Fine Particulate Matter Concentrations

In Outdoor Air

Near Outdoor Wood-Fired Boilers

(OWBs)

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Abstract

Outdoor wood-fired boilers (OWBs), which are freestanding combustion units that burn wood to produce hot water for domestic heating, can be a substantial source of wood smoke and associated fine particulates ($PM_{2.5}$). A 2006 report by the Northeast States for Coordinated Air Use Management indicated that average fine particulate emissions (grams per hour) from one OWB are equivalent to the emissions from 22 United States Environmental Protection Agency (US EPA)-certified wood stoves, 205 oil furnaces, or as many as 8,000 natural gas furnaces. Recent comprehensive testing by US EPA of various types of wood-fired hydronic heaters (a broad category which includes OWBs) under typical homeowner operational conditions found that conventional hydronic heaters emit more fine particulate matter, carbon monoxide, polynuclear aromatic hydrocarbons (PAHs), and polychlorinated dibenzo-p-dioxins and dibenzofurans than other advanced wood combustion devices (on a heat output basis). In this same study, US EPA found that conventional OWBs can emit 10-14 pounds of fine particulate matter when providing the heating needs for a moderately-sized home (2,500 square foot) for a Syracuse winter day. According to the US EPA, much of the health threat from wood smoke comes from fine particles. In rural New York State counties, residential wood combustion is responsible for 90 percent of carbonaceous, fine particles/aerosols.

The New York State Department of Health (NYS DOH) and other government agencies have received complaints of excessive smoke from the use of OWBs. In response, NYS DOH investigators conducted an air monitoring study to evaluate the potential for increased smoke exposures among some people living near OWBs. NYS DOH investigators measured fine particle ($PM_{2.5}$) concentrations in outdoor air at residential yards, and then employed the measured $PM_{2.5}$ concentrations as surrogate indicators of wood smoke exposure among OWB neighbors. NYS DOH investigators compared $PM_{2.5}$ concentrations in the air at residences near OWBs to levels in the air at residences distant from OWBs. Investigators then determined if elevated $PM_{2.5}$ concentrations reported in the air at residences near OWBs coincided with wind conditions favoring local accumulation of OWB smoke (***e.g.***, calm winds), or transport of OWB smoke towards the monitors.

At five of six deployments, $PM_{2.5}$ levels were statistically significantly higher at residences near OWBs than at more distant residences. Indeed, geometric mean $PM_{2.5}$ concentrations at

nearfield monitors were up to 187 percent higher than geometric mean concentrations at paired reference monitors. In addition, downwind status and/or calm conditions were statistically significantly associated with $PM_{2.5}$ concentration spikes at the five monitors deployed near OWBs. The risk of a $PM_{2.5}$ spike was markedly elevated (21-fold) during calm periods near a cluster of OWBs. Alternative local sources of $PM_{2.5}$ (***e.g.***, chimneys, stacks and idling vehicles at the participants' homes; vehicles on roadways) were sometimes present between OWBs and air monitors. However, alternative local sources did not appear to contribute substantially to elevated $PM_{2.5}$ concentrations at monitors near OWBs. Taken together, these observations indicated that people living near OWBs were exposed to elevated amounts of smoke during the study period, that the smoke most likely derived from nearby OWBs, and that even larger amounts of smoke sometimes collected near a cluster of OWBs.

The extent of OWB-derived air pollution observed during the study period was surprising given that topographic features at several study sites did not always favor smoke transport from the OWB to the nearfield monitor, two nearfield monitors were estimated to have been downwind of a nearby OWB during less than 5 percent of the monitoring period, and only one of six study sites included an OWB that was the subject of a smoke or odor complaint. Additional studies would be needed to characterize "worst case" smoke exposure scenarios, as extreme scenarios were unlikely to have been encountered during these investigations.

In addition, it should be noted that this study determined concentrations of only one component of OWB smoke, $PM_{2.5}$, and did not quantify any of the myriad additional noxious substances found in OWB smoke. It is likely that higher $PM_{2.5}$ levels reported at residences near OWBs were accompanied by increased levels of other wood smoke components which, when inhaled as a mixture, may have conveyed greater and more varied health risks than would be expected from inhalation of $PM_{2.5}$ alone.

In summary, this study found evidence that OWBs can increase residential wood smoke exposures in neighborhoods, even in the absence of smoke or odor complaints. This increase is not unexpected. Woodsmoke is the largest source of carbonaceous $PM_{2.5}$ in rural New York counties and emissions studies show that conventional OWBs are significant generators of fine particulates and other pollutants relative to other advanced wood-burning devices and other

common home heating devices. Given the well-established adverse respiratory and cardiovascular health effects of $PM_{2.5}$ exposure, and the adverse quality of life and odor issues associated with excessive smoke exposure, efforts to reduce the public's exposure to OWB smoke are warranted.

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Text Acronyms

CI	confidence interval
E	east
ft	feet
MADAR	Massachusetts Department of Agricultural Resources
Maine DEP	Maine Department of Environmental Protection
mph	miles per hour
N	north
NESCAUM	Northeast States for Coordinated Air Use Management
NYS DEC	New York State Department of Environmental Conservation
NYS DOH	New York State Department of Health
NYS OAG	New York State Office of Attorney General
OWB	Outdoor Wood-Fired Boiler
OR	odds ratio
$PM_{2.5}$	particles with aerodynamic diameters of 2.5 microns and smaller
RPD	relative percent difference
S	south
SW	southwest
W	west
WMO	World Meteorological Organization
WNW	west-northwest
WSW	west-southwest
US EPA	United States Environmental Protection Agency

Summary

Several regulatory, law enforcement, and public health agencies, including the New York State Department of Health (NYS DOH), have received complaints from residents reporting problems from excessive wood smoke migrating from their neighbors' outdoor wood-fired boilers (OWBs), which are free-standing wood combustion units that produce hot water for heating purposes (Maine DEP, 2005; Imrie, 2008; NYS OAG, 2008; Wisconsin DHS, 2008; Michigan DCH, 2009; Minnesota PCA, 2011; NYS DEC, 2011; Valentinetti, 2011; Wittstein, 2011). Wood smoke contains particulate matter and other toxic substances (NYS OAG, 2008; Naeher *et al.*, 2007). According to the US EPA, a major health threat from wood smoke comes from fine particles (US EPA, 2012). In rural New York State counties, residential wood combustion is responsible for 90 percent of carbonaceous, fine particles/aerosols (NYSERDA, 2008). Recent emissions testing by US Environmental Protection Agency (US EPA) scientists found that conventional OWBs (also known as outdoor wood-fired hydronic heaters) emit more fine particulates, carbon monoxide and other pollutants than advanced wood combustion technologies (Gullett, 2011; NYSERDA, 2012). This same testing also found that a conventional OWB can emit 10-14 pounds of fine particulate matter per day while meeting the heating needs of a 2,500 square foot home on a typical upstate New York (Syracuse) winter day (Gullett, 2011; NYSERDA, 2012). Health studies have documented adverse effects from exposures to elevated concentrations of particulate matter on time scales ranging from a few minutes to a few days (see, for example, Michaels, 1996; Delfino *et al.*, 1998; Peters *et al.*, 2001; Michaels & Kleinman, 2000; Urch *et al.*, 2005; Brook, 2008; Brook *et al.*, 2009; Belleudi *et al.*, 2010). Increased exposure to particle pollution, especially fine particles, is associated with adverse respiratory and cardiovascular effects, as well as premature death (US EPA, 2003; 2008). In addition to being an important toxin in its own right, $PM_{2.5}$ is considered a reasonable surrogate for a number of other toxins found in smoke (Adetona *et al.*, 2011).

During the 2007 and 2008 heating seasons, NYS DOH investigators deployed air monitors to record five- or ten-minute average fine particulate ($PM_{2.5}$) concentrations at several residential properties near OWBs. Five of six deployments targeted OWBs that were not known to the investigators to be the subject of smoke complaints, and a sixth deployment targeted an OWB that had been the subject of smoke complaints. At each of the six sites, the investigators

deployed a nearfield monitor located 150 to 1,270 feet distant from the nearest OWB, and a reference monitor located in the same general area as the nearfield monitor, but at least 2,500 feet distant from the nearest OWB. Two nearfield monitors were deployed within 1,500 feet of multiple OWBs. Meteorological stations were deployed near $PM_{2.5}$ monitors to record time of day, air temperature, humidity, dew point, rain amounts, wind direction, wind speed and barometric pressure. Deployments lasted for one to three weeks per study site.

Only $PM_{2.5}$ concentrations that were time-matched (*i.e.*, recorded by a nearfield monitor and its paired reference monitor at approximately the same time) were considered during data analysis. The six monitor deployments generated between 970 and 4,004 time-matched $PM_{2.5}$ concentration observations per monitor. Five of six deployments generated time-matched meteorological data as well. In the case of a sixth deployment, time-matched meteorological data were not available due to an instrument malfunction.

For each monitor pair, the degree to which the nearfield monitor central tendency $PM_{2.5}$ concentration differed from that of the reference monitor was characterized by comparing geometric mean concentrations, which ranged from 3.2 to 15.8 $\mu g/m^3$ for nearfield monitors, and from 2.3 to 9.8 $\mu g/m^3$ for reference monitors. Geometric mean $PM_{2.5}$ concentrations at each of five nearfield monitors were 15, 17, 46, 74 and 187 percent higher than geometric mean concentrations at paired reference monitors. At a sixth study site, designated site 4, the geometric mean $PM_{2.5}$ concentration was 27 percent lower at the nearfield monitor compared with its paired reference monitor. The site 4 nearfield monitor was deployed in a heavily wooded area, relatively far from the nearest OWB (1,270 feet distant).

Student's matched pair *t*-test, adjusted for autocorrelation, was employed to evaluate differences in time-matched $PM_{2.5}$ levels at each nearfield monitor and its paired reference monitor. Elevated $PM_{2.5}$ concentrations at each of the five nearfield monitors with elevated geometric mean $PM_{2.5}$ levels were statistically significant (Student's p = <0.0001 to 0.01), whereas lower $PM_{2.5}$ concentrations at the sixth nearfield monitor with a lower geometric mean $PM_{2.5}$ level were not statistically significant (Student's p = 0.59).

The potential for statistically significant associations between proximity to OWBs and episodes of unusually high $PM_{2.5}$ concentrations ("$PM_{2.5}$ concentration spikes") at monitors was evaluated using logistic regression (logit) models with adjustments for autocorrelation. For each study site, nearfield monitor and reference monitor $PM_{2.5}$ concentrations were combined, and a $PM_{2.5}$ concentration spike was defined as a $PM_{2.5}$ concentration greater than the 95th percentile value in the combined dataset. At each of five study sites where *t*-tests indicated that $PM_{2.5}$ levels were statistically significantly elevated at nearfield monitors, the odds of observing a $PM_{2.5}$ concentration spike at the nearfield monitor were 1.8- to 4.3-fold higher compared with its corresponding reference monitor, and the increased odds were statistically significant (logit p = <0.0001 to 0.04). At a sixth study site where Student's *t*-test indicated that $PM_{2.5}$ levels were not statistically significantly elevated at the nearfield monitor, the odds of observing a $PM_{2.5}$ concentration spike were 20 percent lower at the nearfield monitor compared with its paired reference monitor, but the decrease was not statistically significant (logit $p = 0.22$).

Potential relationships between meteorological parameter values and episodes of unusually high $PM_{2.5}$ levels at nearfield monitors were also evaluated using logistic regression. For each study site, paired $PM_{2.5}$ concentration differences (nearfield $PM_{2.5}$ concentration minus reference $PM_{2.5}$ concentration) were calculated, and a $PM_{2.5}$ difference spike was defined as a paired $PM_{2.5}$ concentration difference greater than the 95th percentile difference for the monitor pair. Thus, each $PM_{2.5}$ difference spike indicated an unusually high $PM_{2.5}$ level reported at a nearfield monitor compared with the simultaneous $PM_{2.5}$ level reported at its corresponding reference monitor. Meteorological parameters that were evaluated included several measured variables, as well as two calculated variables: downwind status (*i.e.*, nearfield winds blowing from the direction of an OWB, or from the two adjacent compass points) and calm conditions (*i.e.*, a reported wind speed of 0 miles per hour (mph) at a nearfield monitor).

At all five sites providing time-matched meteorological data, downwind status and/or calm conditions were significantly associated with $PM_{2.5}$ difference spikes. This was not surprising, because OWBs can release substantial amounts of $PM_{2.5}$ (NYS OAG, 2008; NESCAUM, 2006; Gullett, 2011; NYSERDA, 2012), and calm winds often indicate conditions that promote the local accumulation of air pollutants (MADAR, 2003; Larson *et al.*, 2009). Downwind status was most strongly associated with $PM_{2.5}$ difference spikes at study site 6, where the nearfield monitor was deployed closest to an OWB. The odds of observing a $PM_{2.5}$ difference spike at site 6 were nearly six-fold higher during intervals when the nearfield monitor was approximately downwind of the OWB, compared with intervals when the nearfield monitor was upwind/crosswind of the OWB, and the increase was statistically significant [odds ratio (OR) 5.9; 95 percent confidence interval (CI) 2.6, 13.8]. Statistically significant associations between downwind status and $PM_{2.5}$ difference spikes were also observed at study site 2 (OR 1.7; 95 percent CI 1.1, 2.6) and site 5 (OR 4.0; 95 percent CI 2.2, 7.1). Downwind status significantly increased the odds of observing a $PM_{2.5}$ difference spike at site 5 even though the nearfield monitor was approximately downwind of a nearby OWB for only about four percent of the monitoring period.

Calm conditions were most strongly associated with increased $PM_{2.5}$ levels at study site 1, where the nearfield monitor was deployed near a cluster of three OWBs. The odds of observing a $PM_{2.5}$ difference spike at site 1 were 21-fold higher during intervals when winds were calm, compared with intervals when the nearfield monitor was approximately upwind/crosswind of nearby OWBs (OR 21.0; 95 percent CI 2.8, 155.4). Statistically significant associations between calm conditions and $PM_{2.5}$ difference spikes were also observed at study site 2 (OR 2.1; 95 percent CI 1.4, 3.1), site 3 (OR 2.7; 95 percent CI 1.7, 4.3) and site 5 (OR 4.5; 95 percent CI 2.9, 7.0).

Some alternative (non-OWB) $PM_{2.5}$ sources were identified around nearfield and reference monitors. Alternative sources located between nearfield monitors and nearby OWBs were of greatest concern, due to the potential for those sources to exaggerate apparent associations between downwind status and $PM_{2.5}$ difference spikes. Two unavoidable alternative sources, roadways and homes, were often located between nearfield monitors and nearby OWBs. Roadways were located between nearfield monitors and nearby OWBs at 4 out of 6 locations (sites 1, 2, 3 and 5), although these were often lightly-traveled rural roads. Residences were located either between nearfield monitors and OWBs, or very near OWBs. Homes were thus in the same approximate wind direction, relative to nearfield monitors, as OWBs. With the exception of nearfield monitor N4, residences located between nearfield monitors and OWBs, or very near OWBs, were those of OWB owners.

The possibility that local roads and homes contributed to elevated $PM_{2.5}$ levels observed around study OWBs cannot be ruled out, although there is evidence that such contributions were negligible. Specifically, other studies have determined that $PM_{2.5}$ emissions from vehicles, and primary home heating systems common in rural New York State, are considerably lower than emissions from OWBs (Gillies *et al.*, 2001; NESCAUM, 2006; NYSOAG, 2008). In as much as OWBs are often employed as primary home heating sources, home heating system flues at OWB owners' residences probably emitted minimal, if any, $PM_{2.5}$. With regard to fireplace emissions, no chimney smoke was observed at any OWB owner's home, nearfield monitor location, or reference monitor location over the course of the study, despite frequent site visits.

Although these investigations considered only six residential locations near OWBs, study results indicated that OWBs can significantly increase $PM_{2.5}$ concentrations in outdoor air at nearby residences. The study did not employ regulatory air monitors, so measured $PM_{2.5}$ levels were not compared to air quality standards. None the less, the severity of adverse health effects associated with even short-duration elevated $PM_{2.5}$ air concentrations, along with the demonstrated importance of OWBs as sources of wood smoke and $PM_{2.5}$ in some residential settings, indicate that further efforts to reduce exposures to OWB-derived wood smoke and $PM_{2.5}$ are warranted.

