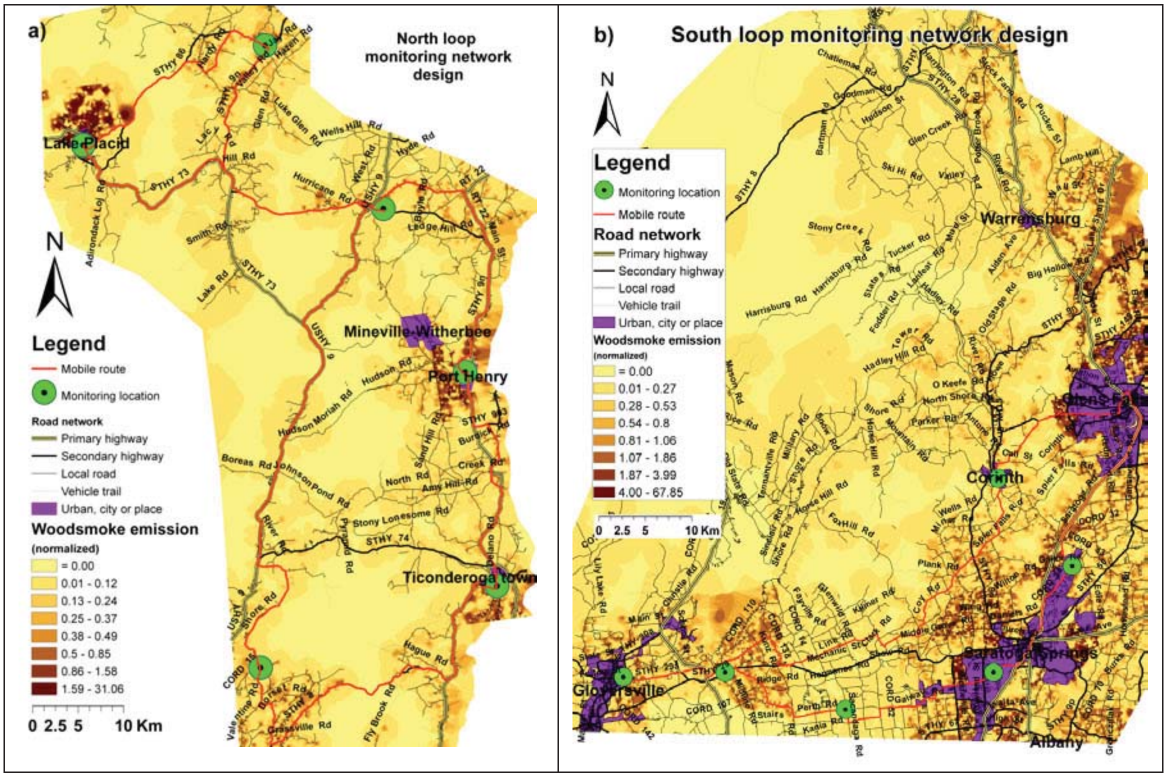


Figure 3-7. Six fixed-site monitoring locations (in green) based on a location-allocation algorithm and corresponding mobile sampling route (in red) using network analysis for the north (a) and the south loop (b).

Fixed Site Monitoring Network Design

The goal of the location-allocation procedure was to then select six primary fixed-site locations from the 20 candidate sites in each of the north or south portions of the region, using the demand surface. Figure 3-7 shows the results of the location-allocation analysis and the optimal placement of the six fixed-sites. Note that at this stage, the north and south portion of the study areas were still treated separately for the monitoring campaign, although original intentions (based on feasibility) were to only focus on one of the portions and to locate six fixed-sites within either the north or south portion of the study areas.

Mobile Route Design

The woodsmoke semi-variance surface (Figure 3-6) along with the locations of the six fixed-site samplers was then used to design routes for mobile monitoring. Network analysis (Wasserman and Faust 1994) was used to select optimized routes (based on semi-variance) for mobile sampling that linked the six fixed site samplers. In most situations, road network analysis was used to minimize the distance traveled or time spent between two or more locations. Another key consideration in the mobile monitoring route design, however, was to also capture to the fullest extent possible a wide range of regional woodsmoke spatial variation. The semi-variance surface was used to achieve this. In addition, the selected routes were constrained to link the six fixed sites within a reasonable driving time (4-6 hours driving time).

The semi-variance was used as a weighting function to define the "costs" of travel. Details of this methodology are described in Appendix B. In brief, semi-variance values are assigned to each road segment to weight the information value of each segment (based on the semi-variance) and estimated travel times for each segment based on the road classification (highway, etc.) and speed limits. These parameters were then utilized in the network analysis.

The optimized mobile routes from the network analysis are displayed in Figure 3-7a for the north loop and Figure 3-7b for the south loop. The north mobile route has in total 298 km and requires approximately 320 minutes to complete. The south loop is 192 km and requires approximately 253 minutes of driving time, based on speed limits.

Originally, sufficient resources were only available to do mobile monitoring along the north or south loops, but not both. Therefore, a number of factors were considered in ultimately deciding to focus initially on the north loop. Later, when more resources became available, a small number of mobile monitoring runs on a shortened southern loop (see Section 1 for more details) were performed. In initially considering which loop to focus on, the intent for the mobile and fixed site monitoring strategies was to capture the greatest degree of variability in predicted woodsmoke emissions in order to fully evaluate the ability of the mapping approach to reproduce the full range of woodsmoke concentrations across the region. The study approach did not want to limit the mobile monitoring to capturing only population centers with relatively high predicted woodsmoke emissions. In order to more thoroughly test the mapping method, population centers with relatively lower predicted woodsmoke emissions were also sought for monitoring in order to determine if the Census data and other information sources truly reflected differences in wood use practices across different population clusters. In addition to population centers, the monitoring strategy also sought to include areas of lower population as well. Furthermore, relatively complex topographic features, such as enclosed valleys, were sought to determine if the catchment basin approach captured the influence of terrain on woodsmoke accumulations in the Adirondacks region.

In consideration of these factors, the mobile monitoring efforts initially began on a shortened north loop (shortened in consideration of the original estimated drive time of about 320 minutes). Both loops provided the same dynamic range in predicted woodsmoke emissions within a feasible driving distance. The challenge of the north loop was the more stringent test it provided for the mapping approach due to the relatively greater topographic range compared to the south loop. Portions of the mobile route followed relatively enclosed valleys near Lake Placid while also traversing more open areas towards Lake Champlain. The north loop provided variability in population, woodsmoke emissions, and topography to either a comparable or greater degree than the south loop, and thus provided a more rigorous test of the mapping technique applied in this project. As a secondary consideration, the north loop was also logistically more convenient for the project team due to its closer proximity to a team member living near the region. This facilitated identifying locations of monitoring sites, interacting with local residents hosting monitoring sites, troubleshooting monitors as problems arose, and collecting data and equipment throughout the study period.

The final mobile routes driven during the study period along with additional details on the fixed site and mobile monitoring techniques are given in Section 1.

RESIDENTIAL WOODSMOKE MODELING

Temporal Adjustments

Corrected residential woodsmoke $PM_{2.5}$ concentrations varied night by night (see Table 3-2). As the purpose was to map and predict spatial patterns in woodsmoke concentrations, corrections for between-day temporal variation were done using Equation (8). This was also applied to the corrected $PM_{2.5}$ obtained during the mobile sampling periods. Examples of sources of temporal variation for regional changes in $PM_{2.5}$ levels include regional meteorological influences and day-of-week influences (e.g., weekday versus weekend).

$$y_{i,j,k} = \frac{\overline{\overline{PM}} * PM_{i,j,k}}{\overline{PM_j}} \tag{8}$$

In Equation (9), $PM_{i,j,k}$ = corrected $PM_{2.5}$ value for 1-second time period i during evening sample period j at location k, $\overline{PM_j}$ = 2-wavelength Delta-C Aethalometer woodsmoke $PM_{2.5}$ average over a fixed monitoring site for sample period j. $\overline{\overline{PM}}$ = average of $\overline{PM_j}$ during all evening sample periods at a fixed monitoring site.

Table 3-2. Descriptive statistics of $PM_{2.5}$ from the mobile residential woodsmoke sampling without between-day adjustments.

Run	Date	Count	Corrected mean $PM_{2.5}$ ($\mu g\ m^{-3}$)
#1	12/25-12/26	33,540	7.54
#2	1/1-1/2	23,103	14.09
#3	1/9-1/9	11,672	3.73

#4	1/15-1/16	33,273	11.49
#4.5	1/25-1/26	17,127	5.76
#5	2/5-2/6	25,245	10.16
#6	2/16-2/17	27,514	1.82
#7	2/24-2/25	21,909	12.43
#8	2/28-3/1	15,095	5.64
#9	3/9-3/10	23,913	7.10
#10	3/14-3/15	26,394	8.74

In adjusting for between-day temporal variation of residential woodsmoke, we first used the six individual fixed sites and the average of the six separately. Adjusted residential woodsmoke concentrations were then correlated with spatial predictors (described in more detail in the following section) to select the best site for adjustment (Figure 3-8, Figures A1-A7 in Appendix C).

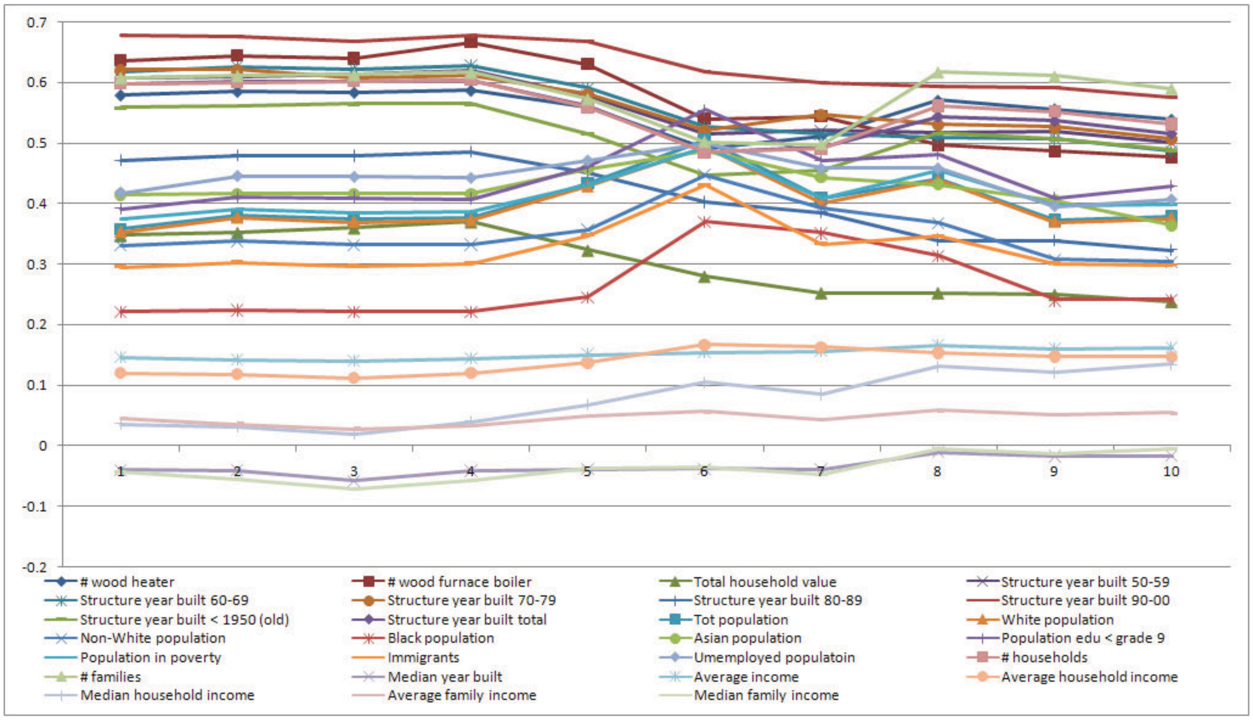


Figure 3-8. Correlation coefficients between corrected residential woodsmoke PM$_{2.5}$ (no between-day adjustment) and the chosen spatial covariates.

Based on the correlation coefficients from the individual sites (Figures A1-A7), the between-day adjustment using the Elizabethtown fixed site best represented the association between residential woodsmoke and the spatial predictors and was used to adjust the measured concentrations for between-day variability to be used in the subsequent modeling. The Elizabethtown site had the lowest average concentration of woodsmoke PM (Figure 3-9). This is consistent with the between-day adjustment approach applied in the model for Seattle (Su et al. 2008), where the adjustments used a monitoring site from a location with low woodsmoke concentration and minimal influence from local sources.