Introduction

Outdoor wood fired-boilers (OWBs) are freestanding combustion units that burn wood to produce hot water. They are usually housed in small sheds located a short distance from the structures that they serve. In parts of New York State, OWBs are increasingly employed to provide heat and hot water to homes, barns, greenhouses, and swimming pools. According to a report issued in 2008 by the Office of the New York State Attorney General, the annual rate of OWB sales in New York State probably increased three-fold between 1999 and 2007, with an estimated total of 14,500 units sold in the state during those years (NYS OAG, 2008).

Several regulatory, law enforcement, and public health agencies, including the New York State Department of Health (NYS DOH), have received complaints from residents reporting substantial exposures to wood smoke migrating from their neighbors' OWBs (Maine DEP, 2005; Imrie, 2008; NYS OAG, 2008; Wisconsin DHS, 2008; Michigan DCH, 2009; Minnesota PCA, 2011; NYS DEC, 2011; Valentinetti, 2011; Wittstein, 2011). The United States Environmental Protection Agency (US EPA, 2009) noted that OWBs are part of a larger group of appliances known collectively as “hydronic heaters,” and stated:

> “Unqualified hydronic heaters can be substantially dirtier and less efficient than most other home heating technologies. With their smoldering fires and short smokestacks (usually no more than six to ten feet tall), hydronic heaters create heavy smoke and release it close to the ground, where it often lingers and exposes people in the area to nuisance conditions and health risks.”

People report health symptoms from exposure to OWB smoke that include eye and nose irritation, breathing difficulty, wheezing, coughing, and headaches (Wisconsin DHS, 2008). Although public complaints concerning excessive smoke from OWBs in New York State are often received by agencies other than the NYS DOH, including local municipalities and the New York State Department of Environmental Conservation (NYS DEC), the NYS DOH has also received complaints from homeowners reporting adverse health effects from exposures to OWB smoke. These complaints make up 58 percent of the total number of calls received by NYS DOH related to residential burning issues.

Wood smoke contains many toxic substances including acrolein, polycyclic aromatic hydrocarbons, carbon monoxide, benzene, polychlorinated dibenzodioxins/dibenzofurans, and inhalable particulate matter (coarse and fine) (Faroon *et al.*, 2008; Gustafson *et al.*, 2007; Naeher *et al.*, 2007; NYS OAG, 2008). According to the US EPA, a major health threat from wood smoke comes from fine particles (US EPA, 2012). In rural New York State counties, residential wood combustion is responsible for 90 percent of carbonaceous, fine particles/aerosols (NYSERDA, 2008). Ambient monitoring of wood smoke in northern New York confirmed that most of the fine particles measured originated from wood smoke with the highest concentrations measured in population centers and during midnight hours (NYSERDA, 2010).

Health studies have documented adverse effects from exposures to elevated concentrations of particulate matter on time scales ranging from a few minutes to a few days (see, for example, Michaels, 1996; Delfino *et al.*, 1998; Michaels & Kleinman, 2000; Peters *et al.*, 2001; Urch *et al.*, 2005; Brook, 2008; Brook *et al.*, 2009; Belleudi *et al.*, 2010). Increased exposure to particle pollution, especially fine particles, is associated with adverse respiratory and cardiovascular effects, as well as premature death (US EPA, 2003; 2008).

Fine particulate matter is produced by incomplete combustion and condensation of combustion gases, and is commonly defined as particles with aerodynamic diameters of 2.5 microns and smaller ($PM_{2.5}$). Such particles are small enough to get deep into the lungs and, in some cases, possibly into the bloodstream (Nemmar *et al.*, 2004; US EPA, 2008). Although $PM_{2.5}$ is only one component of wood smoke, it is considered to be among the best indicators of potential health impacts from combustion sources (Naeher *et al.*, 2007). According to the US EPA (2003):

> "Many health studies have correlated increased exposure to $PM_{2.5}$ with increases in premature death as well as a range of serious respiratory and cardiovascular effects. Respiratory effects include aggravation of lung diseases such as asthma and bronchitis. Other symptoms include coughing, chest discomfort, wheezing and shortness of breath. Cardiovascular symptoms include chest pain, palpitations, shortness of breath, heartbeat irregularities and heart

attacks."

OWBs generate more $PM_{2.5}$ per hour of operation than other household heat sources. According to a recent study, average $PM_{2.5}$ emissions (grams per hour) from one OWB are equivalent to the emissions from 22 US EPA-certified wood stoves, 205 oil furnaces, or as many as 8,000 natural gas furnaces (NESCAUM, 2006).[1] Recent comprehensive testing by US EPA scientists of various types of wood-fired hydronic heaters (a broad category which includes OWBs) under typical homeowner operational conditions found that conventional hydronic heaters emit more fine particulate matter (a significant portion of which is organic carbon), carbon monoxide, polynuclear aromatic hydrocarbons (PAHs), and polychlorinated dibenzo-p-dioxins and dibenzofurans than other advanced wood combustion devices (on a heat output basis) (Gullett, 2011; NYSERDA, 2012). In this same study, US EPA scientists also found that conventional OWBs can emit 10-14 pounds of $PM_{2.5}$ per day when providing the heating needs for a moderately-sized home (2,500 ft^2) for a typical upstate NY (Syracuse) winter day (Gullett, 2011; NYSERDA, 2012).

During the 2007 and 2008 heating seasons, the NYS DOH recorded $PM_{2.5}$ concentrations in outdoor air at six sites. At each site, the NYS DOH deployed a nearfield monitor at a residence within 1,500 feet of one or more OWBs, and a reference monitor at a residence at least 2,500 feet distant from any known OWB. $PM_{2.5}$ levels at nearfield sites and corresponding reference sites were compared to evaluate the potential for OWB emissions to increase $PM_{2.5}$ levels at nearby residences. This report describes study implementation and the results obtained.

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[1] These estimates consider masses of $PM_{2.5}$ emitted per hour of boiler or furnace operation, and are not normalized based upon heat output. Mass per hour comparisons are more relevant than heat output-adjusted comparisons when evaluating the relative potential for nearfield exposure to smoke and smoke components.

Materials and Methods

Study Site Selection. Air monitors were deployed at six sites. Each study site included two monitoring locations: a nearfield monitoring location within 1,500 feet of at least one OWB, and a reference monitoring location in the same general area, but at least 2,500 feet distant from any OWB. Each site required two property owners willing to assist these investigations by allowing investigators to temporarily deploy particulate air monitors and meteorological stations on their properties. Property owners received $40 per week in return for their participation in the study to, in part, compensate them for electricity costs.

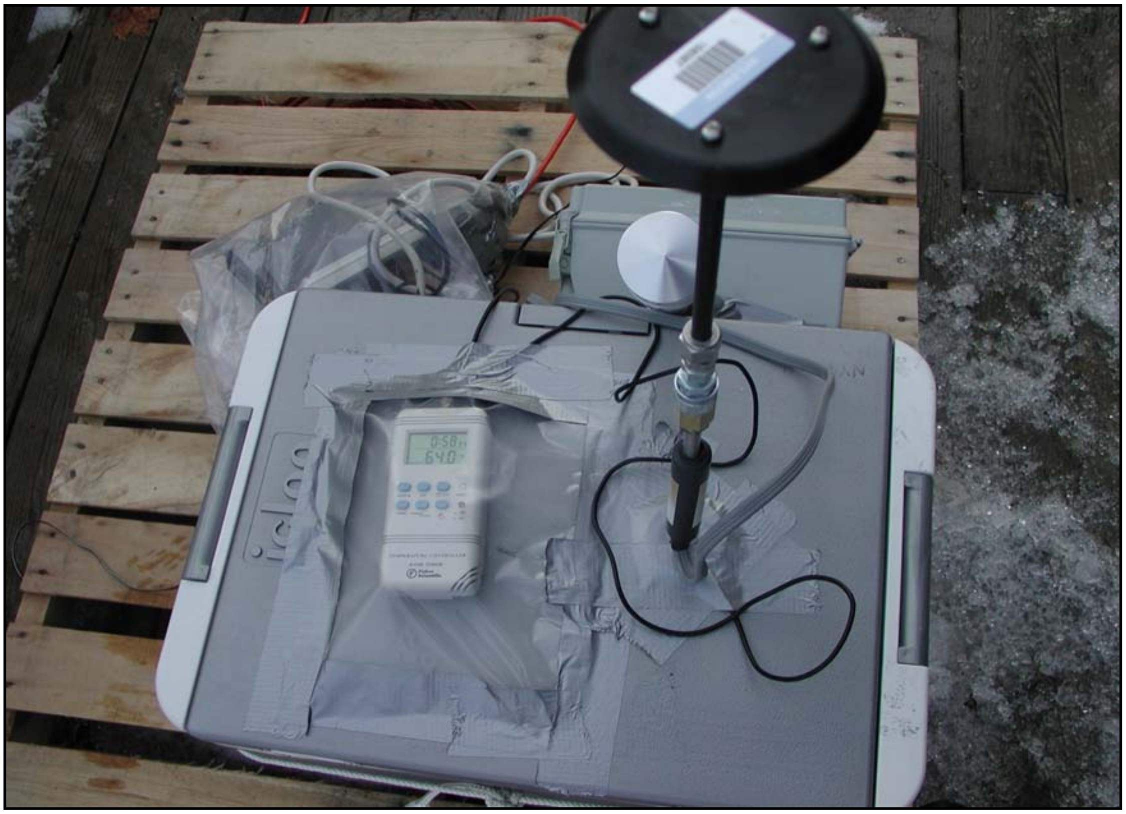
At every candidate nearfield location evaluated, the investigators attempted to recruit property owners nearest an OWB first, and then recruitment efforts progressed outward from the OWB until either recruitment was successful or a 1,500 foot maximum radius was reached. At each nearfield location, the investigators attempted to recruit a reference location property owner beginning 2,500 feet distant from the OWB, and then recruitment efforts progressed outward until either recruitment was successful or a 7,500 foot maximum radius was reached. With regard to site conditions, the investigators required that there be no high terrain between each nearfield monitor and at least one nearby OWB. Also, locations near non-OWB $PM_{2.5}$ sources that were unusual and substantial, such as mining operations and a diesel truck yard, were avoided.

Candidate sites were selected with the aid of digital maps (MapInfo v. 8.5, Pitney Bowes MapInfo, Troy, New York) and field reconnaissance, using multiple strategies. Based on prior knowledge that some local authorities require homeowners to obtain building permits prior to OWB installation, the investigators canvassed building code enforcement officials employed by municipalities in six counties (Albany, Columbia, Greene, Rensselaer, Saratoga, and Washington), and generated a list of 11 permitted OWBs that were not the subject of complaints to local and state officials. The investigators then evaluated areas around the 11 permitted OWBs, and identified three sites meeting the study requirements. Next, the investigators canvassed several NYS DOH and NYS DEC staff, and conducted additional field reconnaissance, to develop a list of 38 non-permitted OWBs that were, again, not the subject of complaints to local and state officials. Non-permitted OWBs were selected from the list at random. After evaluating areas around non-permitted OWBs, two additional study sites were identified. The final site, located in Ontario County, was not selected from a list. Instead, the final site was included to characterize $PM_{2.5}$ levels in air near an OWB that was the source of health complaints arising from excessive OWB smoke.

In this report, nearfield monitors and corresponding reference monitors are abbreviated by the letters "N" or "R," respectively, followed by a site number (1 through 6). Figures A-1 through A-6 (Appendix A) are maps of areas around monitors, indicating locations of nearfield monitors, reference monitors, and OWBs. Additional information pertaining to monitor deployments is summarized in Tables 1 and 2.

$PM_{2.5}$ Monitoring. The initial study protocol called for the use of DataRAM Model DR-4000 (Thermo Fisher Scientific, Inc., Waltham, MA) and Dustscan (Rupprecht & Patashnick Co., Inc., East Greenbush, New York) monitors for recording real-time $PM_{2.5}$ levels in outdoor air (Figure 1). Initial monitoring to evaluate the feasibility of measuring fine particulate levels was performed in April 2006, and then again during the winter of 2006/2007, at a location within a narrow valley approximately 1,000 feet downhill from an OWB. Smoke tended to accumulate at the monitoring location during calm (***e.g.***, thermal inversion) periods (see Appendix B). Additional pilot investigations employed co-deployed DataRAM Model DR-4000 monitors at a residential location where the monitors were sometimes exposed to smoke from a small wood fire that was set nearby (see Appendix B). These exercises provided information to support the selection of DataRAM Model DR-4000 as the preferred monitoring device.

Figure 1. DataRAM Model 4000 and Dustscan Monitors Ready for Deployment. **<u>Note</u>: This study employed only $PM_{2.5}$ concentrations reported by DataRAMs (<u>see</u> Appendix B).**



$PM_{2.5}$ monitors and meteorological stations were deployed for one to three weeks at each site. Real-time $PM_{2.5}$ concentrations were recorded at five- or ten-minute log intervals by DataRAM Model DR-4000 air monitors calibrated according to the manufacturer's instructions and equipped with inlet (temperature conditioning) heaters to avoid bias particle accretion during periods of elevated humidity. This approach may have resulted in the evaporation of some volatile and semi-volatile particles (Thermo Electron Corporation, 2003). The inlet flow rate was two liters per minute. The automatic zeroing feature was enabled during all deployments, but only functioned when the units employed ten-minute log intervals. DR-4000 monitors were operated with the particle size correction feature disabled, so that the units behaved as single wavelength (880 nm) nephelometers with characteristic size dependence. According to the manufacturer, this minimized overestimation of mass concentration when compared to a gravimetric reference. None the less, $PM_{2.5}$ levels reported by DR-4000 monitors may differ from levels that would have been reported by a gravimetric monitor, such as a regulatory $PM_{2.5}$ monitor.

As previously discussed, DataRAM Model DR-4000 units were field tested prior to commencement of the study to confirm that the co-located monitors reported similar $PM_{2.5}$ concentrations (see Appendix B). Although the investigators had no cause to believe that the two DR-4000 units employed for $PM_{2.5}$ concentration monitoring differed in their responses to $PM_{2.5}$, the two instruments were alternated in their monitoring assignments to reduce the possibility of instrument bias (Table 1).

Table 1. Summary of Air Monitor Deployments.

Monitor Pair	**Instrument Pair**	**Monitoring Period**	**Distance Between Nearfield Monitor & OWB(s) (ft)**	**$PM_{2.5}$ Data Log Intervals (min)**	**OWB Status**
N1/R1	DR2/DR1	02/19/08 - 03/04/08	390, 500, 580, 1420	10	non-permitted/no complaints
N2/R2	DR1/DR2	03/12/07 - 03/26/07	260	5	permitted/no complaints
N3/R3	DR1/DR2	03/20/08 - 04/10/08	680	10	non-permitted/no complaints
N4/R4	DR2/DR1	03/30/07 - 04/20/07	1270	5	permitted/no complaints
N5/R5	DR1/DR2	01/07/08 - 01/28/08	350, 1180	10	permitted/no complaints
N6/R6	DR2/DR1	03/06/08 - 03/13/08	150	10	non-permitted/complaints

Notes: Nearfield monitors were designated by an "N" followed by the site number. Reference monitors were designated by an "R" followed by the site number.

Accumulation of $PM_{2.5}$ from all sources around nearfield and reference monitors, as well as transport of $PM_{2.5}$ from OWBs to nearfield monitors, was potentially influenced by surrounding terrain. The investigators therefore attempted to match nearfield and reference monitors with regard to surrounding terrain, with varying degrees of success. Terrain was more complex, and large trees were more prevalent, at nearfield monitor N1 compared with reference monitor R1. These factors were expected to mitigate against the accumulation of OWB-derived wood smoke at nearfield monitor N1. However, of the two monitors, only N1 was located in a low-lying area ("catchment area") where air pollutants may have lingered, and where OWB smoke released at higher elevations may have settled during calm periods.

At study sites 2 and 3, nearfield and reference monitor locations were similar with regard to topographic relief and degree of tree cover. Nearfield monitor N2 was in a flat area, where terrain was expected to have little impact on the transport of wood smoke particles between the OWB and the monitor. Nearfield monitor N3, on the other hand, was situated 50 feet above the nearest OWB, in slightly undulating terrain, so that the degree of OWB-related $PM_{2.5}$ pollution at nearfield monitor N3 depended not only on wind direction, but also on the degree of plume rise from the OWB stack. This requirement may have reduced the potential for OWB smoke at nearfield monitor N3.

At study site 4, nearfield and reference monitoring locations were similar with regard to topographic relief, but the degree of tree cover was greater at nearfield monitor N4 compared with reference monitor R4. Nearfield monitor N4 was relatively far from the nearest OWB, and was surrounded by woodlands, factors that were expected to mitigate against the accumulation of OWB-derived wood smoke at nearfield monitor N4. Terrain was less complex, and the degree of forest cover was lower, at nearfield monitor N5 compared with reference monitor R5. Of the two monitors, only N5 was located in a catchment area.

Terrain was somewhat less complex at nearfield monitor N6 compared with reference monitor R6, although the degree of tree cover at each monitor was similar. Nearfield monitor N6 was situated very near an OWB, in flat terrain, and there were relatively few obstructions between the monitor and a nearby OWB. These conditions, along with a record of complaints related to excessive wood smoke from the nearby OWB, suggested a relatively high probability of detecting OWB-related $PM_{2.5}$ pollution at nearfield monitor N6.

Appendix C (attached) provides additional information regarding $PM_{2.5}$ monitor deployments.

Meteorological Monitoring. Meteorological Stations (Wireless Vantage Pro II, Davis Instrument Corp., Haywood, CA) were deployed near both nearfield and reference monitors at five of six study sites (Figure 2). At study site 6, only one meteorological station was deployed, equidistant between N6 and R6, to conserve resources. At all sites, meteorological stations were deployed in open terrain and, where feasible, were positioned at a distance of at least five-times the height of nearby buildings, trees or other obstructions (***i.e.***, 5x distance). The latter goal was not always obtainable, as indicated in Table 2.

Figure 2. Wireless Vantage Pro II Meteorological Station Deployed at Study Site 2.

Table 2. Meteorological Station Deployments.

Site	Distance between nearfield station and residence(ft)	Distance between reference station and residence (ft)	Nearfield Station		Reference Station	
			Residence Height (ft)	Distance/ Height[1]	Residence Height (ft)	Distance/ Height[1]
1	25	75	25	1.0[2]	28	2.7[2]
2	205	105	30	6.8	30	3.5[2]
3	135	90	30	4.5[2]	25	3.6[2]
4	120	215	25	4.8[2]	20	10.8
5	150	150	25	6.0	25	6.0
6	1,050	1,195	25	42.0[3]	25	47.8[3]

Notes:
(1) Distance to residence divided by residence height.
(2) The preferred minimum 5x distance was not obtained.
(3) One meteorological station was deployed equidistant from the nearfield and reference $PM_{2.5}$ monitors.

The 5x distance was selected to equal or approximate the distances of 4x and 5x recommended by the World Meteorological Organization (Oke, 2006; WMO, 2006) and some meteorological station installation guides (Environdata, 2008; AmbientWeather.com, 2012), but was not as rigorous as the 10x distance required by the National Oceanic and Atmospheric Administration requirements (Egan & Baldelli, 2009). The 5x distance was considered most important for meteorological stations deployed at nearfield monitors, because wind data from those units were used when evaluating the potential for OWBs to elevate $PM_{2.5}$ concentrations at nearfield monitors. Minimum 5x distances were achieved, or approximated, at most nearfield meteorological stations. The exception was the station at nearfield monitor N1, where only 1x distance was obtained. It was not possible to obtain the desired 5x distance near N1 because the meteorological station was deployed on a heavily wooded property that provided few siting options. At two meteorological station deployments the minimum 5x distance was approximated, but not achieved. The meteorological station close to nearfield monitor N3 was deployed at a 4.5x distance to ensure stability in the event of high winds, an important consideration given the sloping terrain around N3. The meteorological station at nearfield monitor N4 achieved a near-5x (4.8x) distance from the nearest residence.

Meteorological stations recorded time of day, air temperature, humidity, dew point, rain amounts, wind direction (16 compass points), wind speed and barometric pressure. Wind direction, wind speed and temperature were sampled every 5 seconds and summarized at 5- or 10-minute intervals. Wind direction data were recorded as the compass point sector with the highest occurrence within each 5- or 10-minute interval. Wind speed data were reported as the average of all wind speeds recorded during the 5- or 10-minute monitoring interval, rounded to the nearest 1 mph. Average wind speeds of 0 mph had an associated wind direction if at least one wind speed was recorded within the 5- or 10-minute log period, but these wind directions were not considered during data analysis.

$PM_{2.5}$ Source Identification and Control. Property owners were asked to refrain from using alternative heat sources (including woodstoves) and from engaging in activities near monitors. Property owners were also asked to maintain observation logs reflecting smoke pollution episodes, vehicle use, and other factors that might influence local $PM_{2.5}$ levels. The investigators attempted to ensure that there were no substantial non-OWB sources of $PM_{2.5}$, such as operating outdoor grills and diesel engines, leaf fires, or burn barrels within 1,500 feet of any $PM_{2.5}$ monitor. Two candidate monitoring locations were eliminated from consideration due to the presence of substantial mobile $PM_{2.5}$ sources. Field staff visited monitoring locations frequently throughout the study, recording the location of substantial new sources of $PM_{2.5}$ near monitors.

However, it was not possible to avoid all non-OWB sources of $PM_{2.5}$ (see Results section for details).

Exploratory Data Analysis. Excel97 (Microsoft Corporation, Redmond, WA), MapInfo, SAS 9.2 (SAS Institute, Inc., Cary, NC), and SYSTAT 11 (SYSTAT Software, Inc., Chicago, IL) were used to explore potential associations between study variables. Data sets downloaded from monitors were prepared for analyses using Excel97, SYSTAT 11, and SAS 9.2. Raw $PM_{2.5}$ concentration data and meteorological data were trimmed to eliminate the first 30 minutes of measurements recorded at the beginning of each monitoring period and instrument start-up. This avoided the analysis of raw $PM_{2.5}$ concentration data reflecting installation and start-up activities. In addition, raw $PM_{2.5}$ observations were ignored if they were recorded by a monitor when concentration data were not available from its paired monitor. For all but one monitor pair (N4/R4), raw $PM_{2.5}$ concentrations were also time-matched with data from meteorological stations to control for regional $PM_{2.5}$ concentration trends and common alternative $PM_{2.5}$ sources, such as vehicle and residential furnace emissions. In the case of monitor pair N4/R4, meteorological data could not be time-matched with $PM_{2.5}$ levels due to a meteorological station malfunction.

Additional outcome variables, such as log-transformed $PM_{2.5}$ concentrations, and paired $PM_{2.5}$ concentration differences (nearfield $PM_{2.5}$ level minus reference $PM_{2.5}$ level), were constructed during exploratory data analysis as required by the various analytical methods employed. Regression diagnostics confirmed a high degree of autocorrelation in reported $PM_{2.5}$ concentration data (***i.e.***, correlations between $PM_{2.5}$ values recorded by a monitor at nearby points in time), as was expected for elements in a time series. Calculated levels of statistical significance were adjusted for autocorrelation during final data analyses, but were not adjusted during exploratory data analysis.

For purposes of comparing the frequency of transient $PM_{2.5}$ pollution episodes at a nearfield monitor with the frequency of episodes at the corresponding reference monitor, nearfield monitor and reference monitor $PM_{2.5}$ concentrations reported by the monitor pair were combined, and a pollution episode was defined as a $PM_{2.5}$ concentration greater than the 95th percentile value reported by either monitor. Transient $PM_{2.5}$ pollution episodes thus defined were termed “$PM_{2.5}$

concentration spikes,” and were indicated within the database by the dichotomous variable PMEVENT.

For purposes of evaluating the potential for increased frequencies of transient $PM_{2.5}$ pollution episodes at nearfield monitors when specified meteorological conditions were present, paired $PM_{2.5}$ concentration differences (nearfield $PM_{2.5}$ concentration minus reference $PM_{2.5}$ concentration) were calculated. A pollution episode was then defined as a paired $PM_{2.5}$ concentration difference greater than the 95th percentile difference for the site. These episodes were termed “$PM_{2.5}$ difference spikes,” and were indicated within the database by the dichotomous variable DIFFEVENT. A $PM_{2.5}$ difference spike indicated an unusually high $PM_{2.5}$ level at a nearfield monitor compared with the nearly simultaneous $PM_{2.5}$ level reported at its corresponding reference monitor.

Predictor variables considered during exploratory data analyses included monitor status (nearfield or reference), time of day (day or night), distance to the nearest OWB, and several meteorological variables: air temperature, humidity, dew point, rain amounts, wind speed and barometric pressure. Monitor status was indicated within the database by the dichotomous variable NEARFIELD.

Each nearfield monitor was assumed to be downwind of a nearby OWB when the monitor’s co-located meteorological station reported that winds were blowing from the direction of the OWB, or from the two adjacent compass points, for a total of 67.5°. The presence of this condition was indicated within the database by the dichotomous variable DOWNWIND. For example, an OWB was located 150 feet west of nearfield monitor N6, so the investigators considered monitor N6 to be downwind of the OWB when the nearfield meteorological station reported west (W), west-northwest (WNW), and west-southwest (WSW) wind directions. Inclusion of adjacent compass points when classifying nearfield monitors with regard to downwind status allowed for some wind shifts during plume transit, as well as a degree of smoke plume dispersion and meander. Inspection of Figures A-19 and A-22 (Appendix A) suggested that winds from the two most distant study OWBs with time-matched meteorological data (located 1,420 SW/SSW of N1 and 1,180 SE of N5) contributed minimally to elevated $PM_{2.5}$ levels at nearfield monitors. Therefore, the two most distant OWBs were not considered when evaluating the influence of

DOWNWIND on nearfield $PM_{2.5}$ levels. For most practical purposes, this approach was equivalent to defining “nearby OWBs” as OWBs within 1,000 feet of a nearfield monitor.

Winds were assumed to be calm at a nearfield monitor whenever the meteorological station deployed at the monitor reported a mean wind speed of 0 mph[2]. The presence of this condition was indicated within the database by the dichotomous variable CALM.

When two or more meteorological variables were well correlated, only one representative variable was employed during analyses. For example, the three variables low barometric pressure, time of day and calm winds were well correlated, so only one of these (calm winds) was employed during analyses.

Two types of plots were used to evaluate the influence of the variables DOWNWIND and CALM at each site: longitudinal graphs and bar charts. Longitudinal graphs indicated trends in paired $PM_{2.5}$ concentration differences over time, and illustrated the occurrence of $PM_{2.5}$ difference spikes. For evaluation of diurnal variations in $PM_{2.5}$ at nearfield monitors, day and night periods were indicated.

For each nearfield monitor, bar charts were also generated indicating relative magnitudes of mean paired $PM_{2.5}$ concentration differences by wind category (calm and 16 wind directions). Wind roses were constructed for each meteorological station, indicating the percentage of total monitoring time that winds originated in each of the 16 compass directions (Figures A-24a through A-28, Appendix A). Bar charts and wind roses could not be constructed for site 4 due to the previously mentioned absence of meteorological data.

The results of exploratory data analysis (data not shown) suggested that most nearfield monitors reported higher levels of $PM_{2.5}$ than their corresponding reference monitors, and that downwind status (DOWNWIND) and/or calm conditions (CALM) appeared to increase $PM_{2.5}$ concentrations at nearfield monitors. Specifically, the investigators noted an apparent tendency for elevated mean paired $PM_{2.5}$ concentration differences at sites 2 and 6 when nearfield

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[2] Meteorological stations sometimes reported dominant wind directions for periods when mean wind speeds were 0 mph. These dominant wind directions were ignored during data analyses, and all periods when mean wind speeds were 0 mph were designated “calm.”

monitors were downwind of OWBs, and at sites 1, 2 and 3 during calm conditions (Figures A-13 through A18, Appendix A). In addition, inspection of graphs constructed during exploratory data analysis suggested that elevated $PM_{2.5}$ concentrations at nearfield monitors were partially explained by transient $PM_{2.5}$ pollution episodes (Figures A-7 through A-9, Appendix A, for examples). Diurnal variations in paired $PM_{2.5}$ concentration differences were sometimes evident as well, in that elevated concentrations (and/or more frequent $PM_{2.5}$ difference spikes) occurred more often during nighttime (Figures A12 and A-13, Appendix A, for examples).

Statistical Analyses. SAS 9.2 (SAS Institute, Inc., Cary, North Carolina) was used for statistical analyses. Whenever possible, the investigators employed paired $PM_{2.5}$ concentration difference, or $PM_{2.5}$ difference spike (DIFFEVENT), as outcome variables to control for the combined effects of regional $PM_{2.5}$ concentration trends and common alternative (non-OWB) $PM_{2.5}$ sources. The assumptions were that, in the absence of a substantial $PM_{2.5}$ source at either monitor, central tendency paired $PM_{2.5}$ concentration differences at each site should approximate 0 $\mu g/m^3$, and the number of $PM_{2.5}$ difference spikes reported by each monitor at a site should be approximately the same. All statistical tests employed an alpha of 0.05 without adjustments for multiple comparisons (Rothman, 1990).

For each monitor pair, Student's matched-pair *t*-test was implemented, with adjustments for autocorrelation (Gilbert, 1987), to test the null hypothesis that the true central tendency paired $PM_{2.5}$ concentration difference was 0 $\mu g/m^3$ (no difference between nearfield $PM_{2.5}$ levels and reference $PM_{2.5}$ levels at the site). Prior to implementation of Student's test, paired $PM_{2.5}$ concentration differences were uniformly incremented (off-set) and log-transformed to better approximate a Gaussian distribution.

Potential associations between monitor status (nearfield or reference) and 95th percentile or greater $PM_{2.5}$ concentrations ("$PM_{2.5}$ concentration spikes") were evaluated using multivariate logit models, which were fit employing the LOGISTIC procedure in SAS with a logit link function. For each site, a logit model was constructed that regressed the outcome variable PMEVENT on the predictor variable NEARFIELD, and an OR for the outcome variable was estimated. ORs indicated the estimated increased (or decreased) relative odds of observing a $PM_{2.5}$ concentration spike at each nearfield monitor compared with its corresponding reference monitor. An OR >1 indicated that the odds of a $PM_{2.5}$ concentration spike were greater at the nearfield monitor. Uncertainty in OR estimates was characterized by 95 percent confidence intervals, with statistical significance indicated by CIs that did not include unity. Logit *p*-values for model variables were also estimated.

Potential relationships between wind conditions and 95th percentile or greater paired $PM_{2.5}$ concentration differences ("$PM_{2.5}$ difference spikes") were also evaluated using multivariate logit models. For each of the five monitor pairs providing time-matched meteorological data, a logit model was constructed that regressed the outcome variable DIFFEVENT on the predictor variables CALM and DOWNWIND, and ORs for the outcome variable were estimated. ORs indicated the estimated increased (or decreased) relative odds of observing a $PM_{2.5}$ difference spike during intervals when winds were reported calm, or when the nearfield monitor was approximately downwind of a nearby OWB, compared with intervals when the nearfield monitor was approximately upwind/crosswind of all nearby OWBs. An OR >1 indicated that the odds of a $PM_{2.5}$ difference spike were greater when the specified wind condition was present. Uncertainty in OR estimates was once again characterized by 95 percent confidence intervals, with statistical significance indicated by CIs that did not include unity. Logit *p*-values for model variables were again estimated.

The occurrence of a $PM_{2.5}$ concentration spike, or a $PM_{2.5}$ difference spike, at a site during any given 5- or 10-minute interval was expected to be related to whether or not another spike was reported at the site during one or more preceding intervals. The investigators know of no universally accepted approach to obtaining unbiased logit estimates under such conditions. The investigators employed dynamic logit models that included as independent variables up to four lagged dependent variables to adjust for the correlation arising from sequential observations (Christakis and Fowler, 2007). These autoregressive terms were fit as linear terms in the logit models.