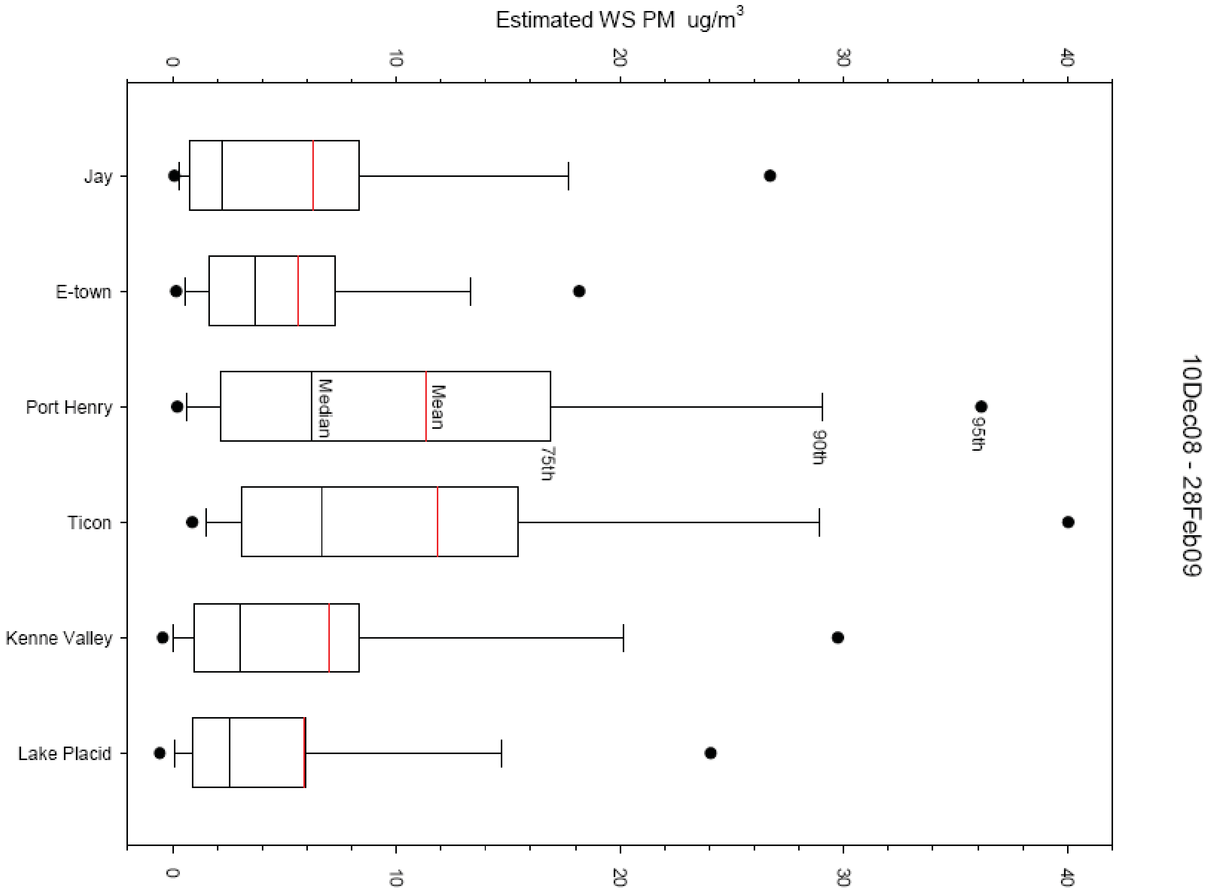


Figure 3-9. The residential woodsmoke concentrations for the six fixed sites during the mobile sampling period (Dec. 10, 2008 – Feb 28, 2009).

Catchment Buffering Technique

The mobile measurements were taken at night during calm, cold stable meteorological conditions when woodsmoke levels were expected to be at a maximum. Under these conditions, the surface wind is influenced by drainage flow and a given measurement location is systematically influenced by emissions from uphill sources. To capture this effect, the hydrological catchments were first defined using U.S. Geological Survey elevation information and a minimum threshold size criterion, and then a search was performed uphill from a given catchment centroid to define which uphill catchment areas drain into that catchment. These concepts are illustrated in Figure 3-10. Figure 3-10a shows an elevation view of terrain potentially defining two catchment basins, A_1 and A_2. If the minimum catchment threshold size is set at A_T, then catchment A_2 is ignored. Catchments were created using a Digital Elevation Model (DEM) with a resolution of 30m. Threshold sizes of 9 km^2, 16 km^2 and 25 km^2 were evaluated and the final size was chosen to maximize model fit. Too large a threshold and there are too few values in the spatial model. Too small a threshold produces small scale features that do not affect air drainage flow patterns. The detailed selection process involved using spatial predictors that have influence on the rate of emission of residential woodsmoke.

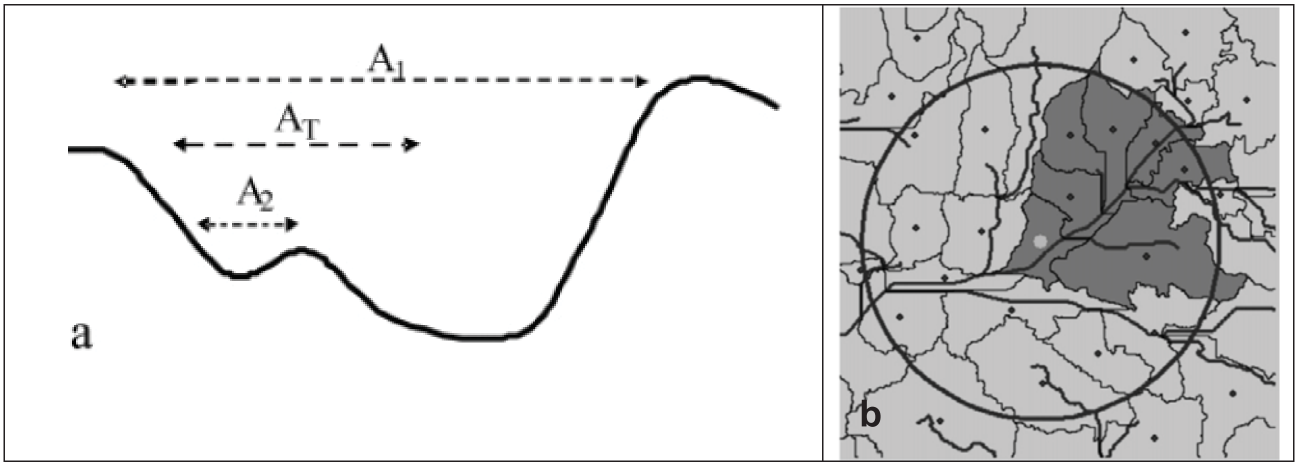


Figure 3-10. Illustration of catchment threshold size (panel a) and upstream search distance (panel b); creek drainages are also shown as dark lines in panel b.

The spatial variables included population, building age, and socioeconomic status, and were obtained at the Census block group level from U.S. Census Bureau for 2000 (Table 3-3). The number of centralized wood heaters and wood heater appliances were calculated based on the survey data as described in the emissions modeling section of this report. A woodsmoke emissions variable was included from an enhanced emission surface. In addition, physical properties from the DEM and remotely sensed data were calculated, including elevation, green vegetation index (i.e., lack of buildings) and soil brightness (an indicator of the presence of buildings).

Table 3-3. Candidate predictors used to model residential woodsmoke concentrations.

Population	Building age	Economic	Physical property
Total	<1950	Average dwelling value	Elevation
White	1951-60	Average household income	Green vegetation index
Non-white	1961-70	Median household income	Soil brightness
Black	1971-80	Median family income	**Emissions**
Asian	1981-90	Average family income	Wood heater appliance density
Immigrants	1991-00	Average income	Centralized wood heater density
Households	Total buildings	Education less than grade nine (pop)	Woodsmoke emissions
Families	Median year built	Population in poverty	
		Unemployment population (age over 25)	

Based on correlation coefficients between corrected residential woodsmoke concentrations and the above chosen spatial covariates, a catchment threshold of 16 km^2 best represented the association between residential woodsmoke and the spatial predictors, and was used as the size of catchment for modeling woodsmoke PM. Figure 3-11 demonstrates the 16 km^2 threshold catchment and the corrected residential woodsmoke over all 10 runs.

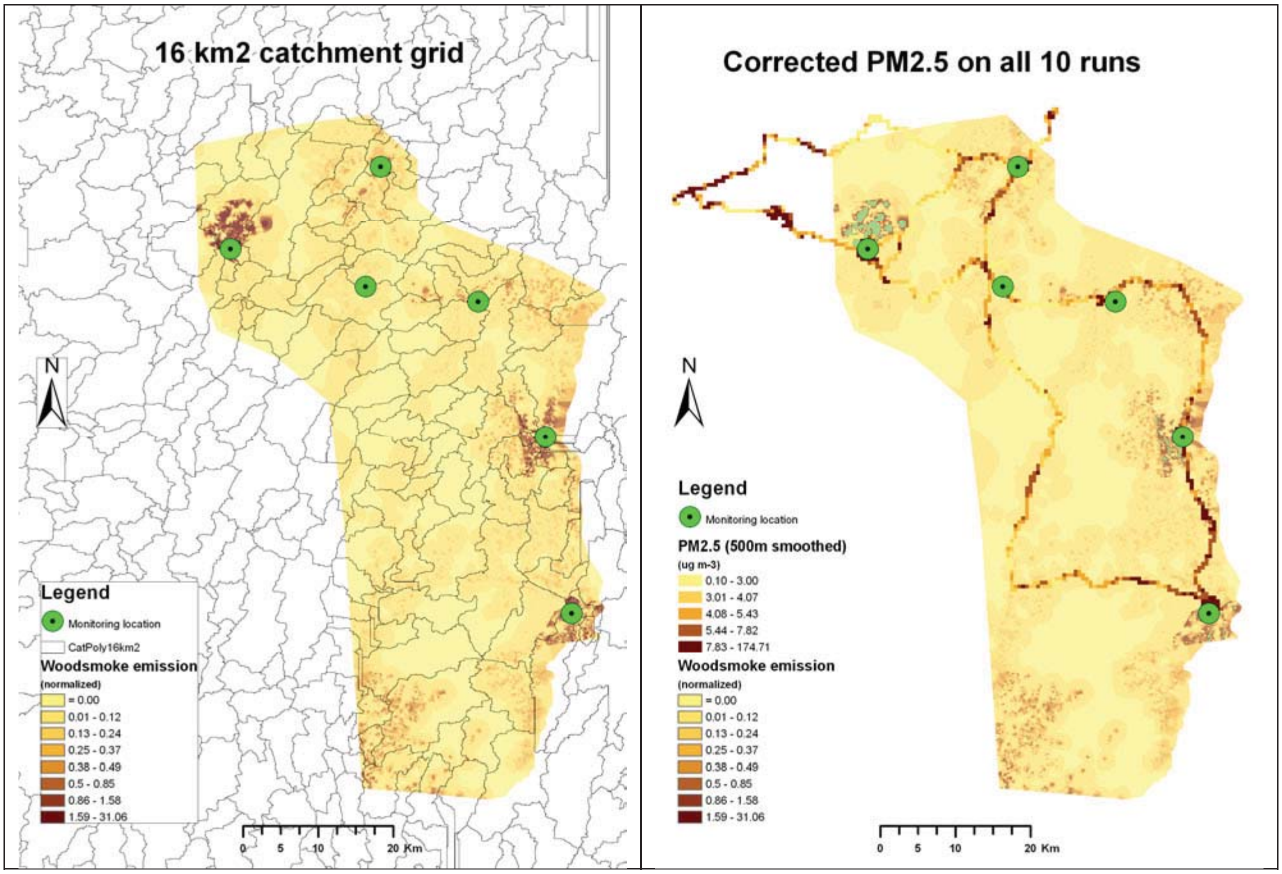


Figure 3-11. Catchment of threshold 16 km^2 on the north loop (left) and the smoothed residential woodsmoke concentrations over all 10 runs (right).