Original logit models retained both meteorological predictors (DOWNWIND and CALM) even when one meteorological predictor was not statistically significant. The potential for this approach to influence ORs and 95 percent CIs estimated for other (significant) predictors was evaluated. For each original logit model that included a non-significant predictor, first the non-significant variable was removed, then an alternative logit model was constructed, and finally the resulting logit OR and 95 percent CI were compared with the original logit OR and 95 percent CI.

Alternative $PM_{2.5}$ Sources. Non-OWB sources of $PM_{2.5}$ around monitors were identified through field surveys, digital maps, and reviews of property owners' observation logs. Daytime source activities were tracked by means of frequent site visits. For each monitor, raw data and graphs were inspected for indications that being downwind of a non-OWB $PM_{2.5}$ source was associated with $PM_{2.5}$ difference spikes. These assessments considered, to the extent feasible, the time and duration of $PM_{2.5}$ releases.

Results

Study results are summarized in Table D-1 (Appendix D), and additional tables and figures in this section. As indicated in Table 3, all six monitor pairs provided time-matched $PM_{2.5}$ concentrations. The greatest number of observations per monitor (*n*=4,004) was recorded by monitor pair N4/R4, and the smallest number (*n*=970) was recorded by monitor pair N6/R6. Time-matched meteorological data were also available for all monitor pairs except for pair N4/R4, which did not provide time-matched meteorological data due to instrument malfunction.

Table 3. Summary of Time-matched $PM_{2.5}$ Monitoring Data.

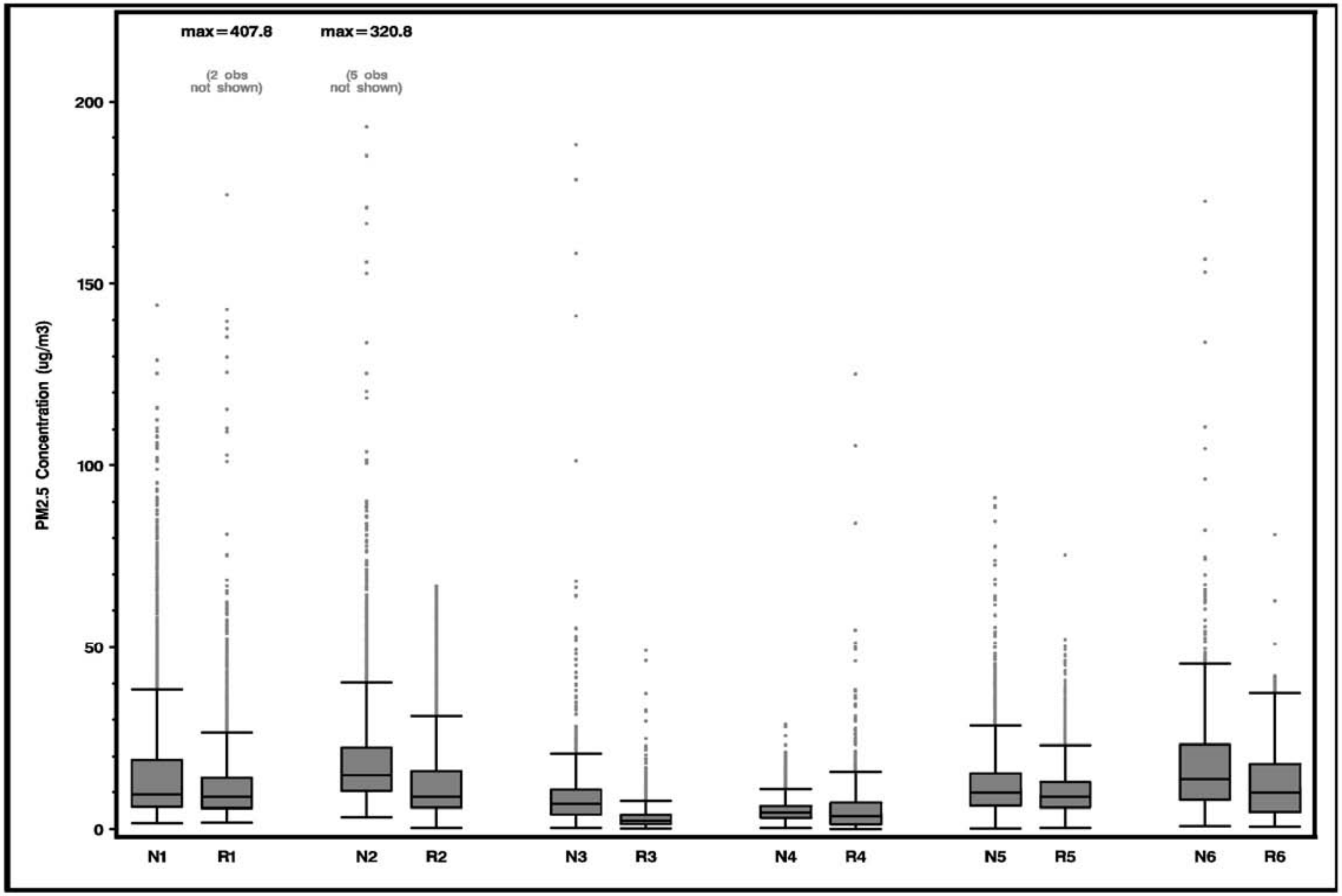
Monitor Pair	Time-Matched $PM_{2.5}$ Concentrations (n)	Time-Matched $PM_{2.5}$ Concentrations with Time-Matched Meteorological Data (n)	Percent of Monitoring Time Downwind (Nearfield)	Percent of Monitoring Time Winds Calm (Nearfield)
N1/R1	1,914	1,802	13.3 %	54.3 %
N2/R2	3,373	3,344	17.7 %	20.5 %
N3/R3	2,689	2,685	1.9 %	28.3 %
N4/R4	4,004	0	--	--
N5/R5	3,001	2,687	4.1 %	33.8 %
N6/R6	970	820	28.1%	24.8%

Note: The notation "--" indicates that time-matched meteorological data were not available for the monitor pair.

Considering only time-matched observations, the percentage of time that nearfield monitors were approximately downwind of one or more OWBs varied considerably. Two nearfield monitors, N3 and N5, were rarely downwind of an OWB during $PM_{2.5}$ monitoring. The percentage of time-matched $PM_{2.5}$ concentrations reported while winds at nearfield monitors were calm also varied considerably, but all nearfield monitors experienced calm periods at least 20.5 percent of the time.

$PM_{2.5}$ Concentration Distributions. Figure 1 is a box-and-whisker plot summarizing distributions for time-matched $PM_{2.5}$ concentrations reported by nearfield and reference monitors. Two extremely high $PM_{2.5}$ values reported by reference monitor R1 (261.0 and 407.8 $\mu g/m^3$), and five extremely high values reported by nearfield monitor N2 (214.0, 229.5, 240.5, 250.8 and 320.8 $\mu g/m^3$), were not plotted. For most sites, $PM_{2.5}$ concentration distributions for nearfield monitors were skewed high compared with distributions for corresponding reference monitors. This was indicated by, among other things, comparatively high medians and 75th percentile values. Site 4 (monitor pair N4/R4) was the exception.

Figure 3. Boxplots of Time-matched $PM_{2.5}$ Concentrations.



Notes:
The bottom and top edges of each shaded box indicate the 25th and 75th percentile $PM_{2.5}$ concentration values, respectively, for each distribution. These boxes contain about half of the $PM_{2.5}$ concentrations reported by each monitor. Horizontal lines drawn within shaded boxes indicate medians. Horizontal lines (whiskers) above and below shaded boxes indicate $PM_{2.5}$ concentrations that are 1.5-times interquartile ranges, and values outside 1.5-times interquartile ranges are indicated by gray dots.[3]

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[3] $PM_{2.5}$ concentrations outside of 1.5-times interquartile ranges are often considered statistical outliers, but in this case the apparent outliers are at least partially due to skewed (approximately log-normal) data distributions.

Comparisons of Geometric Means. Table 4 compares nearfield and reference monitor geometric mean $PM_{2.5}$ concentrations. Geometric mean $PM_{2.5}$ concentrations ranged from 3.2 to 15.8 µg/m^3 for nearfield monitors, and from 2.3 to 9.8 µg/m^3 for reference monitors. Geometric mean $PM_{2.5}$ concentrations at each of five nearfield monitors were 15, 17, 46, 74 and 187 percent higher than geometric mean concentrations at paired reference monitors. At a sixth study site, designated site 4, the geometric mean $PM_{2.5}$ concentration was 27 percent lower at the nearfield monitor compared with its paired reference monitor. The site 4 nearfield monitor was deployed in a heavily wooded area, relatively far from the nearest OWB (1,270 feet distant).

Student's Matched-Pair *t*-test. Table 4 summarizes the results of matched-pair *t*-tests evaluating mean paired $PM_{2.5}$ concentration differences for each monitor pair. Mean paired $PM_{2.5}$ concentration differences ranged from 0.2 to 6.6 µg/m^3, and differences at five of six sites were statistically significant (Student's matched-pair p = <0.0001 to 0.01, after adjustment for autocorrelation). This indicated that five of six nearfield monitors reported significantly higher $PM_{2.5}$ concentrations compared with their corresponding reference monitors. Only the smallest mean paired difference (0.2 µg/m^3), calculated for monitor pair N4/R4, was not statistically significant (p = 0.59, after adjustment for autocorrelation).

Table 4. Comparisons of $PM_{2.5}$ Concentrations at Nearfield Monitors and Corresponding Reference Monitors.

Monitor Pair	Nearfield Monitor Geometric Mean $PM_{2.5}$ Concentration (µg/m^3)	Reference Monitor Geometric Mean $PM_{2.5}$ Concentration (µg/m^3)	Mean Paired $PM_{2.5}$ Concentration Difference(1) (µg/m^3)	Student's p(2)
N1/R1	11.5	9.8	4.3	0.01
N2/R2	15.8	9.1	6.6	<0.0001
N3/R3	6.6	2.3	5.4	<0.0001
N4/R4	3.2	4.4	0.2	0.59
N5/R5	9.8	8.5	2.0	<0.0001
N6/R6	13.3	9.1	5.2	<0.0001

Notes:
(1) Mean of nearfield $PM_{2.5}$ levels minus time-matched reference $PM_{2.5}$ levels.
(2) After off-set and log-transformation of paired $PM_{2.5}$ concentration differences, and adjustment for autocorrelation.

$PM_{2.5}$ Concentration Spikes. Table 5 indicates the increased or decreased odds of experiencing a $PM_{2.5}$ concentration spike at each nearfield monitor compared with its corresponding reference monitor.

At the five study sites where *t*-tests indicated that $PM_{2.5}$ levels were statistically significantly elevated at nearfield monitors, the odds of observing a $PM_{2.5}$ concentration spike at the nearfield monitor were 1.8- to 4.3-fold higher compared with its corresponding reference monitor, and the increased odds were statistically significant (logit p = <0.0001 to 0.04). At a sixth study site where the *t*-test indicated that $PM_{2.5}$ levels were not statistically significantly elevated at the nearfield monitor, the odds of observing a $PM_{2.5}$ concentration spike were 20 percent lower at the nearfield monitor compared with its paired reference monitor, but the decrease was not statistically significant (logit p = 0.22).

Table 5. Relative Odds of Observing a 95th Percentile or Greater $PM_{2.5}$ Concentration (“$PM_{2.5}$ concentration spike”) at each Nearfield Monitor Compared with its Corresponding Reference Monitor, with 95% Confidence Intervals and Regression *p*-values(1).

Site	95th Percentile $PM_{2.5}$ Concentration Cutpoint ($\mu g/m^3$)	Odds Ratio	95% Confidence Interval	logit *p* NEARFIELD(2)
1	56.3	1.9	1.1, 3.1	0.016
2	46.9	1.8	1.2, 2.6	0.004
3	15.6	4.3	2.6, 7.1	<0.0001
4	13.5	0.8	0.5, 1.2	0.22
5	26.2	1.8	1.3, 2.5	0.0001
6	37.8	2.0	1.02, 3.8	0.043

Notes:
(1) Odds ratios, confidence intervals and *p*-values were adjusted for autocorrelation.
(2) NEARFIELD was a dichotomous variable indicating nearfield monitor status [0 (no) or 1 (yes)].

Longitudinal Graphs and Bar Charts. Figures A-7 through A-12 (Appendix A) are longitudinal graphs of $PM_{2.5}$ nearfield and reference $PM_{2.5}$ concentrations for each site, with night hours (6 pm to 6 am) also indicated. These graphs indicate several data gaps due to $PM_{2.5}$ and meteorological station malfunctions. Despite these gaps, the graphs clearly show a tendency for higher $PM_{2.5}$ concentrations at nearfield monitors (blue dots) compared with reference monitors (black dots). The exception is site 4, where there is no directional tendency.

Figures A-13 through A-18 (Appendix A) are longitudinal graphs of paired $PM_{2.5}$ concentration differences for each monitor pair, with nearfield meteorological conditions and night hours (6 pm to 6 am) also indicated. Figures A-19 through A-23 (Appendix A) are bar charts that illustrate, among other things, calm conditions and wind directions associated with elevated mean paired $PM_{2.5}$ concentration differences levels. The figures support four key observations:

- Paired $PM_{2.5}$ concentration differences tended to be greater than 0 $\mu g/m^3$, indicating a preponderance of higher $PM_{2.5}$ levels at nearfield monitors, at all study sites except site 4 (Appendix A, Figures 13-15,17,18);

- Transient $PM_{2.5}$ pollution episodes at monitors, indicated on longitudinal graphs by periods of $PM_{2.5}$ concentration differences plotted considerably above or below 0 $\mu g/m^3$, were most often positive, indicating substantially elevated $PM_{2.5}$ levels reported at nearfield monitors compared with nearly simultaneous levels reported at paired reference monitors (Appendix A, Figures 13-15,17,18);

- Transient $PM_{2.5}$ pollution episodes at nearfield monitors often occurred at night (shaded regions on longitudinal graphs) when calm conditions prevailed (purple dots on longitudinal graphs; purple bars on bar graphs) (Appendix A, Figures 13-15,17-19, 21,22); and

- For sites 2, 3, 5 and 6, transient $PM_{2.5}$ pollution episodes at nearfield monitors appeared to be associated with downwind status (orange dots on longitudinal graphs; orange bars on bar graphs) (Appendix A, Figures 14, 18, 20-23).

Influence of Wind Speed and Direction on Nearfield $PM_{2.5}$ Levels. Table 6 provides mean paired $PM_{2.5}$ concentration differences for each nearfield wind direction and each monitor pair other than N4/R4, the pair for which no time-matched meteorological data were available. Mean $PM_{2.5}$ concentration differences in Table 6 were among the summary data employed to generate Figures A-19 through A-23 (Appendix A).

Table 6. Mean Paired $PM_{2.5}$ Concentration Differences (µg/m^3) by Wind Direction. Values were Rounded to the nearest 0.1 µg/m^3. Shaded Cells Indicate that The Nearfield Monitor was Approximately Downwind of a Nearby OWB.

Wind Direction	**N1-R1**	**N2-R2**	**N3-R3**	**N5-R5**	**N6-R6**
CALM	7.9	6.3	7.8	3.2	2.2
N	-0.6	8.5	4.4	***7.4***	1.2
NNE	-1.3	6.0	6.6	***-0.6***	-1.0
NE	***-1.9***	5.8	***9.1***	1.3	0.1
ENE	**--**	7.4	***4.9***	-0.6	-1.4
E	***-1.5***	8.0	***8.1***	0.3	--
ESE	***-0.8***	1.5	7.3	0.6	--
SE	**-0.1**	6.8	5.4	0.9	3.4
SSE	***1.8***	6.1	6.8	1.1	3.9
S	***0.2***	6.1	6.7	1.7	2.0
SSW	***0.2***	4.7	5.8	1.1	1.7
SW	-0.6	4.0	4.9	0.3	6.4
WSW	0.5	***8.1***	4.5	0.7	***9.2***
W	-0.2	***12.6***	5.9	0.9	***18.2***
WNW	-0.3	***8.0***	4.3	-0.0	***7.4***
NW	-0.1	3.3	2.8	2.0	4.3
NNW	-0.3	6.3	2.2	***7.6***	3.2

Note:

The symbol "--" indicates that the wind direction was not observed during the monitoring period.

At each monitor pair for which time-matched meteorological data were available, the greatest mean paired concentration difference was reported when the nearfield monitor was approximately downwind of a nearby OWB, or when calm (0 mph) winds were reported at the nearfield monitor. When mean differences during calm periods were ignored, the greatest mean differences calculated for each monitor pair were reported when the nearfield monitor was downwind of a nearby OWB. Calm conditions were most strongly associated with substantial $PM_{2.5}$ elevations at nearfield monitor N1, as evidenced by a mean paired $PM_{2.5}$ concentration difference for site 1 of 7.9 µg/m^3 during calm conditions, considerably higher than differences reported for site 1 when conditions were not calm (-1.9 to 1.8 µg/m^3).

As indicated in Table 6, as well as in Figures A-22 and A-23 (Attachment A), downwind status was most clearly associated with elevated mean paired $PM_{2.5}$ concentration differences at nearfield monitors N5 and N6. Also indicated in Table 6, and in Figure A-19 (Attachment A), a relatively high mean paired $PM_{2.5}$ concentration difference was observed for site 1 during south-

southeast winds, when the nearfield monitor was approximately downwind of two nearby OWBs. This suggested that the two OWBs were substantial sources of $PM_{2.5}$ at monitor N1. However, mean differences for adjacent wind directions were negative (southeast winds), or only slightly elevated (south winds), inconsistent with the two OWBs being substantial sources of nearfield $PM_{2.5}$.

Table 7 indicates the increased or decreased odds of experiencing a paired $PM_{2.5}$ concentration difference spike ("$PM_{2.5}$ difference spike") at each site when the nearfield monitor was approximately downwind of an OWB, and when winds at the nearfield monitor were calm. At all five sites providing time-matched meteorological data, downwind status and/or calm conditions were significantly associated with $PM_{2.5}$ difference spikes. This was not surprising, because OWBs can release substantial amounts of $PM_{2.5}$ (NYS OAG, 2008), and calm winds often indicate conditions that promote the local accumulation of air pollutants (MADAR, 2003; Larson *et al*., 2009).

Table 7. Relative Odds of Observing a 95th Percentile or Greater Paired $PM_{2.5}$ Concentration Difference ("$PM_{2.5}$ difference spike") at Each Study Site that Provided Time-matched Meteorological Data, with 95% Confidence Intervals and Regression *p*-values$^{(1)}$.

Site	CALM$^{(2)}$ Odds Ratio (95% CI)	CALM$^{(2)}$ logit *p*	DOWNWIND$^{(3)}$ Odds Ratio (95% CI)	DOWNWIND$^{(3)}$ logit *p*
1	21.0 (2.8, 155.4)	0.003	0.24 (0.03, 1.8)	0.17
2	2.1 (1.4, 3.1)	0.0002	1.7 (1.1, 2.6)	0.009
3	2.7 (1.7, 4.3)	<0.0001	2.0 (0.7, 5.3)	0.17
5	4.5 (2.9, 7.0)	<0.0001	4.0 (2.2, 7.1)	<0.0001
6	0.8 (0.3, 2.1)	0.69	5.9 (2.6, 13.6)	<0.0001

Notes:

(1) Odds ratios, confidence intervals and *p*-values were adjusted for autocorrelation.

(2) "CALM" indicates that the mean nearfield wind speed was 0 mph

(3) "DOWNWIND" indicates that the nearfield monitor was approximately downwind of a nearby outdoor wood-fired boiler.

Downwind status was most strongly associated with $PM_{2.5}$ difference spikes at study site 6, where the nearfield monitor was deployed closest to an OWB, and was also deployed upon relatively flat terrain. The odds of observing a $PM_{2.5}$ difference spike at site 6 were nearly six-fold higher during intervals when the nearfield monitor was downwind of the OWB, compared with intervals when the nearfield monitor was upwind/crosswind of the OWB, and the increase was statistically significant [OR 5.9; 95 percent CI 2.6, 13.8]. Statistically significant associations between downwind status and $PM_{2.5}$ difference spikes were also observed at study site 2 (OR 1.7; 95 percent CI 1.1, 2.6) and 5 (OR 4.0; 95 percent CI 2.2, 7.1). Downwind status increased the odds of a $PM_{2.5}$ difference spike at site 5, even though the nearfield monitor was approximately downwind of an OWB for only about four percent of the time-matched observations recorded at site 5.

Calm periods were most strongly associated with increased $PM_{2.5}$ levels at study site 1, where the nearfield monitor was deployed near a cluster of three OWBs. The odds of observing a $PM_{2.5}$ difference spike at site 1 were 21-fold higher during intervals when winds were calm, compared with intervals when the nearfield monitor was approximately upwind/crosswind of nearby OWBs (OR 21.0; 95 percent CI 2.8, 155.4). Based on Table 6, which indicated a relatively high mean $PM_{2.5}$ concentration difference at site 1 when winds at the nearfield monitor were from the south-southeast (1.8 $\mu g/m^3$), two additional logit models were estimated for site 1: one model that considered only the OWB located approximately 580 feet south of the nearfield monitor, and another model that considered only the OWB located approximately 390 feet southeast of the nearfield monitor. These additional models confirmed a strong and statistically significant association between calm conditions and $PM_{2.5}$ difference spikes, and confirmed the absence of a significant association between downwind status and $PM_{2.5}$ difference spikes (Table 8).

Table 8. Relative Odds of Observing a 95th Percentile or Greater Paired $PM_{2.5}$ Concentration Difference ("$PM_{2.5}$ difference spike") at Study Site 1 Considering Individual OWBs.

Site	CALM(2) Odds Ratio (95% CI)	CALM(2) logit *p*	DOWNWIND(3) Odds Ratio (95% CI)	DOWNWIND(3) logit *p*
1 (south OWB only)	23.8 (3.2, 176.3)	0.002	0.58 (0.08, 4.3)	0.59
1 (southeast OWB only)	22.3 (3.0, 167.7)	0.003	0.53 (0.07, 4.0)	0.54

Non-significant predictor variables were originally retained when fitting logit models for study sites 1, 3 and 6. Removal of these non-significant predictors had little effect on OR estimates, and so did not alter study findings with regard to associations between predictors (CALM, DOWNWIND) and $PM_{2.5}$ difference spikes (alternative ORs not shown).

Alternative (non-OWB) $PM_{2.5}$ Sources. Although frequent site visits provided information on the location and timing of some smoke emissions at all study sites, the quality of observation logs kept by residents participating in the study varied, and some residents provided few observations. In addition, the potential for alternative (non-OWB) $PM_{2.5}$ sources to have increased $PM_{2.5}$ levels reported by site 4 monitors could not be thoroughly evaluated due to the absence of time-matched meteorological data.

Non-OWB $PM_{2.5}$ emissions sources reported in the general vicinity of nearfield and reference monitors were of six basic types: masonry chimneys, metal stovepipes, primary home heating system flues, idling vehicles and roadways (road dust and vehicle exhaust). Visible masonry chimney emissions were reported within 1,500 feet of only one nearfield monitor, N4, but were observed near reference monitors R2, R3 and R4 (Table 9). N2 was the only nearfield monitor deployed near (*i.e.*, within 1,000 feet of) a visible masonry chimney or metal stovepipe emission.

Table 9. Potential Non-OWB Sources of $PM_{2.5}$ Within 1,500 Feet of Monitors.

Monitor	Distance from Monitor (ft)	Potential $PM_{2.5}$ Source	Direction of Source Relative to Monitor
N2	700	visible metal stovepipe emissions	NW
R2	1,390	visible metal stovepipe emissions	SE
R3	150	visible masonry chimney emissions	WNW/NW
R3	467	visible masonry chimney emissions	NNE/NE
R3	1,146	visible masonry chimney emissions	N
N4	1,190	visible masonry chimney emissions	NNW
N4	1,220	visible masonry chimney emissions	NNW
N4	1,310	visible masonry chimney emissions	NW
R4	940	visible masonry chimney emissions	N
R4	1,280	visible masonry chimney emissions	SW

Although precise periods of alternative source emissions were often not determined, inspection of graphs, maps and raw data suggested that smoke releases unrelated to OWBs could have contributed to $PM_{2.5}$ concentration spikes reported at nearfield monitor N2 and reference monitor R2 (Table 10). In addition, two such releases occurred approximately upwind of nearfield monitor N2 at times when the monitor reported $PM_{2.5}$ concentration spikes. These two releases are highlighted in Table 10. No other reported non-OWB $PM_{2.5}$ releases were associated with elevated $PM_{2.5}$ concentrations at nearfield monitors.

Table 10. Smoke Releases Unrelated to OWBs That Could Have Contributed to $PM_{2.5}$ Concentration Spikes Reported at Study Monitors.(1)

Monitor	Date of $PM_{2.5}$ Release	Time Period Assumed for $PM_{2.5}$ Release(2)	Description of $PM_{2.5}$ Source (Direction of $PM_{2.5}$ Source from Monitor)	Actual Wind Direction
N2	03/14/07	15:20 - 15:45	Car exhaust (NNW, N, NNE)	WSW, W, WNW
N2	**03/15/07**	**5:20 - 5:55(3)**	**Truck exhaust (NNW, N, NNE)**	**WSW, W, WNW, NNW(5)**
N2	03/15/07	8:00 - 18:00(4)	Metal stovepipe emissions (NW)	N
N2	**03/19/07**	**7:15 - 7:50**	**Car exhaust (NNW, N, NNE)**	**N, NNE(5)**
N2	03/26/07	8:00 - 18:00(4)	Metal stovepipe emissions (NW)	E, S, SW, WSW, W, WNW
R2	03/26/07	8:00 - 18:00(4)	Metal stovepipe emissions (SE)	NNW

Notes:
(1) $PM_{2.5}$ concentration spikes that were reported during calm periods (0 mph wind speed), were not considered.
(2) Time period considered included the one-hour period around the exact time that the release was observed.
(3) There were no $PM_{2.5}$ concentration spikes before 5:20am on March 15, 2007.
(4) The exact time of the observed release was not recorded. Therefore, the potential for a release at any time during the day to be associated with a $PM_{2.5}$ concentration spike was considered.
(5) $PM_{2.5}$ release appeared to occur approximately upwind of nearfield monitor

Two unavoidable alternative sources, roadways and residences, were often located between nearfield monitors and nearby OWBs. Roadways are indicated on maps attached as Figures A-1 through A-7 (Appendix A). Roadways were located between nearfield monitors and nearby OWBs at 4 out of 6 locations (sites 1, 2, 3 and 5). Although most roadways in study areas appeared to the investigators to be lightly-traveled rural roads, the roadway near monitor N2 was a major highway. Homes were located either between nearfield monitors and OWBs, or very near OWBs. Residences were therefore in the same approximate wind direction, relative to nearfield monitors, as OWBs. With the exception of nearfield monitor N4, homes located between nearfield monitors and OWBs, or very near OWBs, were those of OWB owners. No chimney smoke was observed at any OWB owner's home over the course of the study, despite frequent site visits.

As previously indicated in Appendix C, $PM_{2.5}$ monitors were usually deployed upon pallets or, in one case, a picnic table. Several air monitors were also deployed on wooden decks. One monitor (N6) was deployed on frozen ground. Snow depth reported around monitors ranged from a dusting to 10 inches.

Also as indicated in Appendix C, air monitor sampling inlet heights ranged from 31.5 to 95.5 inches (0.8 to 2.4 meters) above the ground surface. This range was somewhat below the height of 3 meters that has been employed to measure $PM_{2.5}$ near roads (Chen *et al.*, 2009), and considerably below the height of 10 meters that was recommended by the United States Department of Transportation for purposes of characterizing $PM_{2.5}$ levels near highways (Federal Highway Administration, 2006).

Discussion

$PM_{2.5}$ concentrations, and the odds of experiencing transient $PM_{2.5}$ pollution episodes ($PM_{2.5}$ concentration spikes), were significantly elevated at five of six outdoor air monitors deployed close to OWBs, compared with reference monitors deployed farther from OWBs. This was the case even though two of the five monitors were downwind of nearby OWBs less than five percent of their respective monitoring periods. Downwind status was associated with higher odds of experiencing $PM_{2.5}$ pollution episodes ($PM_{2.5}$ difference spikes) at sites 2, 5 and 6, providing evidence that elevated $PM_{2.5}$ levels at nearfield monitors were at least partially due to OWB emissions and not alternative $PM_{2.5}$ sources. Downwind status was most strongly associated with $PM_{2.5}$ episodes at monitor N6, the monitor deployed in flat terrain and closest to an OWB.

This study was too small for the investigators to estimate the probability of detecting a statistically significant increase in $PM_{2.5}$ levels at any given distance from an OWB or OWB cluster. It is likely that several factors determine the amount of OWB-related $PM_{2.5}$ pollution measured in outdoor air at a specific location. These factors include, but are not limited to, the number of OWBs present, distances to those OWBs, OWB stack heights, OWB $PM_{2.5}$ emission rates, $PM_{2.5}$ monitor height, and the extent to which meteorological conditions, intervening structures and terrain favor migration of smoke from OWBs to the $PM_{2.5}$ monitor. It would be a challenge to deploy air monitors at enough sites to adequately represent ranges for all of the relevant variables, and this study did not attempt to do so.

Similarly, the investigators do not believe that the inability of the study approach to detect elevated $PM_{2.5}$ levels at nearfield monitor N4, compared with its corresponding reference monitor R4, inferred a distance from OWBs at which OWB-related $PM_{2.5}$ pollution is unlikely to be observed. Many additional deployments would be needed to estimate such a distance using the study methods. Outside of the study settings, the investigators have observed OWB smoke plumes migrating farther than 1,270 feet (the distance between monitor N4 and its nearest OWB).

Study results illustrated the importance of considering the impacts of not only wind direction, but also of calm winds and OWB clustering, when evaluating the potential for OWB-related $PM_{2.5}$ pollution at a residence. Higher frequencies of transient $PM_{2.5}$ pollution episodes at nearfield monitors were associated with calm conditions at monitors N1, N2, N3 and N5. Calm conditions were most strongly associated with transient $PM_{2.5}$ pollution episodes at monitor N1, the study monitor near a cluster of several OWBs. During much of the heating season in Upstate New York, calm winds at night are associated with temperature inversions which result in the local accumulation of wood smoke and other pollutants, especially in low-lying areas (Larson ***et al***., 2007; NYSERDA, 2010). During such times gravity and topography, rather than wind direction, may largely determine the direction of woodsmoke $PM_{2.5}$ migration through outdoor air (NYSERDA, 2010).

Although $PM_{2.5}$ levels were significantly elevated at nearfield monitor N1 (Student's $p = 0.01$), the odds of a $PM_{2.5}$ difference spike were not significantly increased when N1 was approximately downwind of nearby OWBs (logit $p = 0.17$). There are at least two possible explanations for this observation. Elevated $PM_{2.5}$ levels at nearfield monitor N1 may have been due to deployment of N1 in a catchment area, where $PM_{2.5}$ pollution from upgradient sources can sometimes accumulate, rather than to pollution from nearby OWBs. The corresponding reference monitor, R1, was not deployed in a catchment area. Alternatively, it is possible that elevated $PM_{2.5}$ levels at N1 were at least partially due to pollution from nearby OWBs, but wind direction data for N1 was not representative. This may have resulted from our placement of the site 1 meteorological station near obstructions, or from the presence of intervening structures and/or terrain features. These factors may have obscured the relationship between wind direction and $PM_{2.5}$ difference spikes at N1. This explanation is supported by study data indicating that downwind status was significantly associated with $PM_{2.5}$ difference spikes at site 5, where again the nearfield monitor, but not its paired reference monitor, was deployed in a catchment area. The meteorological station at nearfield monitor N5 was deployed at a sufficient distance from nearby structures to minimize interferences (6x).