Once the catchments were defined, a specified distance uphill was searched for adjacent catchments. For a typical drainage wind speed of 1 m/s maintained over a 3 hour period, an upstream influence of approximately 10 km would be expected. Figure 3-10b illustrates this concept. Catchment centroids are shown as dark points and the centroid of the catchment of interest is shown with a larger dark point. The actual creek beds are the thin light gray lines. The final adjusted mobile measurement values were averaged within the catchment of interest and used as the dependent variable in a land use regression model. The circle extends radially outward from the centroid of this catchment to the upstream search boundary. If the centroid of an upstream catchment is within the search boundary, then that catchment is included in the final buffer area associated with the catchment of interest (shaded region). In this example, not all catchments are upstream (i.e., uphill) of the catchment of interest. This procedure was repeated over all catchments in the model region. Upstream search distances from 1 to 10 km were examined. The final distance used over was chosen to maximize model performance, as determined by the weighted correlation defined by:

$$Corr_i^w = \sqrt{\frac{\sum_{j=1}^{n} Corr_{i,j}^2}{n-1}}$$

$Corr_{i,j}$ represents the correlation between the temporally-adjusted light scattering measurements and covariate j at an upstream search distance of i km, and n is the total number of selected covariates for the modeling. The spatial covariate values were determined within this final buffer area. Some of the covariates were derived from Census data that are aggregated to census block groups. For those block groups that straddled the buffer boundaries, a fraction of the block group variable was assigned based on the fraction of the block group area that was inside the buffer. The average buffer values of the covariates were regressed on the dependent variable representing the catchment of interest.

MODELING RESIDENTIAL WOODSMOKE

Spatial Covariates

The dependent variable in the land use regression models was $\overline{Y_x}$. This represents the spatial average across each catchment of the temporally adjusted and corrected mobile woodsmoke values. For each catchment area, the corresponding catchment buffer was established based upon the uphill search procedure described earlier. Predictive spatial variables included stove usage factors, population, building age, socioeconomic status (Table 3-3) and physical properties described earlier and were aggregated from the relevant buffer associated with $\overline{Y_x}$.

Spatial Models

The resulting land use regression models for both the measured and between-day adjusted residential woodsmoke are summarized in Table 3-4. The catchment buffering approach using measured concentrations gave similar results in all cases to the catchment buffering approach using between-day adjusted concentrations. Woodstove emissions (base-case model) were first examined as a single predictor of nighttime woodsmoke PM (variable group A in Table 3-4). Wood heater appliances, centralized wood heaters, and the enhanced woodsmoke emissions surfaces predicted 30-40% of the variance in both measured and adjusted residential woodsmoke concentrations. The predictability of the final enhanced emissions surface was also tested on measured woodsmoke PM without using the uphill search function. This was found to explain 32.3% of the variance from the measured and 27.8% from the between-day adjusted measures.

Models were then examined that excluded the emission variables listed in Table 3-3; these models performed better than the previous ones with 52% of the variance explained. Dwelling value (+), non-white population (+), # families (+) and elevation (-) were consistent across the models. The best model in both regions used catchment-based buffering and included both an emissions variable (i.e., centralized wood heater density) as well as other socioeconomic status variables. The model performance in terms of predicted measured woodsmoke improved slightly as the upstream search distance increased from 1 to 4 km, and started to decrease from 5 to 10 km. In both situations, the models explained 58% of the variance in measured and adjusted woodsmoke concentrations. Similar spatial patterns held for the predicted adjusted woodsmoke, except a far decrease after 5 km. Centralized wood heater density (+), non-white population (+), white population (-), total structures built (+) and elevation (-) were consistent across both models.

Table 3-4. Prediction of nighttime residential woodsmoke by land use regression.

Modeling type	Variable Groups	R^2	Intercept	Variable(s)[3]	β	p-value
Measured[1]	A	0.44	4.208	Centralized wood heater density	2523.504	<0.001
		0.34	5.715	Wood heater appliance density	102.464	<0.001
		0.27	6.301	Emissions surface	4.298	<0.001
	B	0.52	7.942	Dwelling value	0.0003	0.05
				Non-white population	0.03	0.01
				# families	20.215	<0.001
				Elevation	-0.007	<0.001
	C	0.58	7.913	Centralized wood heater density	2423.836	<0.001
				Non-white population	0.048	0.001
				White population	-0.007	0.015
				Total structure built	0.007	0.081
				Elevation	-0.008	<0.001
Between-day adjusted[2]	A	0.44	5.291	Centralized wood heater density	2380.843	<0.001
		0.41	6.599	Wood heater appliance density	105.193	<0.001
		0.23	7.199	Emissions surface	3.347	<0.001
	B	0.53	8.235	Dwelling value	0.0005	0.001
				Non-white population	0.04	0.006
				White population	-0.006	0.021
				# families	19.864	0.001
				Total structure built	0.01	0.019
				Elevation	-0.005	0.006
	C	0.58	10.361	Centralized wood heater density	2596.175	<0.001
				Non-white population	0.049	0.001
				White population	-0.009	0.001
				Total structure built	0.012	0.004
				Median household income	-8.90E-09	0.091
				Elevation	-0.005	0.006

A = woodstove use variable only; B = socioeconomic status variables and physical properties only (see Table 3-3): C = best fit model.

[1] No between-day adjustment was made.

[2] Adjusted based on Elizabethtown Aethalometer data.

[3] All the covariates had an uphill search distance of 4 km except median household income (3 km), elevation and total structure built (on uphill distance).

Given concerns regarding potential non-normality of the woodsmoke concentrations and co-linearity between the white and non-white population (Pearson correlation = 0.7) variables in several of the models, additional models were built using only the non-white population variable and evaluated the distributions of the woodsmoke measurements. Models in which the total population was the only population variable were also attempted, but this variable was not significant (Pearson correlation between total population and non-white population = 0.73) and therefore not included in multivariate models. The initial models presented above are retained for ease of interpretation, but the new models are also presented below as a sensitivity analysis. Specifically, the concentrations of woodsmoke without any between-day adjustment were found to be highly right-skewed and were consequently (natural) log transformed. A new model of these log-transformed data was constructed and explained 45% of the variance (Table 3-5). After applying between-day adjustments to the measured woodsmoke $PM_{2.5}$ concentrations, the resulting distribution was near-normal and the (log) transformed distribution was strongly right-skewed. Therefore, no transformation was applied to the between-day adjusted concentrations. A revised best-fit model with a single population variable for the between-day adjusted measurements is also presented in Table 3-5. Note that in all models the most important predictor variable based on the size of the coefficient and its explained variance in univariate models is the centralized wood heater density. Including this variable alone explains 44% of the variability in the measured woodsmoke concentrations in both the unadjusted and adjusted models. Addition of other spatial variables only improves the models marginally.

Table 3-5. The best fit model of measured residential woodsmoke concentrations.

Modeling type	Variable Groups	R^2	Intercept	Variable(s)[3]	β	p-value
Measured[1]	C[#]	0.45	1.981	Centralized wood heater density	209.677	<0.001
				Non-white population	0.004	0.035
				Elevation	-0.001	<0.001
Between-day adjusted[2]	C[*]	0.49	8.965	Centralized wood heater density	2231.464	<0.001
				Non-white population	0.024	0.023
				Median household income	-1.14E-008	<0.039

C = best fit model. Dependent Variable: [#]log transformed $PM_{2.5}$; [*]$PM_{2.5}$ after between-day adjustment. [1]No between-day adjustment was made. [2]Adjusted based on Elizabethtown Aethalometer data.

For both models, all the chosen spatial covariates are statistically significant at a 0.05 level with signs in the expected directions. For the unadjusted model and between-day adjusted models, the maximum variance inflation factors were 1.33 and 1.22, respectively. The tolerance of each variable in the unadjusted and adjusted models were greater than 75% and 81%, respectively, demonstrating a lack of significant co-linearity between the chosen spatial covariates.

Nonlinear models were also built for the between-day adjusted data, but the prediction model R^2 was not improved, with the highest model R^2 of 0.33.

In order to verify that the modeled values (from the DR4 mobile measurements) were indeed reflecting woodsmoke concentrations, six fixed monitoring sites using Aethalometer DC were set up and their results were compared with the mobile DR4 measurements. The Aethalometer DC monitors at the six fixed sites ran continuously during the mobile sampling period. The fixed site measurements from 8 p.m. to 4 a.m. local time were extracted for each mobile running period and aggregated to a heating season mean (Table

3-6). As seen from Table 3-6, Port Henry, Ticonderoga and Lake Placid have the highest woodsmoke concentrations, consistent with the original monitoring site design. Jay and Keene Valley are intermediate, with Elizabethtown having the lowest woodsmoke concentrations. The modeled mobile DR4 concentrations at the catchments that included the six fixed sites were then compared to the measured DC concentrations. Figure 3-12 shows the scatterplot of seasonal average DC at each fixed site in the north loop versus the corresponding values of the catchment average (Y_{x1}, Figure 3-12 upper plot) and the between-day adjusted values (Y_{x2}, Figure 3-12 lower plot). Both Y_{x1} and Y_{x2} variables showed high correlations with the fixed site DC measures ($R^2 = 0.67$ for Y_{x1} and 0.80 for Y_{x2}). This demonstrates that the mobile DR4 measurements were indeed mainly from residential woodsmoke and the models used to estimate residential woodsmoke concentrations are reliable.

Table 3-6. Fixed site residential woodsmoke concentrations based on Aethalometer (DC) monitored $PM_{2.5}$ (µg/m-3).

	Fixed monitoring site						
Run*	Jay	Elizabethtown	Port Henry	Ticonderoga	Keene Valley	Lake Placid	Average
#1	8.95	8.63	28.53	12.22	7.78	12.82	13.16
#2	39.78	14.40	25.78	32.08	48.99	39.45	33.41
#3	5.44	4.65	31.00	29.12	6.43	21.46	16.35
#4	44.17	10.11	28.30	46.45	14.37	65.32	34.78
#4.5	8.23	2.45	8.22	6.50	2.63	6.37	5.73
#5	26.82	10.05	24.36	52.39	19.22	25.80	26.44
#6	2.58	2.69	1.79	3.69	2.25	3.37	2.73
#7	9.92	5.23	35.50	22.34	9.75	17.53	16.71
#8	15.46	5.32**	18.72	3.37	7.35	10.15	10.06
#9	9.32	2.02	17.71**	9.09**	5.91	2.94	7.83
#10	2.28	9.36	21.13**	19.20	19.75	13.78	14.25
Average	15.72	6.81	21.91	21.50	13.13	19.91	16.50

* Statistics for each run are the average DC concentrations measured starting at 8 p.m. and ending at 4 a.m.