Although $PM_{2.5}$ levels were significantly elevated at nearfield monitor N3, and downwind status was associated with a two-fold increase in the odds of observing $PM_{2.5}$ difference spike at site 3, the increased odds were not statistically significant (95 percent CI 0.7, 5.3). Nearfield monitor N3 was downwind of a nearby OWB during only 1.9 percent of the monitoring period, the smallest fraction of any nearfield monitor, so failure of the association between downwind status and $PM_{2.5}$ difference spikes to achieve statistical significance may have been due to insufficient statistical power. When implementing study methods to evaluate $PM_{2.5}$ pollution from OWBs, it may be necessary to conduct air monitoring for more than a week or two, depending on the wind directions that prevail during investigations.

Although air monitor sampling inlet heights ranged from 31.5 to 95.5 inches (0.8 to 2.4 meters) above the ground surface, below heights commonly employed for monitoring outdoor air $PM_{2.5}$, the placement of monitors on pallets and wooden decks, along with the surrounding frozen and snow covered ground, created conditions that were not conducive to significant interference from natural resuspension immediately around air monitors. The potential for anthropogenic resuspension due to deck sweeping or walking past monitors cannot be ruled out, but residents reported that they complied with the investigators' requests not to conduct any activities near air monitors and, at any rate, seasonally cold weather probably discouraged outdoor activity. Overall, placement of air monitor sampling inlets at heights within the breathing zone appears to have been beneficial, in that it increased the likelihood that relative increases in $PM_{2.5}$ levels reported nearfield monitors compared with reference monitors reflected increases in actual residential exposures to $PM_{2.5}$.

Study Merits and Limitations

To the investigators' knowledge, this was the first study to compare $PM_{2.5}$ concentrations in outdoor air at multiple residences near OWBs with levels at residences farther from OWBs. Merits of the study included the determination of $PM_{2.5}$ levels under conditions of actual OWB use, rather than under artificial or experimental conditions. Also, by employing same air-shed reference monitors and portable meteorological stations, the investigators avoided potential problems associated with reliance upon (distant) network monitors, which can be poor surrogates for local conditions.

Another advantage of the current study was that OWB-related $PM_{2.5}$ pollution was characterized in a manner that maximized, to the extent practical, the degree to which study data reflected $PM_{2.5}$ exposures among OWB neighbors. For example, the study determined $PM_{2.5}$ levels near OWB neighbors' homes. In addition, the study determined $PM_{2.5}$ levels at heights within the personal breathing zone, as opposed to atop flagpoles or buildings. However, the study did not employ regulatory air monitors, so measured $PM_{2.5}$ levels were not compared to air quality standards. Indeed, the investigators know of no state or federal standards, guidelines, or risk-based comparison values for outdoor air $PM_{2.5}$ concentrations measured using the study protocol. Current US EPA standards for $PM_{2.5}$ in air are based on fixed monitors employing a federal reference method, whereas this study used portable monitors that did not employ the federal reference method.

Despite the study advantages, the investigators were limited in their ability to characterize exposures to OWB smoke. For example, this study determined concentrations of only one component of OWB smoke, $PM_{2.5}$, and did not quantify any of the myriad additional toxic substances found in OWB smoke. It is likely that elevated $PM_{2.5}$ levels reported at residences near OWBs were accompanied by elevated levels of other wood smoke components which, when inhaled as a mixture, may have conveyed greater and more varied health risks than would be expected from inhalation of $PM_{2.5}$ alone.

Another limitation of this study was the small number of sites (six). OWB emissions may vary due to a number of factors (*e.g.*, unit design, wear, quality of maintenance, fuel selection, the heating requirements of the OWB owner), and $PM_{2.5}$ transport is influenced by several more factors (*e.g.*, release height, wind speed, wind direction, terrain, structures). This study probably captured only a few of the many possible combinations of emissions- and transport-related conditions. Due to this limitation, the study data cannot be employed to infer the distribution of $PM_{2.5}$ concentrations in neighborhoods around the many OWBs currently operating in New York State. Nor can the data be used to infer a “setback” or “buffer zone” -- a specific distance from an OWB beyond which the probability of experiencing unacceptable increases in OWB-derived smoke or $PM_{2.5}$ approaches zero.

Additional limitations related to the brief duration of some monitoring deployments (minimum one week), the lack of monitoring during the months of May through December, and the incomplete nature of residents' logs indicating the timing of activities, such as fireplace use, that may have released $PM_{2.5}$ near monitors. Brief deployments contributed to two nearfield monitors, N3 and N5, being only rarely downwind of OWBs. None the less, downwind status was associated with increased odds of observing a $PM_{2.5}$ pollution episode at nearfield monitor N5, and the increase was statistically significant ($p < 0.0001$). The lack of information from residents did not pose a major problem, because other information (*i.e.*, data from the investigators' observations) was available that allowed the investigators to evaluate the potential for non-OWB sources of $PM_{2.5}$ to have influenced study conclusions.

Deployment of the site 1 nearfield meteorological station close to a building may have limited the investigators' ability to accurately record local wind speed and wind direction at the nearfield $PM_{2.5}$ monitor, which in turn may have limited our ability to detect an association between downwind status and $PM_{2.5}$ spikes at nearfield monitor N1.

Deployment of nearfield monitors N1 and N5 in catchment areas, when paired reference monitors were deployed outside of catchment areas, was not an optimal approach. Catchment areas may accumulate $PM_{2.5}$, confounding associations between monitor status (nearfield or reference) and $PM_{2.5}$ levels. None the less, clear indications of OWB-derived $PM_{2.5}$ pollution were detected at nearfield monitor N5, where not only $PM_{2.5}$ monitor type (nearfield), but also nearfield monitor downwind status (approximately downwind), was statistically significantly associated with increased odds of $PM_{2.5}$ pollution episodes. Downwind status was statistically significantly associated with increased odds of observing a $PM_{2.5}$ pollution episode at nearfield monitor N5, even though N5 was rarely downwind of a nearby OWB.

Due to the presence of roadways, and OWB owner's homes, between nearfield monitors and study OWBs, the possibility that local roads and OWB owners' homes contributed to elevated $PM_{2.5}$ levels observed around study OWBs cannot be ruled out. There is evidence, however, that such contributions were negligible. Specifically, roadways and homes were present around each reference $PM_{2.5}$ monitor as well, yet nearfield $PM_{2.5}$ levels were statistically significantly elevated at five of six nearfield monitors and no reference monitor. Moreover, other studies have determined that $PM_{2.5}$ emissions from vehicles, and primary home heating systems relying on oil, propane or natural gas, are considerably lower than emissions from OWBs (Gillies *et al.*, 2001; NESCAUM, 2006). In as much as OWBs are often employed as primary home heating sources, home heating system flues at OWB owners' residences probably emitted little or no $PM_{2.5}$. Finally, with regard to fireplace emissions, no chimney smoke was observed at any OWB owner's home over the course of the study, despite frequent site visits.

Conclusions

Other studies have demonstrated associations between increased exposure to fine particles ($PM_{2.5}$) in air and increased rates of premature death, respiratory illnesses, and cardiovascular effects (US EPA, 2008). On an individual basis, OWBs are far more substantial sources of $PM_{2.5}$ than oil- or natural gas-fired heating systems (NESCAUM, 2006; Gullett, 2011; NYSERDA, 2012). This study documented elevated levels of $PM_{2.5}$ in air at residences near OWBs, and determined that increased numbers of transient $PM_{2.5}$ pollution episodes, likely due to OWB emissions, occurred at residences near OWBs. During these episodes, $PM_{2.5}$ levels in air temporarily increase to several times prevailing levels. It is likely that elevated $PM_{2.5}$ levels reported at residences near OWBs were accompanied by elevated levels of other wood smoke components which, when inhaled as a mixture, may have conveyed greater and more varied health risks than would be expected from inhalation of $PM_{2.5}$ alone (Naeher ***et al.***, 2007; Adetona ***et al.***, 2011).

The study approach appeared sensitive, in that elevated $PM_{2.5}$ levels were detected during five of six deployments, and even when residences were only rarely downwind of OWBs. Study results indicated that investigators evaluating the potential for elevated $PM_{2.5}$ concentrations near OWBs may need to consider not only terrain and wind directions, but also smoke accumulation during calm conditions (temperature inversions) and OWB clustering. Given the severity of adverse health effects associated with elevated wood smoke and $PM_{2.5}$ air concentrations, and the demonstrated importance of OWBs as major sources of wood smoke and $PM_{2.5}$ in some residential settings, further efforts to reduce exposures to OWB-derived wood smoke and $PM_{2.5}$ are warranted.

Only one study OWB, located at site 6, was known to have generated odor or nuisance health complaints prior to initiation of the study. It appeared that pollution from the site 6 OWB was substantial for this cohort, as indicated by, among other things, a nearly six-fold increase in the risk of a $PM_{2.5}$ pollution episode when nearfield monitor N6 was downwind of the OWB. This implied that nearfield wood smoke and $PM_{2.5}$ concentrations may be considerably higher downwind of OWBs that generate complaints compared with OWBs that do not generate complaints. This reinforces the need for interventions when OWB smoke exposures reach levels high enough to elicit complaints.

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Appendix A. Supplemental Figures

Figure A-1. Map of Site 1.

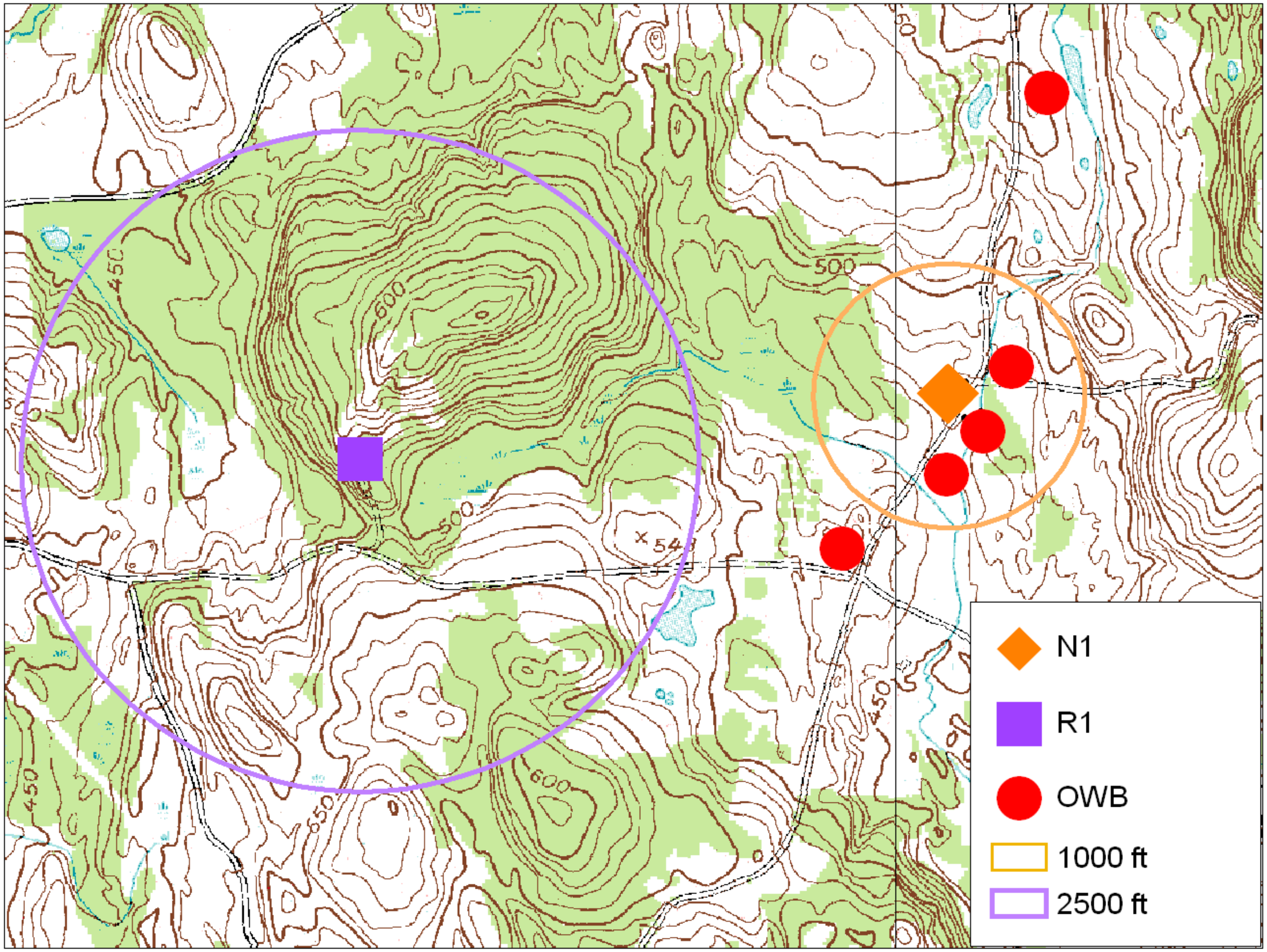


Figure A-2. Map of Site 2.

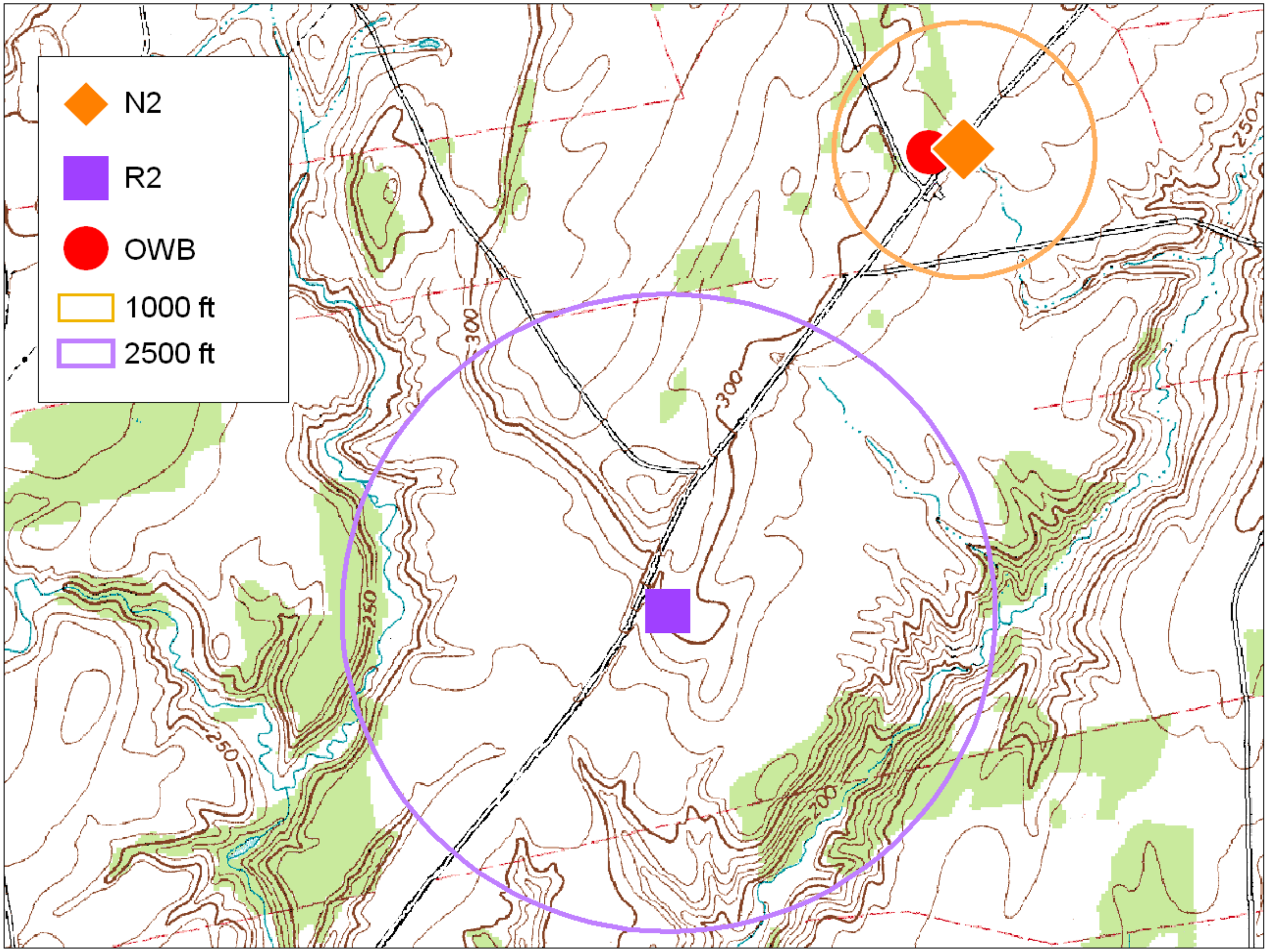


Figure A-3. Map of Site 3.