** Interpolated based on a different fixed site having the highest correlation with this site.

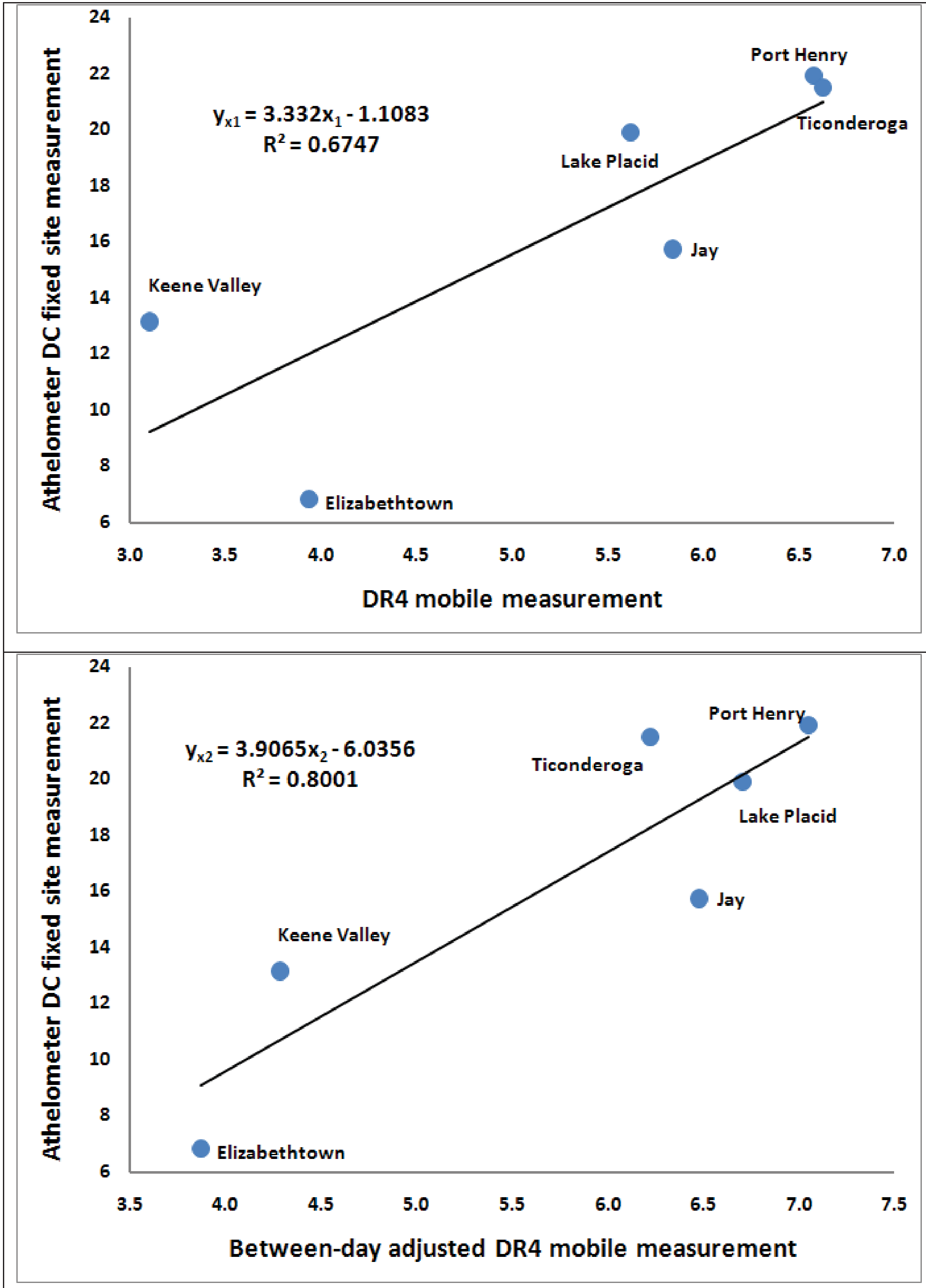


Figure 3-12. Comparison of fixed-site Aethalometer DC concentrations with modeled DR4 concentrations without (Y_{x1} on upper plot) and with between-day adjustment (Y_{x2} on lower plot) (X-axis: µg m^{-3}; Y-axis: µg m^{-3}).

Maps of the modeled woodsmoke PM concentrations for Essex County with the average mobile monitoring values are presented in Figure 3-13.

Estimating Population Exposure

The population exposure for Essex County, where the extensive mobile monitoring was conducted, was estimated based on the residential woodsmoke prediction surfaces from the north loop (Table 3-7). This was also estimated for the other seven counties in the study area. Considering the population residing in areas with the upper third of modeled woodsmoke $PM_{2.5}$ concentrations as exposed, more than 50% of people along the north loop and in Essex County were estimated to be exposed to residential woodsmoke. The proportion was even higher for the non-white population (62% exposed on average). For the whole research region, the percentage of the population exposed to residential woodsmoke was lower, with an average of 26% with a higher proportion of the non-white population exposed (37%).

Table 3-7. Estimated population exposure to residential woodsmoke in Adirondacks region.

	Population	Exposed A*	%	Exposed B*	%	Average %
North loop						
Total population	57000	30600	0.54	28800	0.51	0.52
Non-Hispanic whites	54170	28870	0.53	27000	0.50	0.52
Non-White population	2830	1730	0.61	1800	0.64	0.62
Seven counties						
Total population	610960	187730	0.31	127670	0.21	0.26
Non-Hispanic whites	588170	177890	0.30	120860	0.21	0.25
Non-white population	22790	9840	0.43	6810	0.30	0.37

* Exposed A = estimated without using the between-day adjustment method and Exposed B = with the adjustment.

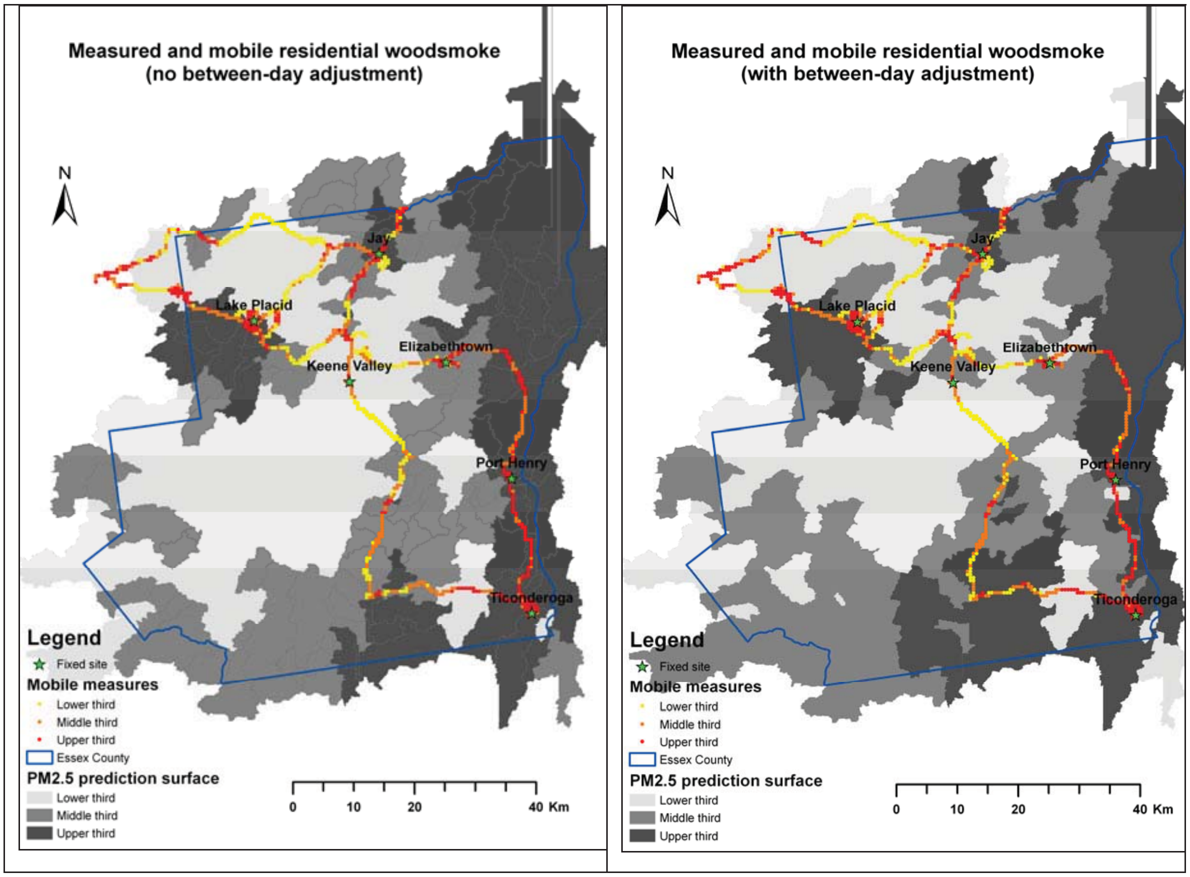


Figure 3-13. Modeled residential woodsmoke surface without (left) and with (right) the between-day adjustments for Essex County.

The final prediction surfaces for the seven counties (extended from the original six counties to include Montgomery) are displayed in Figure 3-14.

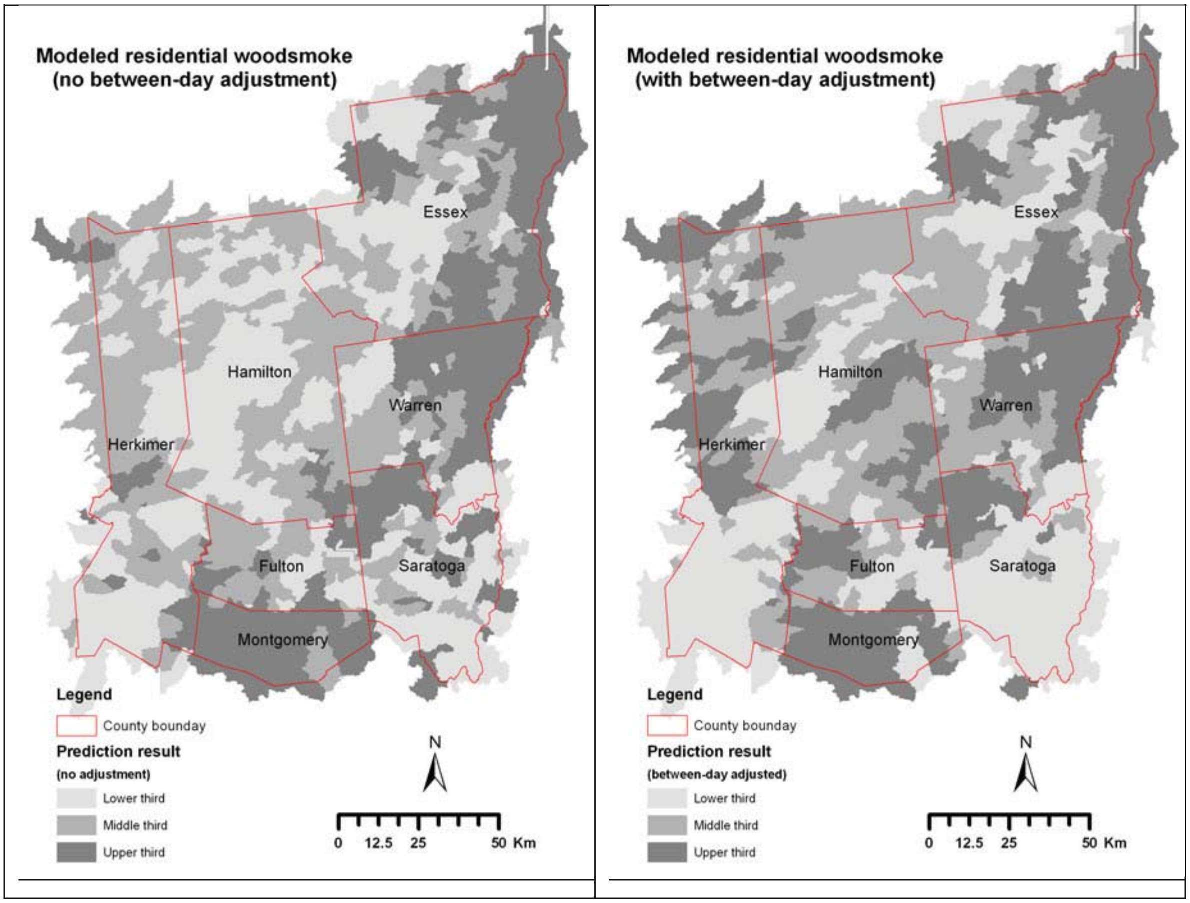
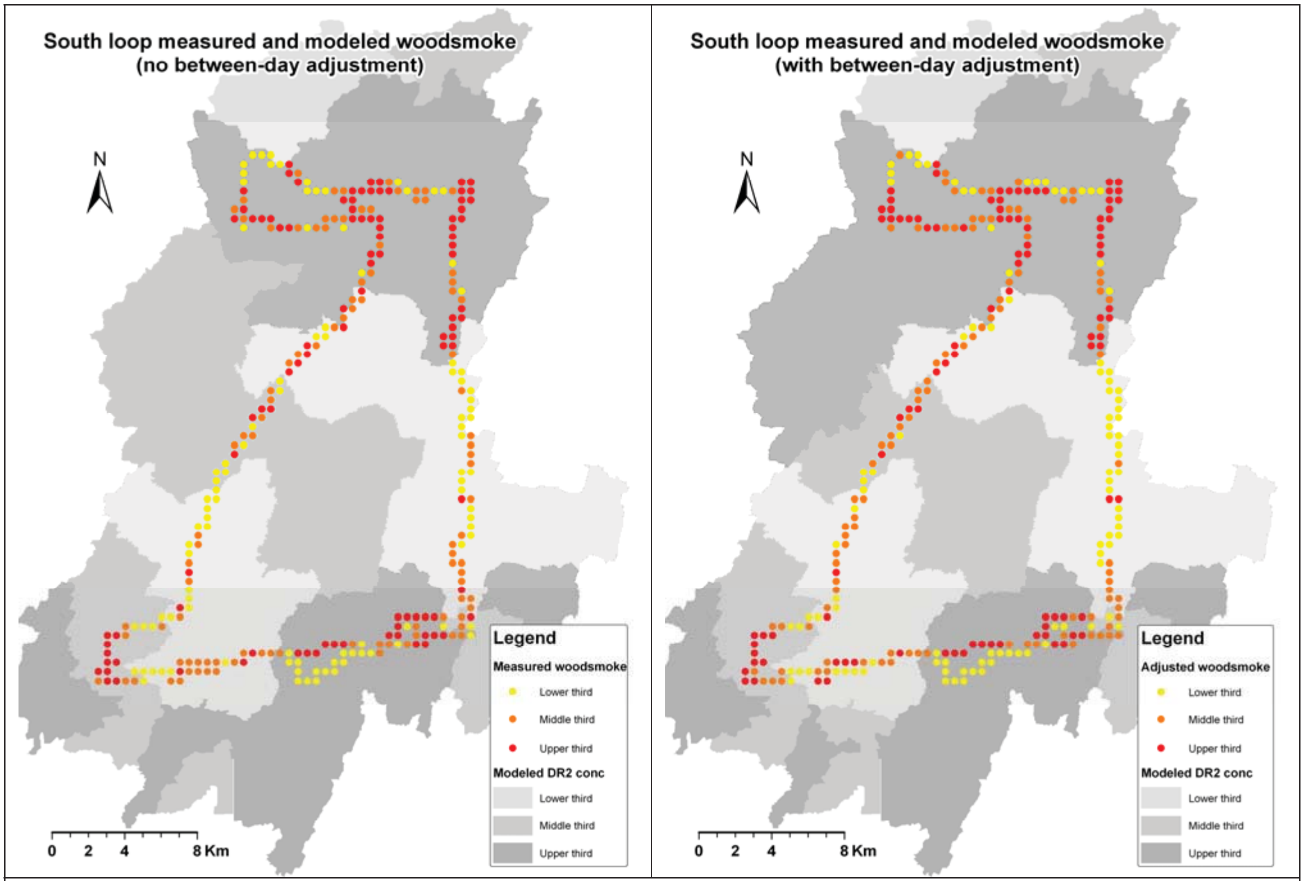