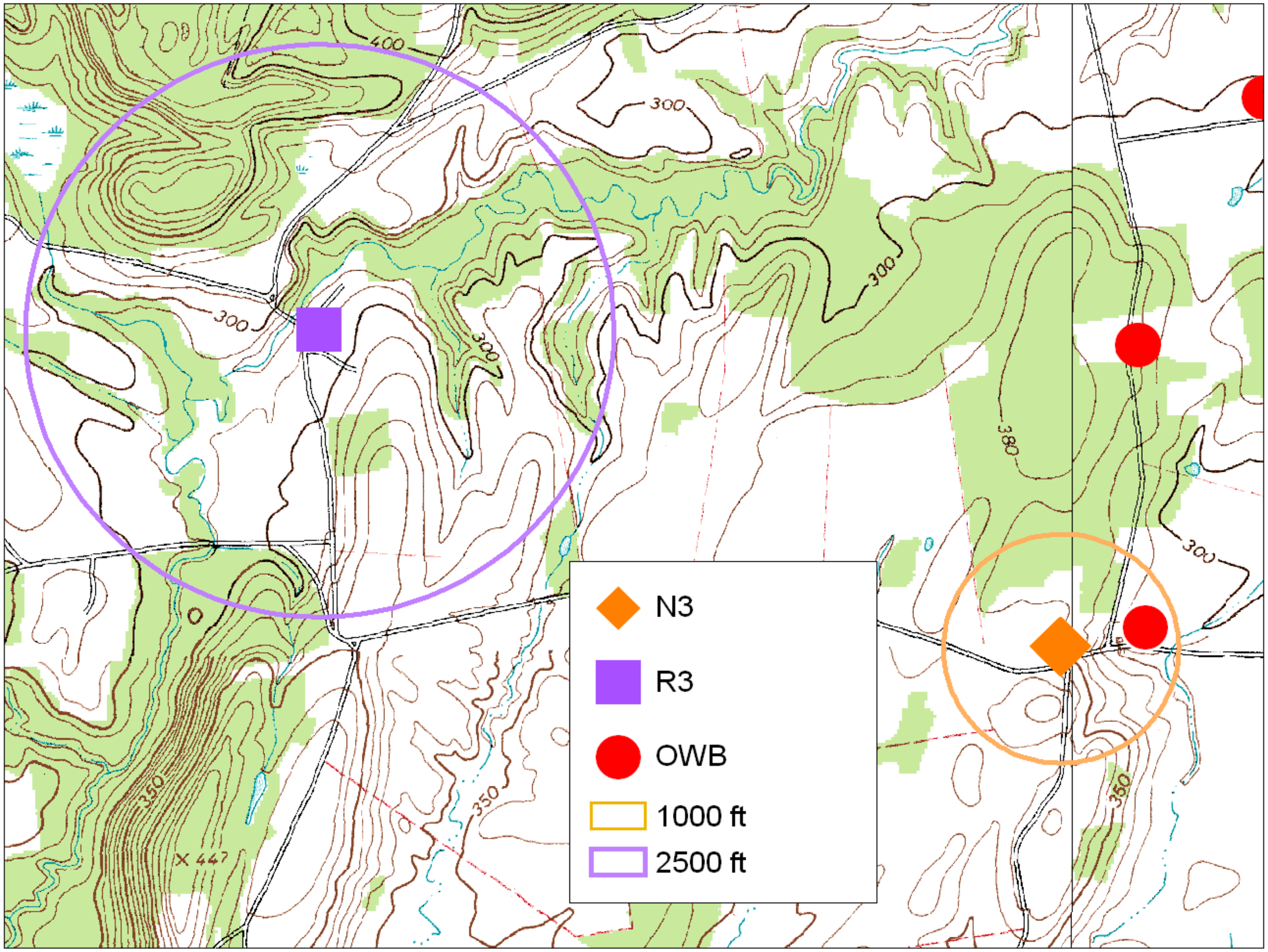


Figure A-4. Map of Site 4.

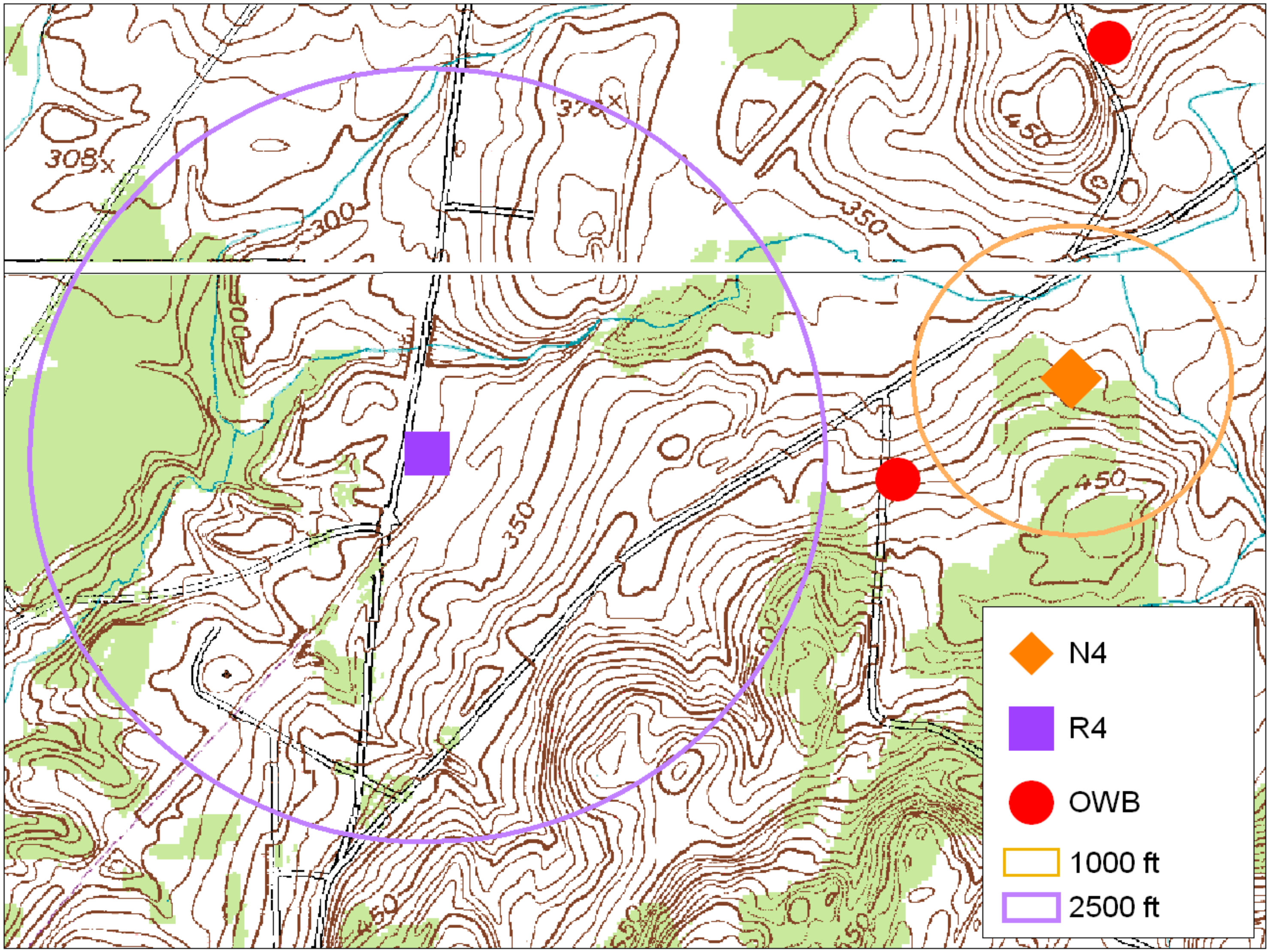


Figure A-5. Map of Site 5.

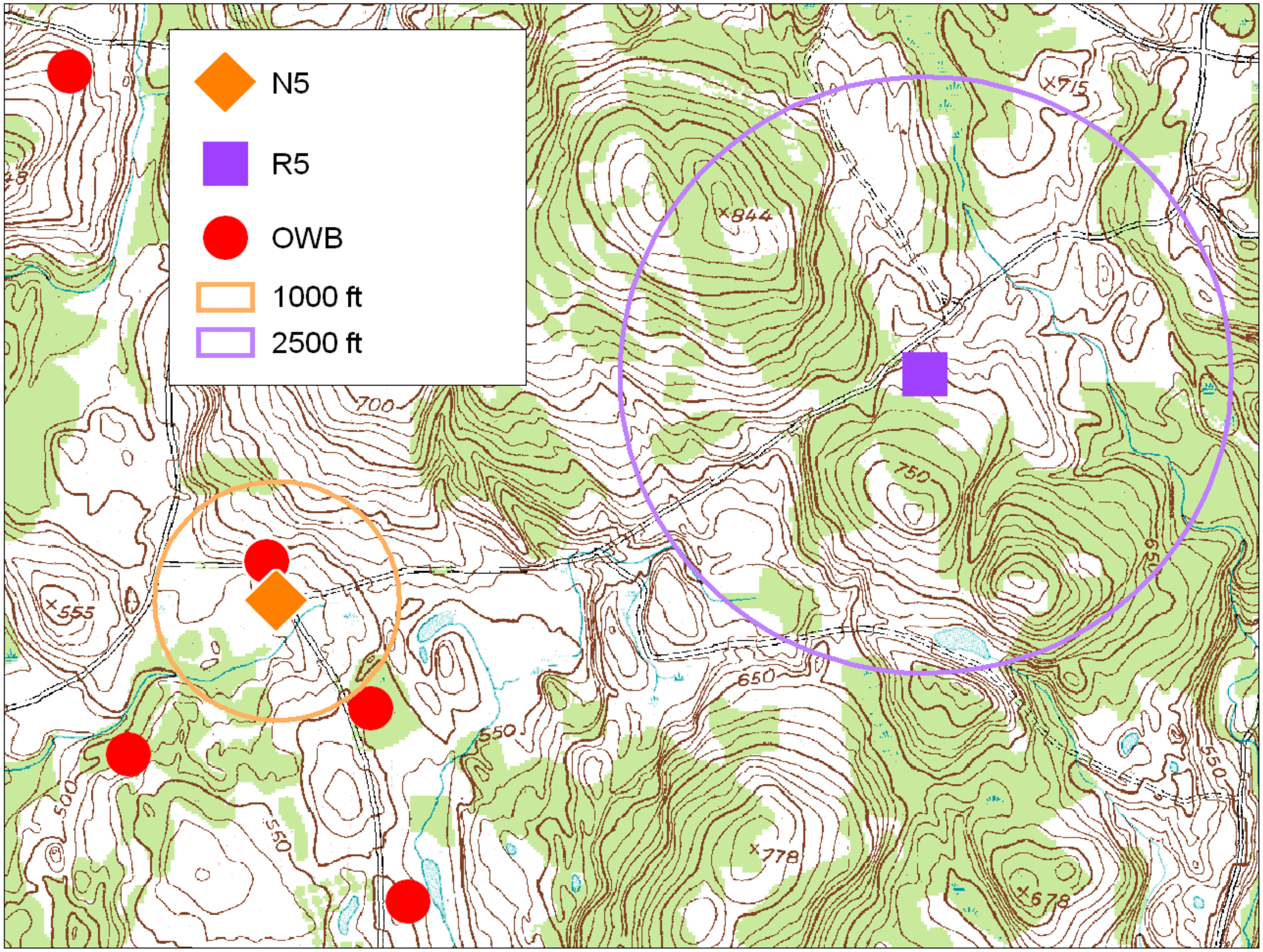


Figure A-6. Map of Site 6.

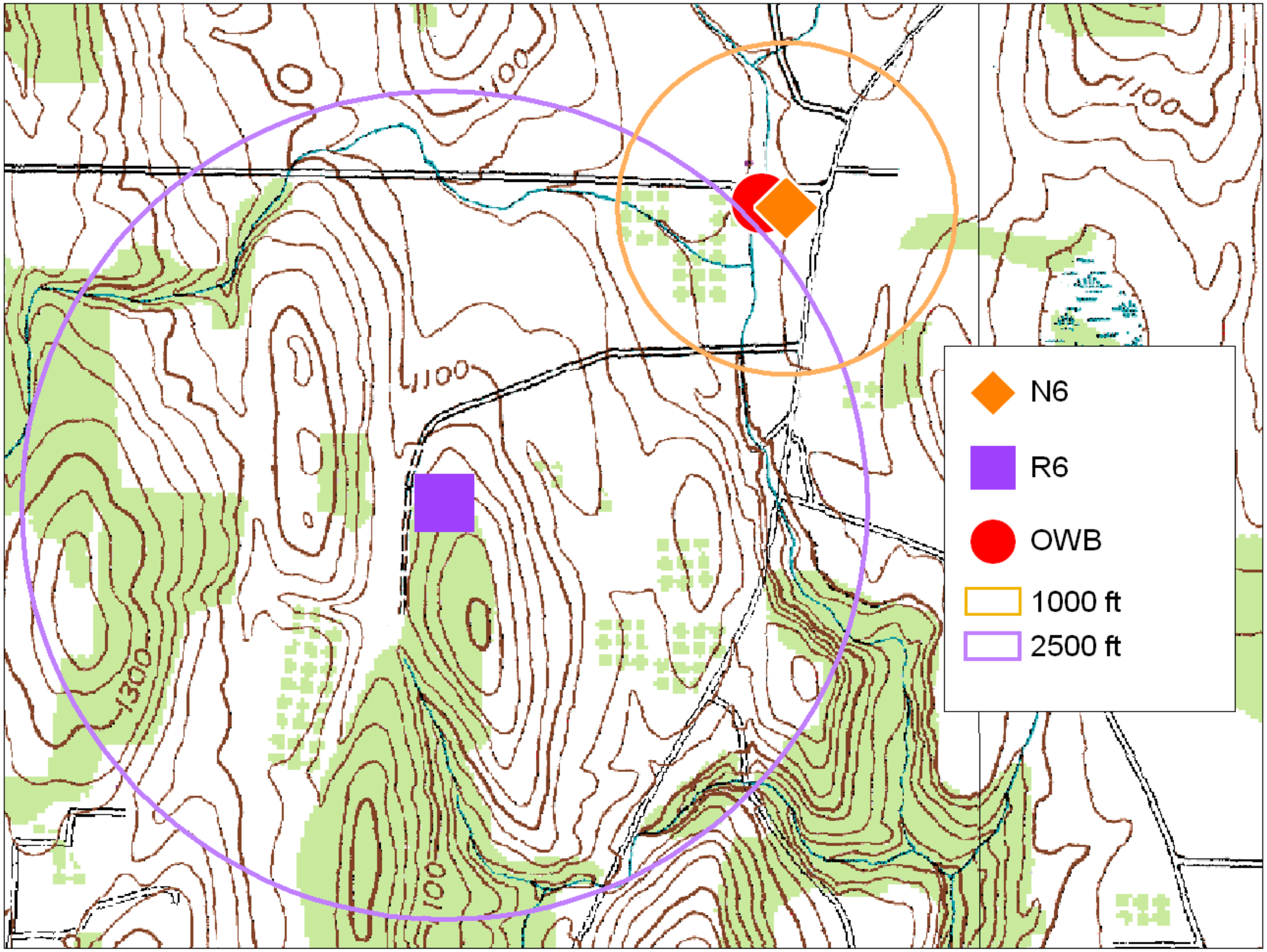


Figure A-7. Longitudinal Graph of $PM_{2.5}$ Concentrations Site 1.