Figure 3-14. Modeled residential woodsmoke spatial patterns without (left) and with (right) the between-day adjustments for seven counties. Darker gray shades indicate higher modeled woodsmoke levels.

Sensitivity Analysis Using South Loop Data

Three nighttime mobile measurements of residential woodsmoke using the DR2 nephelometer were conducted on February 28/March 1, March 15/16 and March 20/21. A fixed site at Saratoga was set up to measure black carbon and DC for the winter period when residential woodsmoke is widespread. The sampling period ranged from January 15 to April 1, 2009.


South loop measured and modeled woodsmoke (no between-day adjustment)

South loop measured and modeled woodsmoke (with between-day adjustment)

Figure 3-15. South loop measured and modeled residential woodsmoke concentrations.

Similar to the north loop, the between-day adjustments were made to the three night mobile measurements based on the measurements from Aethalometer DC at Saratoga site. The average measured and between-day adjusted residential woodsmoke concentrations in the south loop were 5.50 and 5.62 μg m^{-3}, respectively: much lower than the north loop concentrations (mean 8.37 μg m^{-3}). The tertile maps for the measured and between-day adjusted residential woodsmoke concentrations smoothed at 500 m interval are displayed in Figure 3-15 along with the modeled concentrations (based on the mobile measurements from the north loop). Unlike the north loop mobile monitoring results, the high woodsmoke concentrations are not as highly clustered and this reflects smaller and shallower valleys. At the same time, the northern and southern areas of the south loop showed higher concentrations than the middle area. To identify if the prediction models for the north loop could be extended to predict woodsmoke concentrations in the south loop, catchments of threshold 16 km^2 in size were also created. The spatial predictors used for the final models on the north loop were used in the uphill search for 1-10 m. The correlation matrices between the spatial covariates and the mobile measurements on the south loop are displayed in Figure 3-16. Comparing Figure 3-16 with Figure 3-8, the distance of uphill influence on the south loop is far greater than on the north loop, and the drainage process is much weaker on the south than on the north. On the north loop, the distance of influence rarely changed from 1 to 4 km and 1-4 km showed the highest contribution to woodsmoke concentrations (Figure 3-8); however on the south loop, the first 5 km contributed much less to its woodsmoke concentrations and then increased to the maximum level at 7 km. Additionally, the single highest contributor to woodsmoke explained less than 25% of the variance in the south loop, compared to 44% for the north loop. However, in both the north and south portions of the study areas, the density of wood heater appliances and centralized wood heaters is the best predictor for residential woodsmoke. This differs from experience in modeling urban environments (Seattle, Vancouver, Victoria) where socioeconomic status variables are the strongest predictors (Larson et al. 2007; Su et al. 2008).

Results from a preliminary analysis that modeled the mobile measurements from the DR2 using the predictors in the final prediction models for the south loop are listed in Table 3-8.

Table 3-8. Preliminary modeling analysis of residential woodsmoke for the south loop.

Modeling type	R^2	intercept	Variable(s)	β	p-value
measured[1]	0.54	3.243	Wood heater appliance density	16.1179	0.001
			White population	-0.00019	0.007
			Centralized wood heater density	0.7398	0.007
between-day adjusted[2]	0.33	3.843	Centralized wood heater density	11.352	0.028
			Non-white population	-0.00013	0.098
			White population	0.584	0.053

[1] No between-day adjustment was made.

[2] Adjusted based on Saratoga Aethalometer data.

All the covariates used had an uphill search distance of 7 km except centralized wood heater density (no uphill distance).

Though having only limited data (three days of measurement), the modeling results still showed that the spatial patterns of residential woodsmoke can be mapped reasonably well. Because of differences in topography, population distribution, and degree of woodsmoke, the models developed for the north loop cannot be mechanically fitted into the south loop. Separate models could be developed to maximize model performance, but the general model seems to provide a reasonable prediction of woodsmoke PM throughout the study area.

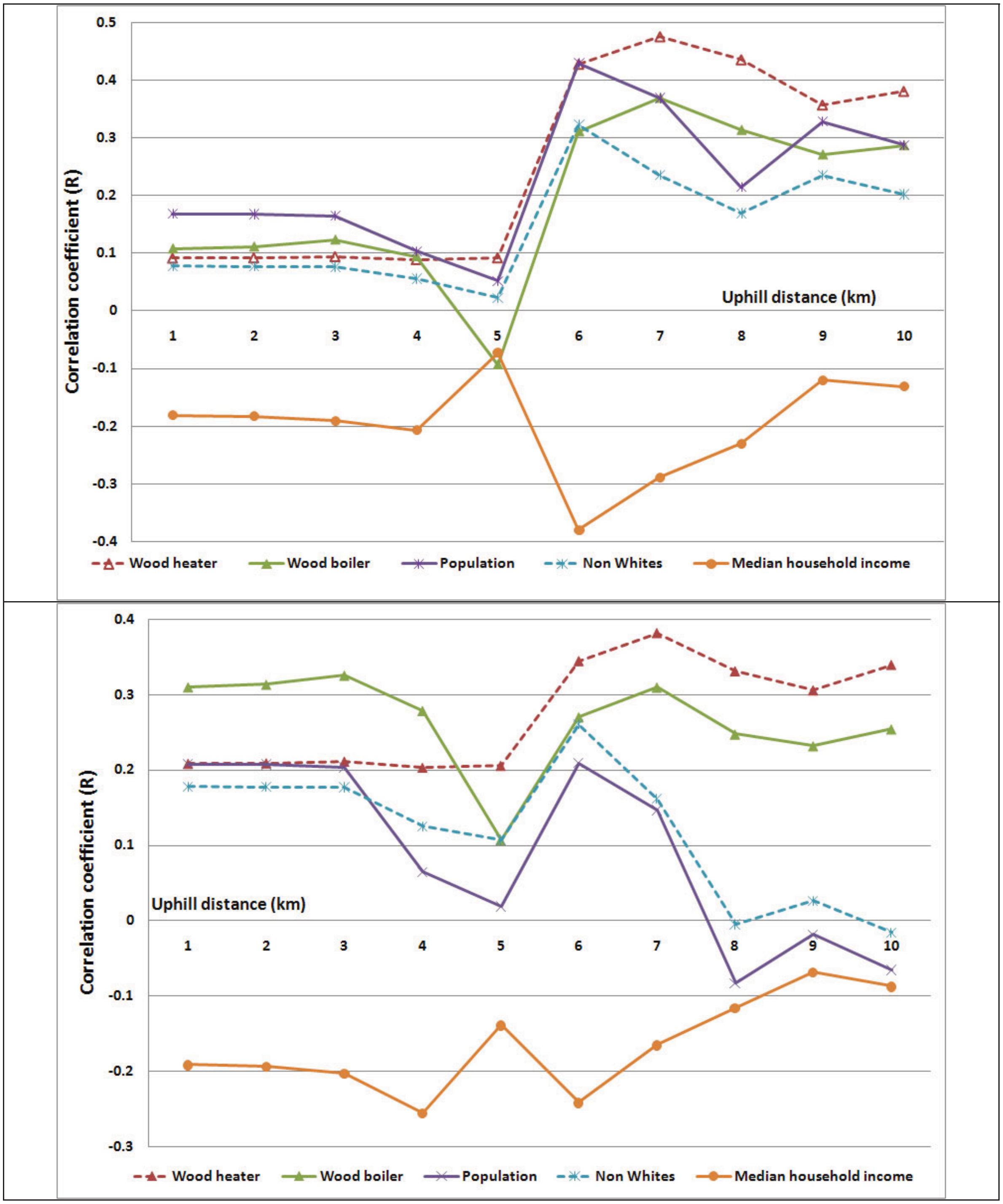


Figure 3-16. The correlation matrices between the measured (upper) and between-day (lower) adjusted woodsmoke concentrations and chosen spatial covariates for the south loop.

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Section 4

CONCLUSIONS AND RECOMMENDATIONS

Based on the experience and results obtained in this study, the following conclusions and recommendations can be made that respond to the four objectives the study set out to address.

1. **Develop a modeling tool that provides a reasonable representation of woodsmoke spatial variability in a non-urban setting in light of relatively sparse air monitoring data and incomplete emissions source information.**

- The mapping results indicate that it is feasible to use readily accessible public information (e.g., census and survey data) in conjunction with a GIS-based mapping technique to produce a "screening" assessment of woodsmoke spatial patterns in complex terrains.
- Low elevation, increased wood heater density, increased dwelling value, increased number of families and increased non-white population all were associated with higher downslope woodsmoke $PM_{2.5}$.
- The model performance improved slightly as the upstream search distance increased from 1 to approximately 4 km, suggesting that 4 km is the distance of maximum influence for woodsmoke sources in the study area.

2. **Apply the modeling tool to a complex topographical region to test its capabilities in providing useful information for air quality and health planning needs.**

- In all models tested, the most important predictor variable was the wood heater (density) emissions variable. Including this variable alone explained 44% of the variability in the measured woodsmoke concentration. Addition of other spatial variables only improves the models marginally.
- The best model explained 58% of the variability in measured woodsmoke $PM_{2.5}$ and included both an emissions variable (e.g., wood heater appliance density) as well as other socioeconomic and geographic variables.
- Considering the population residing in areas with the upper third of modeled woodsmoke $PM_{2.5}$ as exposed, more than 50% of the population in the north loop and Essex county areas were exposed to elevated woodsmoke concentrations.
- For the whole study region (7 counties), 26% of the population (equivalent to approximately 128,000 people) was exposed to residential woodsmoke.

3. **Explore the limitations of the modeling tool, and recommend possible improvements in the approach.**

- While the modeling technique provides reasonable spatial representation of woodsmoke variability across the region, the model does not identify the very high, short-term woodsmoke concentration peaks observed during the mobile monitoring. These peaks would not be covered under current longer time-average air quality standards set at lower concentrations, but they can be a public health concern.

- Permitting requirements, locally specific sales data (e.g., county level), or other public reporting options for wood burning appliances would help fill knowledge gaps. Spatially resolved emissions data are particularly important for wood combustion sources given their location in residential areas and the fact that their impact on air quality is more localized than many other sources (e.g., power plants).
- The modeling technique had to make simple, and perhaps incorrect, assumptions about trends in residential wood combustion activity in response to changes in home heating oil prices and other factors in the absence of any specific information on wood-burning proportions by year. Given the simple assumptions, the methodology used in this study is not appropriate to estimate the magnitude of woodsmoke emissions.
- If this modeling approach is to be applied to other areas to estimate the potential impact of woodsmoke $PM_{2.5}$ without any measurements for evaluation, improvements in the emissions data will be useful and important to include. Two specific areas for improvement include updating the proportion of homes using wood as a main heating fuel and better identification of locations and numbers of potentially high emitting sources such as outdoor wood boilers.

4. Identify potential applications of the monitoring and modeling techniques that can help address air quality and public health planning needs

- The fixed-site monitoring approach is a relatively low maintenance technique for continuously tracking woodsmoke levels in communities during the course of a winter that can help identify conditions leading to high woodsmoke concentrations, thus help in pollution forecasting and public outreach efforts in locally-specific areas.
- The ability of the mobile monitoring method to detect short term spikes in woodsmoke may have application in developing better information on the locations of OWBs and other high emitting wood combustion sources. Because it can be conducted fairly quickly and easily along roadways in a local area, it may provide some ability to identify specific OWBs or other wood combustion sources that pose public health concerns at the local level.
- A mobile monitoring field campaign to gauge the prevalence of high woodsmoke spikes in a local region may provide emission inventory developers with a better sense of the prevalence of OWBs and other high emitting woodsmoke sources compared to assumptions made in inventory models.
- The modeling technique provides a monitoring network analysis tool that can help prioritize where to locate fixed monitoring sites and mobile monitoring routes for targeted field campaigns that best reflect where public exposure and woodsmoke levels may be highest.

- The modeling approach is readily transferable across regions because it uses publicly available information (e.g., census and survey data) that is common across the country. As such, it has potentially broad application for public exposure assessments to woodsmoke where extensive ambient monitoring networks are lacking (although regionally specific woodsmoke emissions and monitoring information can help improve the modeled woodsmoke spatial patterns).
- The modeling technique can be a screening tool to help identify high woodsmoke locations for targeted woodstove change-out programs or other strategies aimed at reducing woodsmoke emissions and public exposure.

Appendix A

WOODSMOKE MOBILE MONITORING FIELD PROTOCOL

This protocol covers routine operations for the monitoring done in the car for the woodsmoke “loop” route. The parameters measured are:

- BC/UVC by Aethalometer, with $PM_{1.0}$, 5 liter per minute (LPM) cyclone inlet
- PM-fine by DR-4 nephelometer with PM-10 inlet and PM-2.5 2 LPM size cut, run at 3 LPM
- Ambient and inside car temperature by RTD probe and Hobo logger combo
- Recording GPS (Delorme Earthmate and BR-305 raw GPS), both on laptop
- OBD data logger (for car speed and miles driven)
- Barometric pressure from BGI tetraCal

A laptop PC is used to record both GPS systems and Aethalometer data in real-time. All parameters are recorded at 1-second intervals except the Aethalometer (1-minute) and Hobo temperature (5-seconds). Most systems are powered by car power inverters; for the one that feeds the UPS, instruments are plugged into the four UPS sockets marked “Battery.” The OBD and temperature loggers are self-powered; the BR-305 raw GPS runs directly off the 12-volt cigar lighter power. Note that the UPS should be fully charged before each run before it is installed in the car.

All run data should be emailed back to NESCAUM (gallen at nescaum_org) the morning after each run for review. All data files should include the run date in the filename, as well as the parameter or instrument. For example: hobo-temp18nov08.csv (in this example, both in-car and ambient temperature are in the same file). All car run data files should be zipped up into a single zip file before being emailed.

1.0 Pre-run setup

1.1 Warm-up period.

The car (with heater and all instruments running) should be run for at least 30 minutes before the loop is started. Time spent driving to the start of the loop can be included in this startup period. The inside-car temperature should be kept as constant and as warm as possible. The DR-4 should be started inside two hours before the loop is run to let it warm up completely; the instrument’s time must be set before EACH car loop run (it does not keep good time).

Before each loop run setup, the PC time must be set to atomic clock time: http://www.time.gov/timezone.cgi?Eastern/d/-5/java. Instrument and logger times should be within five seconds of this time; reset times as needed before the run starts. All instrument and sensor times should always be EST even during daylight savings time (starting the first Sunday in March). The raw GPS system does not need to have time set (it runs on GMT from the satellites). The Hobo, BP, Delorme GPS, and OBD loggers take their time from the PC. The Hobo, Delorme GPS, and BP loggers do this automatically; the OBD logger time is set manually with the CarChip software before each run.

1.2 Probe locations.

The temperature probe should be secured to some part of the car on the outside, towards the front. The cyclone inlet for the Aethalometer and the PM10 inlet for the DR-4 should be secured in a similar fashion; for these inlets, they should be as high off the ground as possible to avoid large coarse mode particles from the car's wake. The DR-4's $PM_{2.5}$ inlet size-cut device is also used, mounted on the DR-4 chassis.

2.0 Instrument configuration

2.1 Aethalometer (for BC and Delta-C woodsmoke).

A bench-top small spot Aethalometer is used at a flow rate of 5-LPM, using the PM-1, 5-LPM cyclone inlet and a 1-minute timebase; data are written to a diskette in the Aethalometer. The serial RS-232 port data output of the Aethalometer is recorded on the laptop using Hyperterminal; this is to determine when a manual tape advance is needed as well as provide a retrospective view of recent data. When the UV-channel attenuation (the last data column) exceeds ~100-120, the driver must pull over and stop to manually advance the tape (just after the end of a measurement interval). This avoids a 10-minute data gap from an automatic tape advance (which will occur at UV attn = 150). Data are valid 2-3 minutes after the manual advance is done; driving the loop must wait until the Aethalometer data are valid after a tape advance. How often this occurs will depend on the woodsmoke concentrations measured, and may occur several times during the loop drive. A new disk should be used for each night's run; each disk is to be labeled with the run date and not re-used.

2.2 DR-4 Nephelometer (for PM-fine).

The DR-4 is run at 3-LPM and 1-second data recording to increase the response time and reduce the size cut-point. Size and RH correction are off. A 5-minute zero (baseline) filter test must be run just before the start of the loop measurements, and again about half-way through the loop and at the end of the loop. The DR-4 baseline drifts with chamber temp, at about -0.6 μg per degree C decrease in chamber temperature (a positive temperature coefficient). The car DR-4 is run with a positive $PM_{2.5}$ offset so that baseline drift can be observed (the DR4 does not record negative #s). Note that the DR-4's internal Auto-Zero function is NEVER used for car work as long as a positive dynamic external filter zero can be obtained.

The DR-4 automatically increments the data "tag #" for each run. DR-4 data are downloaded to the laptop after the end of each run using DR4.com software. The highest existing "tag" number must be selected for the next set of data to be recorded; by default this will be the case. All memory should be cleared after a run’s data are downloaded. This does not reset tag #s, and they do not need to be (and should not be) reset unless they will exceed 99.

2.3 Temperature Probe (ambient and in-car).

An Onset Hobo RTD probe and logger is used for ambient and inside car temperature measurements. The Hobo logger must be started using the PC before the loop run starts, but after that is self-contained. The Logger “launch” setup should set the data log interval to 5 seconds, record both the internal temperature and the RTD probe external channel, and the “stop when full” option MUST be set to yes. Use the auto-launch time function to insure that the logger interval time is synched to the top of the minute; set the start time to 2 minutes later than the current time. The logger itself should be inside the car, not outside. The logger should be stopped and data downloaded at the end of each run.

2.4 Delorme “EarthMate” GPS

This GPS runs with Delorme Streets software on the laptop. The GPS sensor should be on the very front and middle of the dashboard to get the best signal. Data (track) logging must be started manually, using the “record” feature on the “GPS” tab in the Streets software (or the Delorme GPS software configuration can be set to start both the GPS and logging automatically when the Streets software is started). Data are recorded at 1-second intervals to the laptop. The Delorme GPS track (log) .gpl file should be saved at the end of each run segment (normally two segments per loop).

2.5 Stand-alone GPS

The BR-305 GPS sends raw GPS data to hyperterminal on the laptop for data capture. Data (Lat/Lon, elevation in feet, and date/time as GMT) are recorded at 1-second intervals. The GPS sensor can be on the front of the dashboard or on the top of the car (it has a magnetic base) if it works properly at the cold temperatures to be encountered (TBD) during the loop run. Proper operation of this GPS system is determined by the presence of reasonable Lat/Lon data in the “GPRMC ” data line. The Hyperterm data capture to file feature must be used, since it is the only record of raw GPS data.

A line of valid data looks like:

```
$GPRMC,171007.520,A,4221.8276,N,07103.6836,W,0.08,163.15,290908,,*14
```

This line indicates time as 17:10:07 GMT, Lat/Lon as 42E21.82' N, 71E10.37' W, elevation as 163 feet, and GMT date as Sept. 29, 2008.

Invalid data (too few satellite locks) looks like:

```
$GPRMC,162859.356,V,0000.0000,N,00000.0000,E,,,250908,,*13
```

2.6 OBD logger

The Davis Instruments “Car Chip” OBD logger is plugged into the car’s OBD socket (near the driver seat, under the dash) before the start of each run, and removed after the end of the run. Car speed is recorded at 1-second intervals. Data are downloaded (and memory cleared) after each run using the Davis CarChip software on the laptop. The car must be off when the CarChip is installed and removed.

2.7 Barometric Pressure

Barometric pressure in mm-Hg is measured at 1-second intervals using the BGI tetraCal flow calibrator and the BGI-Open software for data logging. The tetraCal must be hooked up to Com-1 on the laptop, since the BGI software only works with that com port. The BP data will be used to correct the DR-4 PM data to STP. Data logging is started and stopped using the BGI software. The data MUST be exported at the end of each run -- otherwise it is not saved.

Notes:

The DR-4 and Aethalometer should be in the back-seat of the car, with sample lines running out the front of an insulated rear window. The aerosol inlet lines should be as short as possible. The laptop should be on the front passenger’s seat so it can be easily read.

The UPS should be fully charged before each run before it is installed in the car. It should be left plugged in inside when not in use.

Appendix B

EMISSIONS SURFACE ADJUSTMENT AND SEMIVARIOGRAM ANALYSIS

To make surfaces comparable and amenable to later enhancements, a one-mean normalization shown in Equation (1) was applied to all the surfaces. The one-mean normalization has the mean of the transformed data set to 1, the minimum value to 0 and the maximum value to ∝ (infinity).

$$V = \frac{X - Min}{Mean - Min} \tag{1}$$

Where X and V are the values before and after normalization; *Mean* and *Min* are the average and minimum values before transformation. Accordingly, the household level interpolated surface was normalized as:

$$Emi_i^{norm} = (IniEmi_i - \underset{i=1,n}{Min}(IniEmi_i)) \Big/ (\underset{i=1,n}{Mean}(IniEmi_i) - \underset{i=1,n}{Min}(IniEmi_i)) \tag{2}$$

Where $IniEmi_i$ is the interpolated emission value at location i; *Min* and *Mean* are the minimum and average emission values within the study area; Emi_i^{norm} is a normalized emission at location i with output values ranging from zero to +∝. The minimum woodsmoke emission of a household was assumed to be zero and the random burning of wood created uncertainty of identifying the possible highest emissions. Therefore, the normalization process created a woodsmoke emission with values between [0, +∝] as follows:

$$Den_i^{norm} = \left(\frac{N_i^{fp-ws}}{Area_i^{bg}} - \underset{i=1,n}{Min}\left(\frac{N_i^{fp-ws}}{Area_i^{bg}}\right)\right) \Big/ \left(\underset{i=1,n}{Mean}\left(\frac{N_i^{fp-ws}}{Area_i^{bg}}\right) - \underset{j=1,n}{Min}\left(\frac{N_i^{fp-ws}}{Area_i^{bg}}\right)\right) \tag{3}$$

Where $N_i^{fp\text{-}ws}$ represents the number of fireplaces and woodstoves within the i^{th} block group; $Area_i^{bg}$ is the area of the i^{th} block group; *Min* and *Mean* are the minimum and average fireplace and woodstove density values within the study area; Den_i^{norm} is a normalized fireplace density of the i^{th} block group with output values ranging from zero to +∝. The adjusted emission surface was computed as follows:

$$Emi_i = IniEmi_i^{norm} * Den_i^{norm} \tag{4}$$

Semivariogram analysis

Semivariograms are applied to identify the distance where data are no longer spatially autocorrelated. The semivariogram is a function of distance and is based on the average sum of the squared differences in attribute values for all pairs of points of a defined distance interval. In this case, the attribute values are the residential woodsmoke concentrations estimated in Section 1 of this report. It can be expressed by:

$$\hat{\gamma}(d) = \frac{1}{2N(d)} \sum_{(s_i - s_j = d)} (Z_i - Z_j)^2 \tag{5}$$

where γ γ is the symbol for a semivariogram, and z_i and z_j are the woodsmoke concentrations of points s_i and s_j. The summation is over all pairs of points that are separated by a distance d and $N(d)$ is the number of these pairs (O'Sullivan and Unwin 2003). To reduce the number of points on the semivariogram, pairs of locations are binned based on their distances from each other.

The semi-variance surfaces are created for both north and south loops using Equation (6):

$$\hat{\gamma}(x) = \frac{1}{2N} \sum_{(h \le 1200)} (Z_x - Z_{(x+h)})^2 \tag{6}$$

For a given cell x, the variability is calculated by applying the summation over the pairs that are formed between x and all the cells within 1200 m from x. Z_x Z_x and $Z_{(x+h)}$ Z_{x+h} are the estimated residential woodsmoke concentrations (see Section 1 of this report) at cell x and another cell of distance $x+h$ to cell x. While Equation (2) resembles the standard semivariogram of Equation (1), its usage in this context is different. The maximum distance h is fixed and it equals to 1200 m. To estimate a surface of demand, Equation (2) is applied to all locations within the study region.

To reduce computing time and still maintain precision of placing fixed monitoring sites, the original grid of 25 m resolution is re-sampled to a resolution of 500 m. The centroid of each grid cell is used to represent a demand location and this creates a lattice of 11,790 and 18,102 potential demand locations for the north and south loop, respectively. Each loop has 20 candidate sites for the fixed-site monitoring network design.

In assigning costs to a road segment, the semi-variance value closest to the midpoint of a road segment is used. All the roadways are split into segments of maximum length of 100 m. Because network analysis always uses minimum costs for travel from one point to another while the study's goal is to design routes of maximum woodsmoke variation, the assigned costs (i.e., semi-variance values) on the whole road network are therefore inversed to have the optimized mobile network go through the maximum variation areas. To avoid extreme situations, a road segment of adjusted cost greater than 1,000 (i.e., $\hat{\gamma}(x) > 0.001$) is assigned the value of 1,000 and if less than 1 (i.e., $\hat{\gamma}(x) > 1.0$) then a value of 1 is assigned to that road segment. The adjusted cost ∂ of road segment x is expressed in Equation (7):

$$\begin{cases} \partial(x) = 1 \quad if\ \hat{\gamma}(x) > 1.0 \\ \partial(x) = \frac{1}{\hat{\gamma}(x)} \quad if\ 0.001 \le \hat{\gamma}(x) \le 1.0 \\ \partial(x) = 1000 \quad if\ \hat{\gamma}(x) < 0.001 \end{cases} \tag{7}$$

To estimate the time spent for a loop, the road network is first classified as primary highway, secondary highway, local road, or vehicle trail with speed limits of 50, 35, 25, and 20 miles per hour, respectively. Travel time on each road segment is calculated by dividing the length of that road segment by its speed limit. The total time spent and distances traveled for a loop are a summation of each individual road segment of the loop.

The road network with assigned traveling costs from Equation (3) is then imported into a feature dataset inside a geodatabase. The feature class of the road network is then used to create a new geometric network for final network analysis in ArcGIS. Because of the existence of two fixed-site monitoring networks, the mobile sampling also includes two networks.

Appendix C

CORRELATION COEFFICIENTS FOR FIXED SITE MONITORS AND SPATIAL COVARIATES

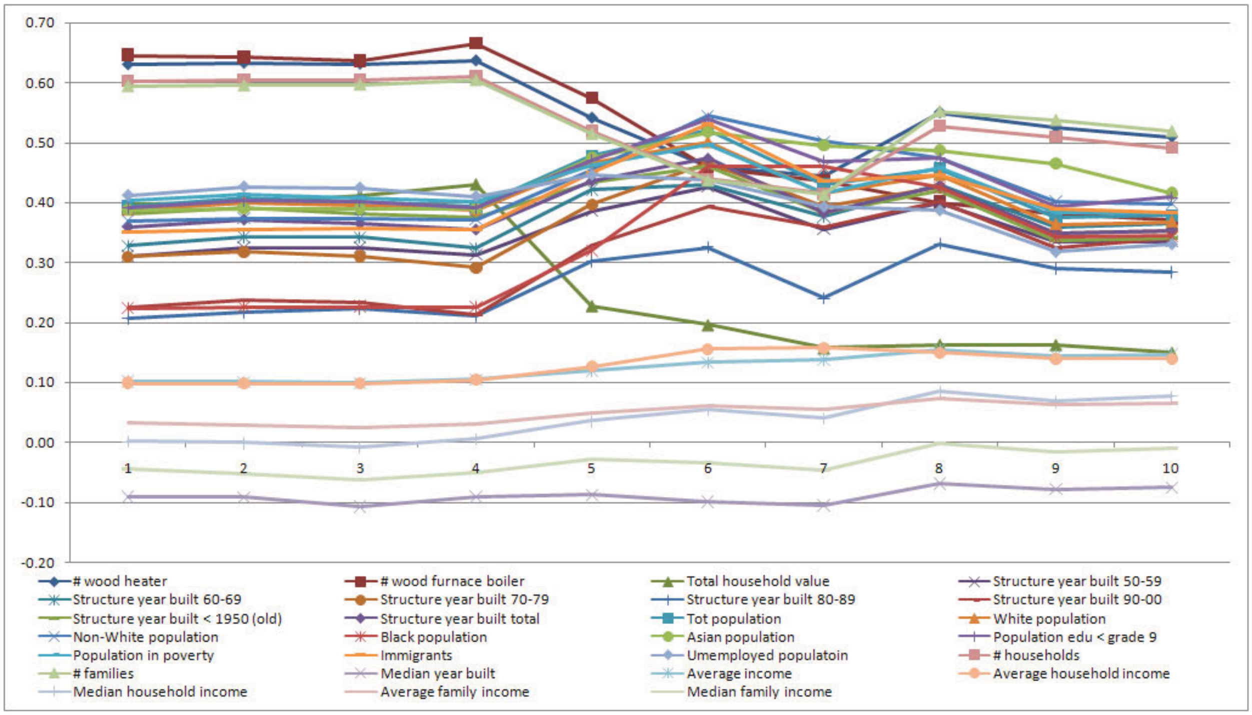

Figure C-1. Correlation coefficients between between-day adjusted residential woodsmoke $PM_{2.5}$ (based on Elizabethtown) and the chosen spatial covariates.

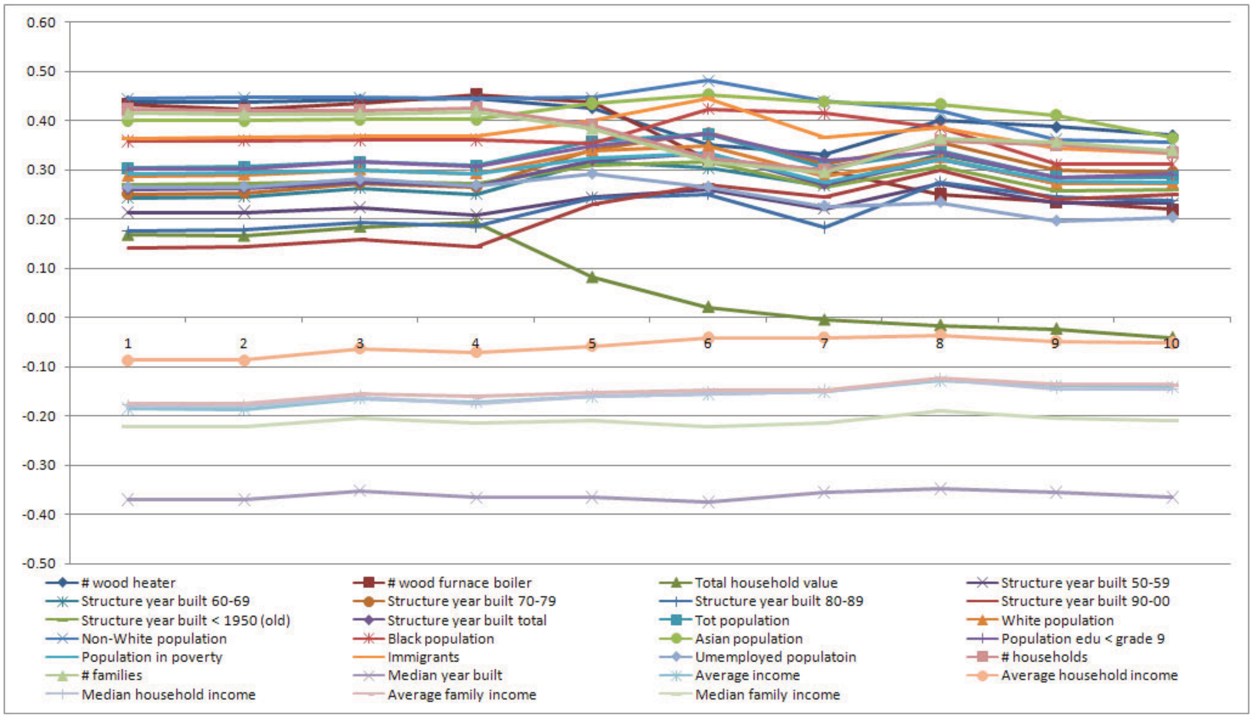

Figure C-2. Correlation coefficients between between-day adjusted residential woodsmoke $PM_{2.5}$ (based on Ticonderoga) and the chosen spatial covariates.

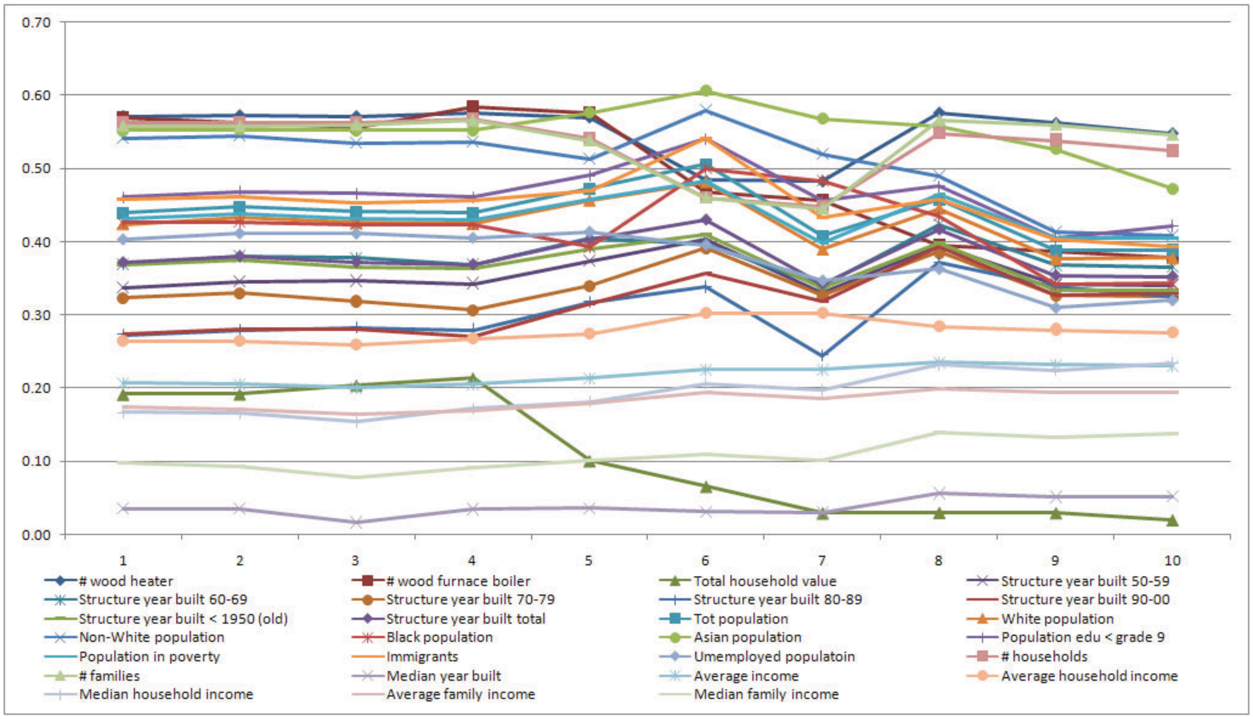

Figure C-3. Correlation coefficients between between-day adjusted residential woodsmoke $PM_{2.5}$ (based on Jay) and the chosen spatial covariates.

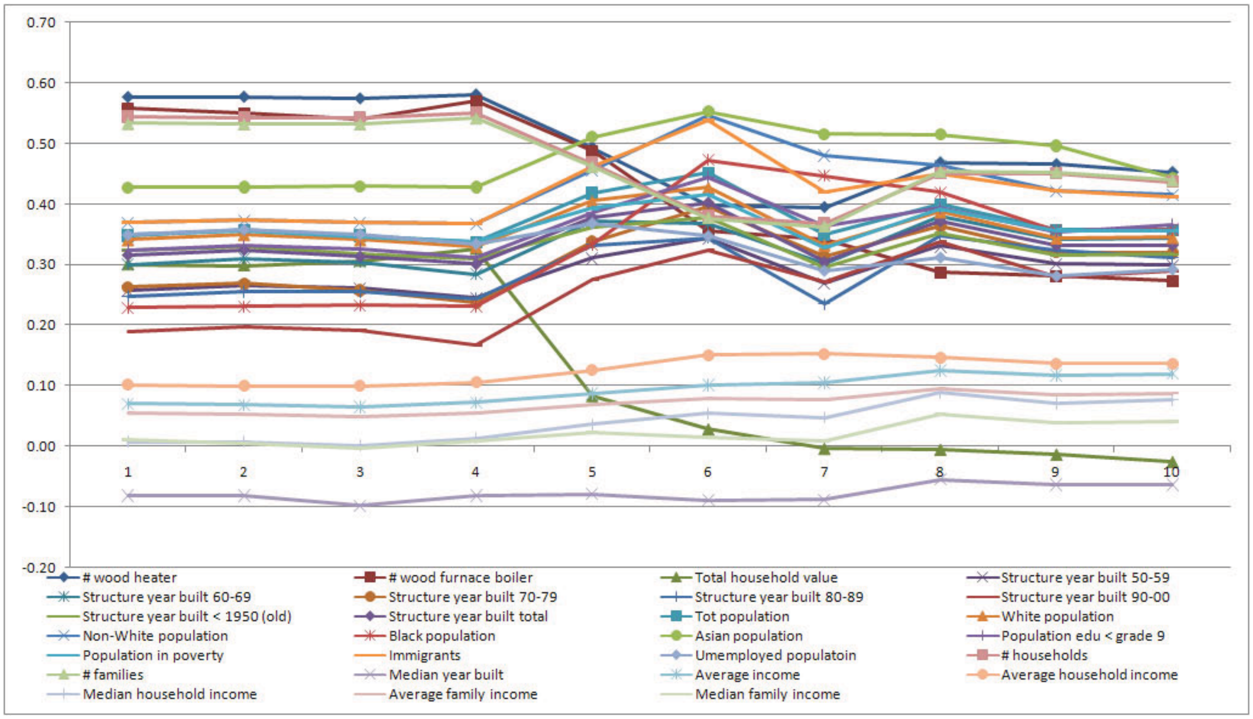

Figure C-4. Correlation coefficients between between-day adjusted residential woodsmoke $PM_{2.5}$ (based on Keene Valley) and the chosen spatial covariates.

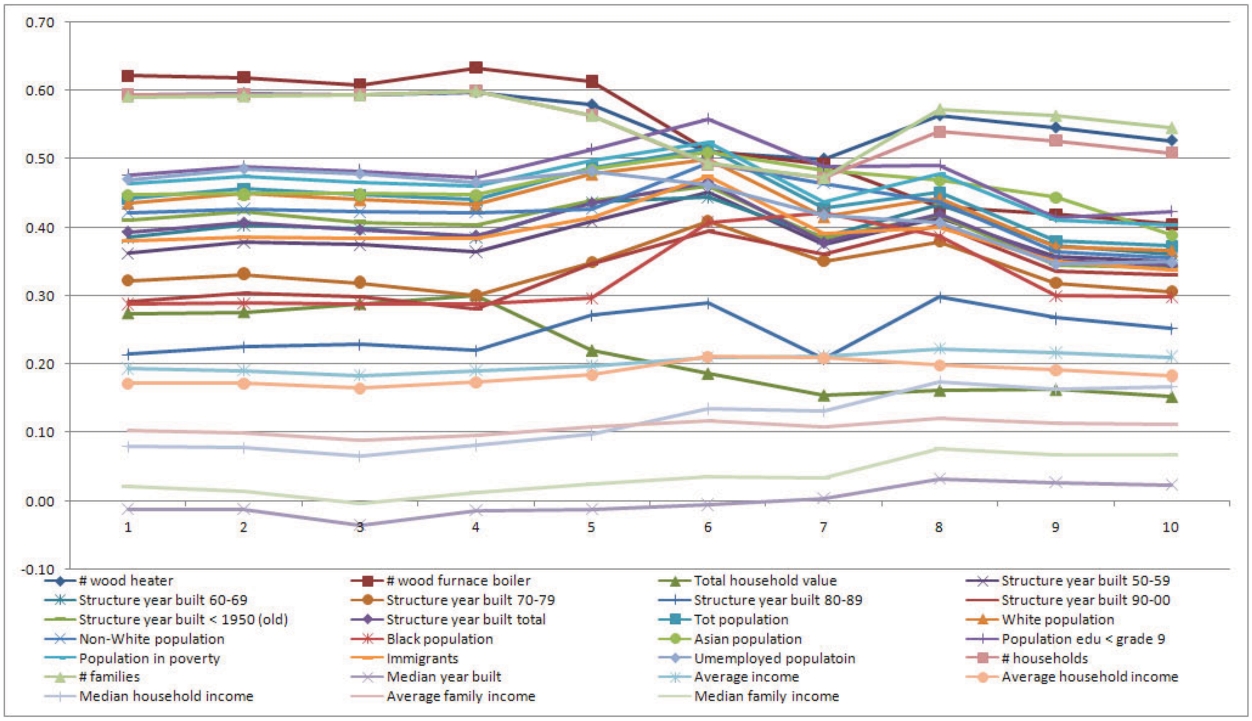

Figure C-5. Correlation coefficients between between-day adjusted residential woodsmoke $PM_{2.5}$ (based on Lake Placid) and the chosen spatial covariates.

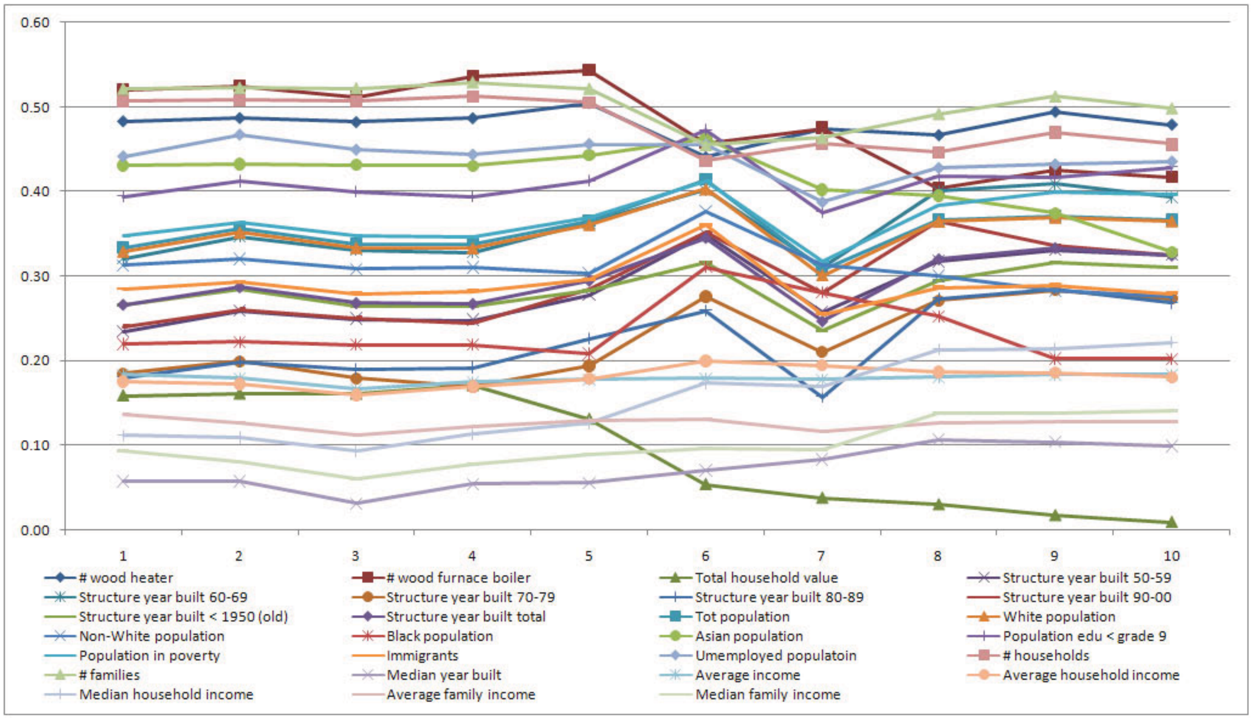

Figure C-6. Correlation coefficients between between-day adjusted residential woodsmoke $PM_{2.5}$ (based on Port Henry) and the chosen spatial covariates.

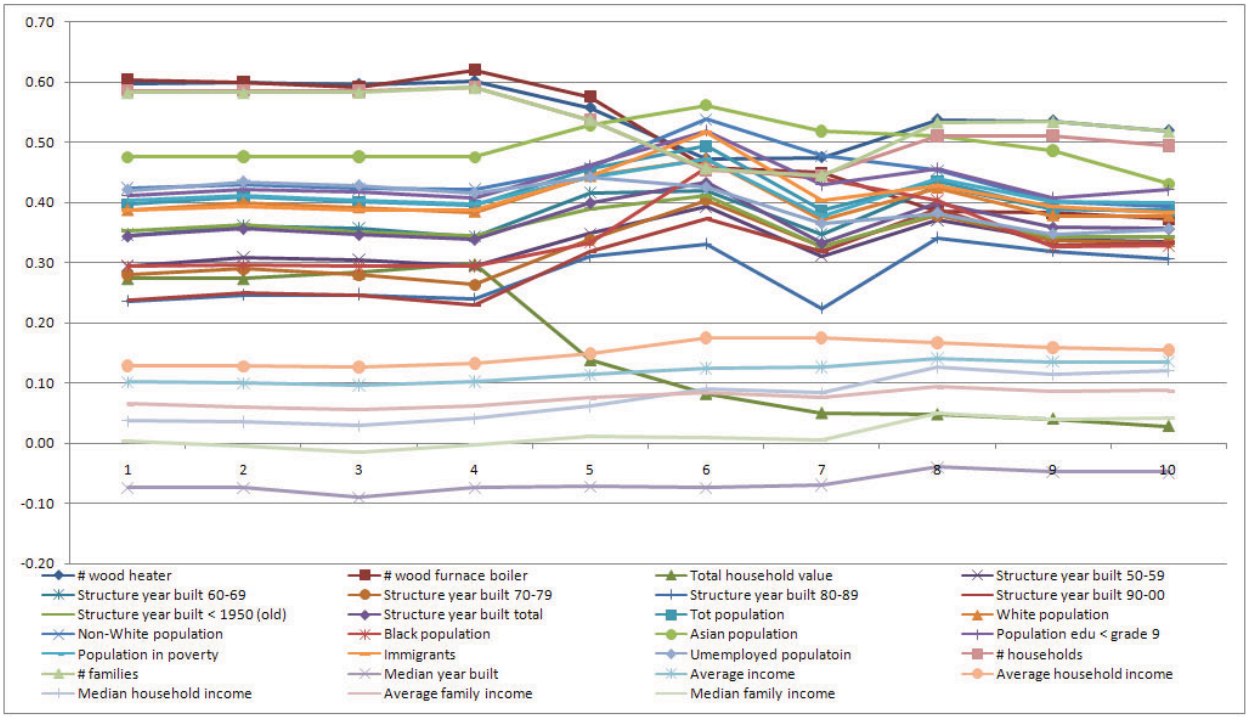

Figure C-7. Correlation coefficients between between-day adjusted residential woodsmoke $PM_{2.5}$ (based on the six fixed sites) and the chosen spatial covariates.

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SPATIAL MODELING AND MONITORING OF RESIDENTIAL WOODSMOKE ACROSS A NON-URBAN UPSTATE NEW YORK REGION

FINAL REPORT 10-02

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