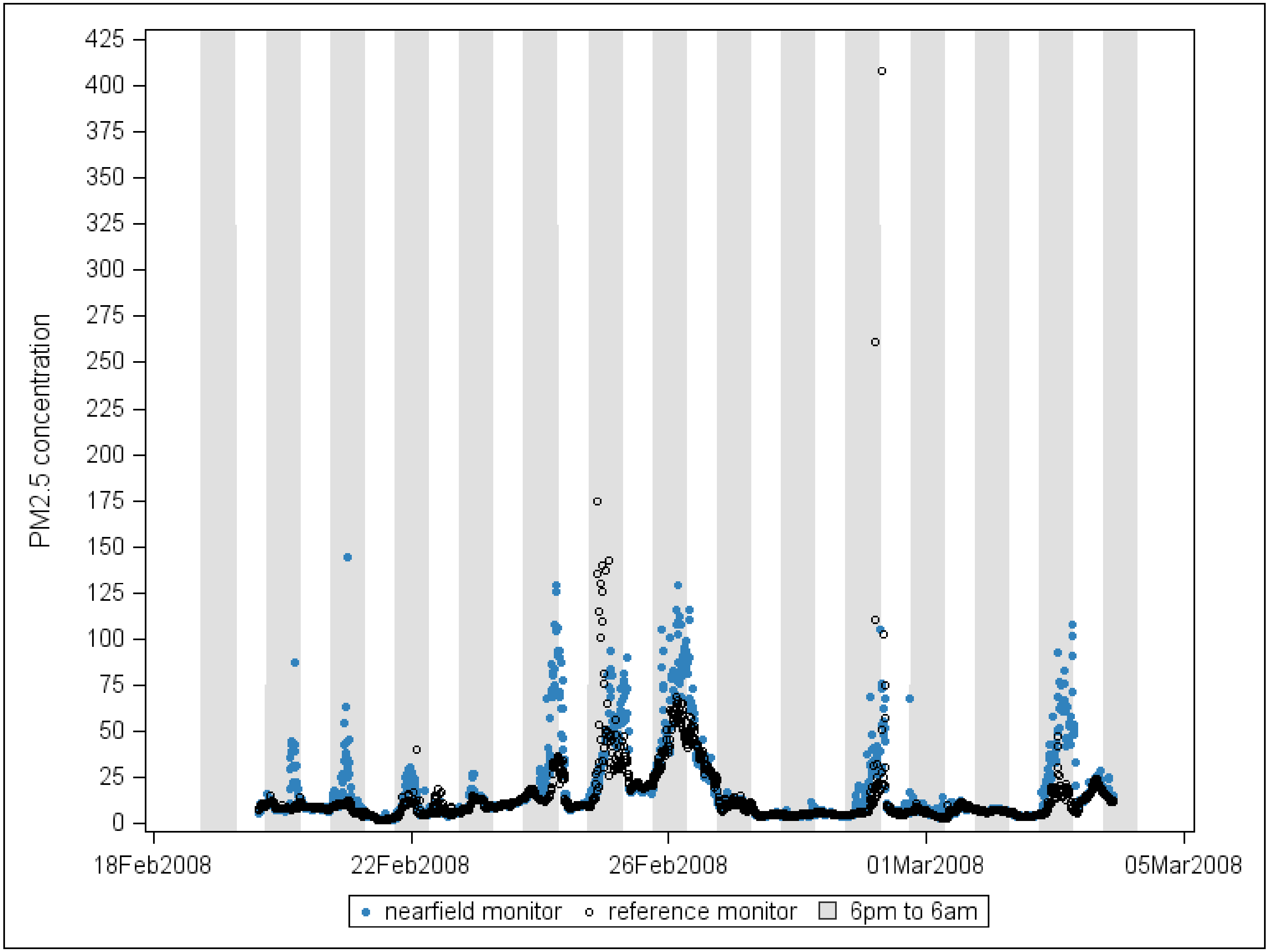


Figure A-8. Longitudinal Graph of $PM_{2.5}$ Concentrations - Site 2.

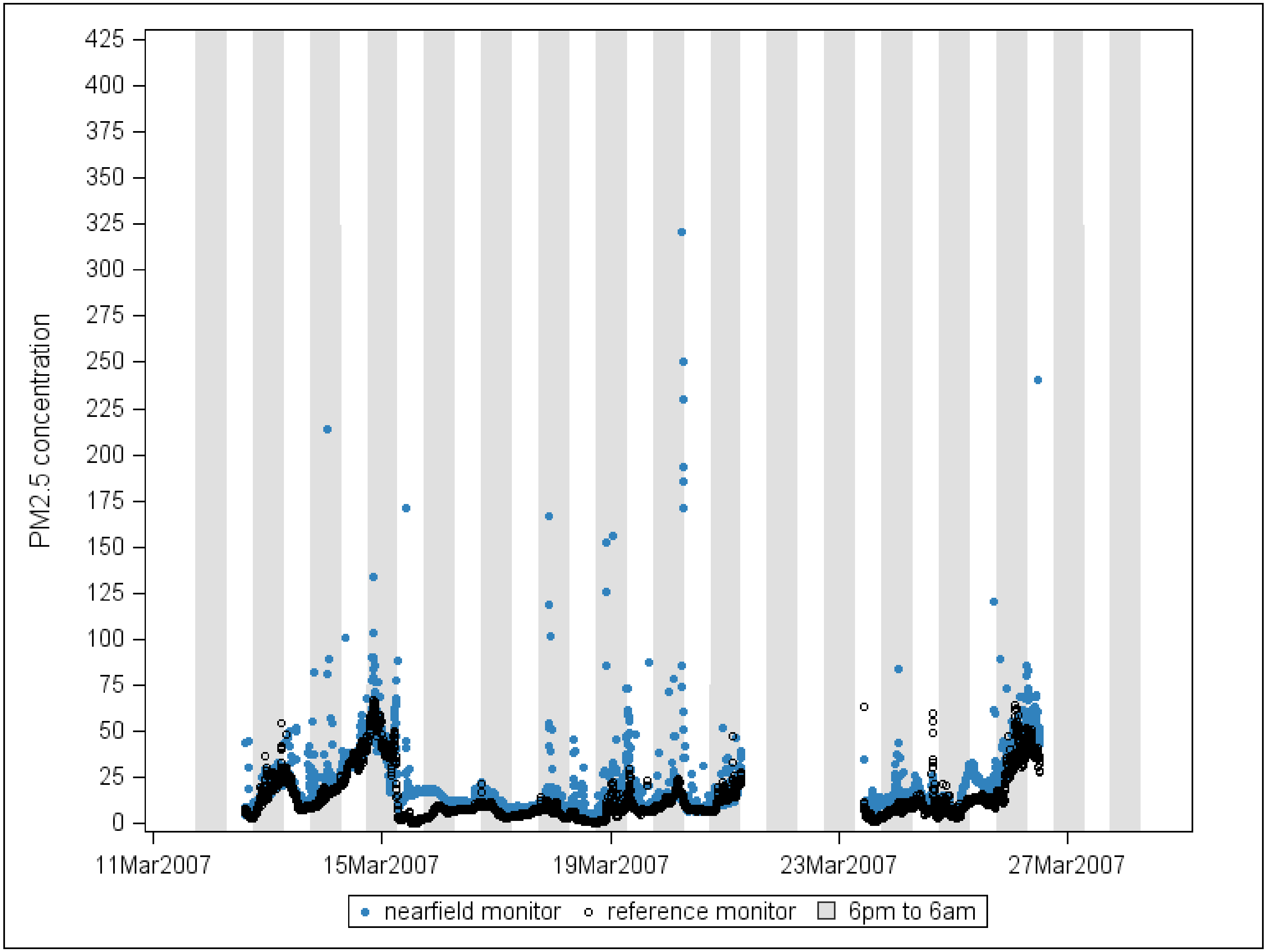


Figure A-9. Longitudinal Graph of $PM_{2.5}$ Concentrations - Site 3.

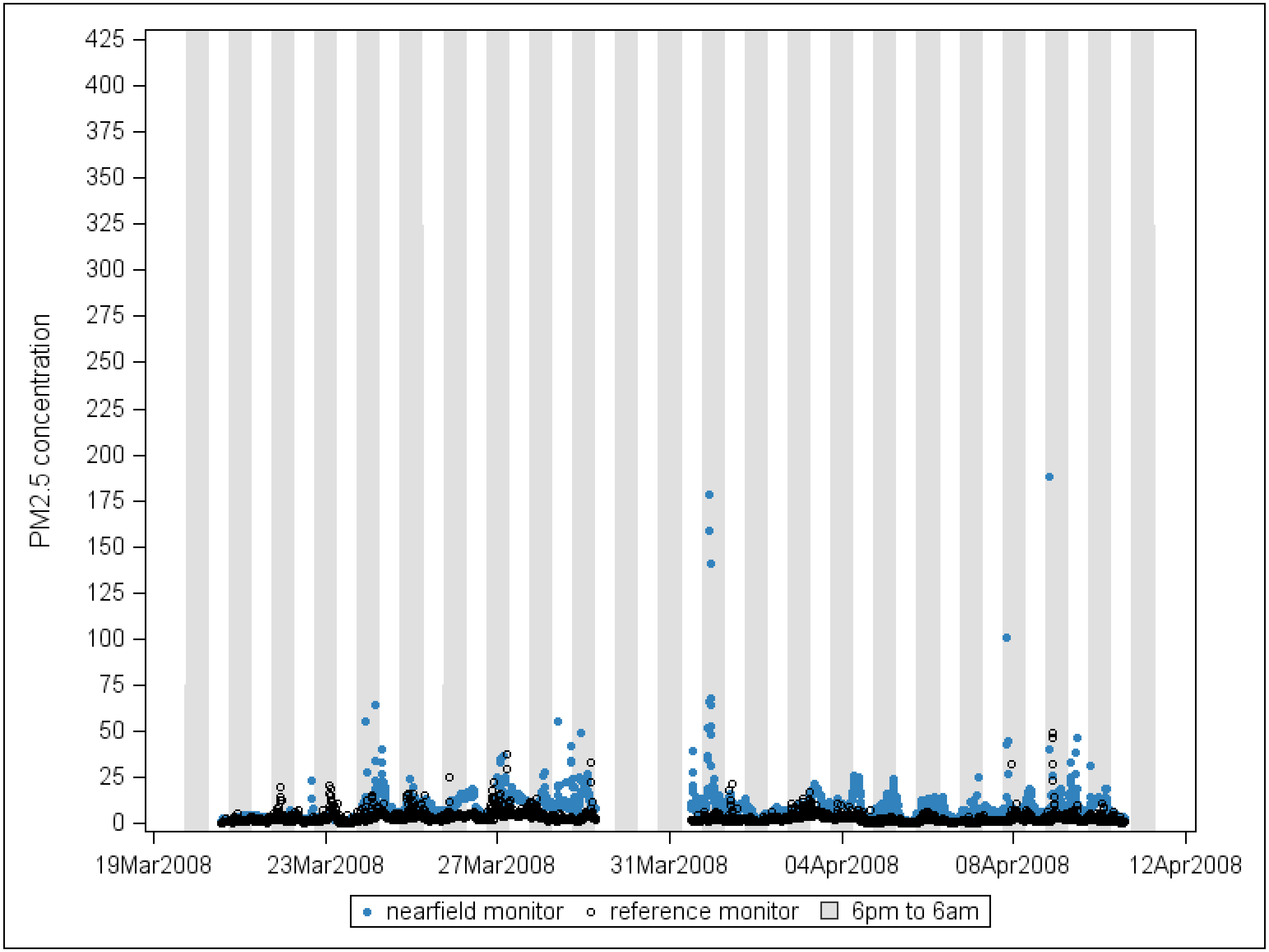


Figure A-10. Longitudinal Graph of $PM_{2.5}$ Concentrations - Site 4.

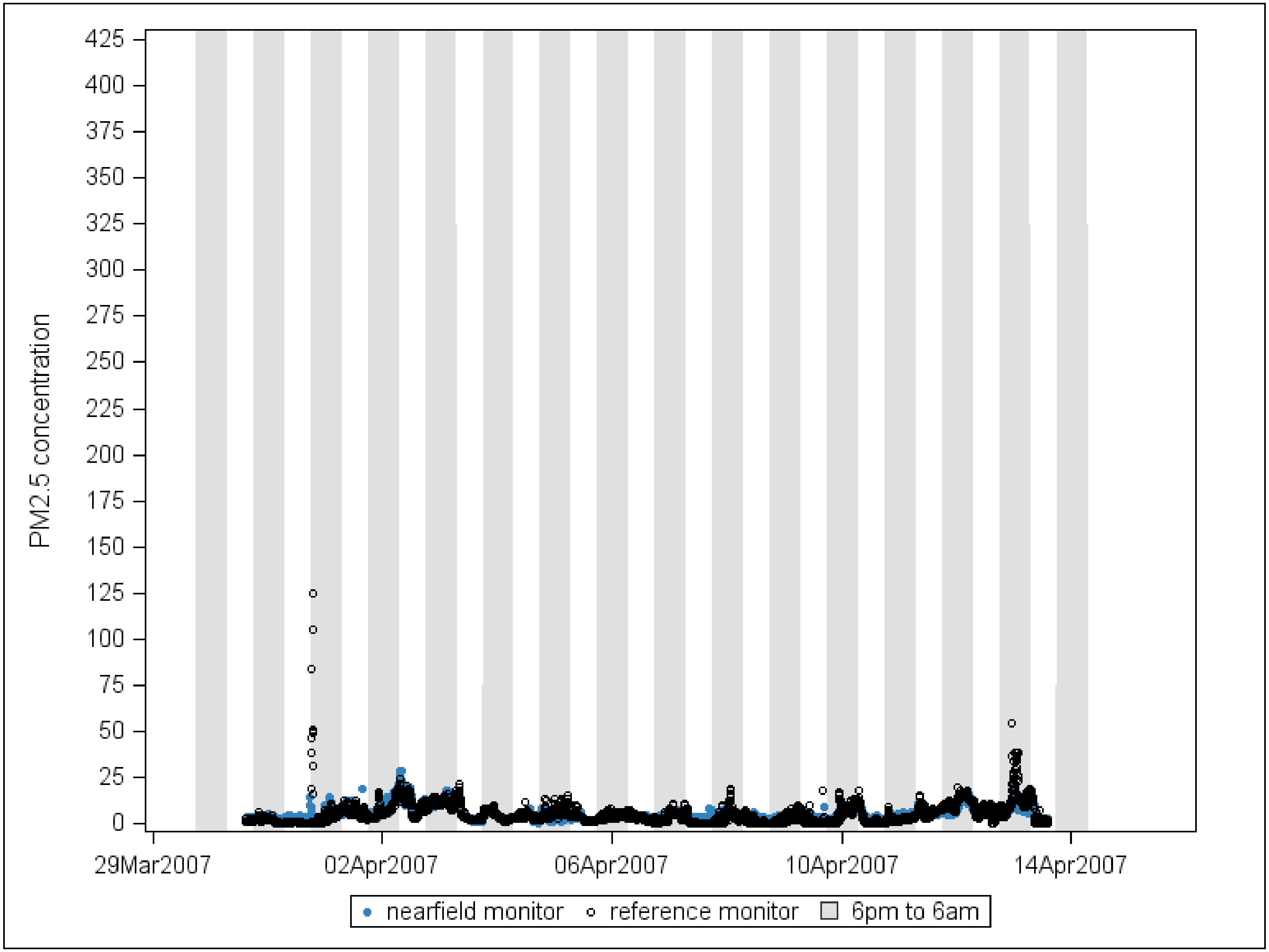


Figure A-11. Longitudinal graph of $PM_{2.5}$ concentrations - Site 5.

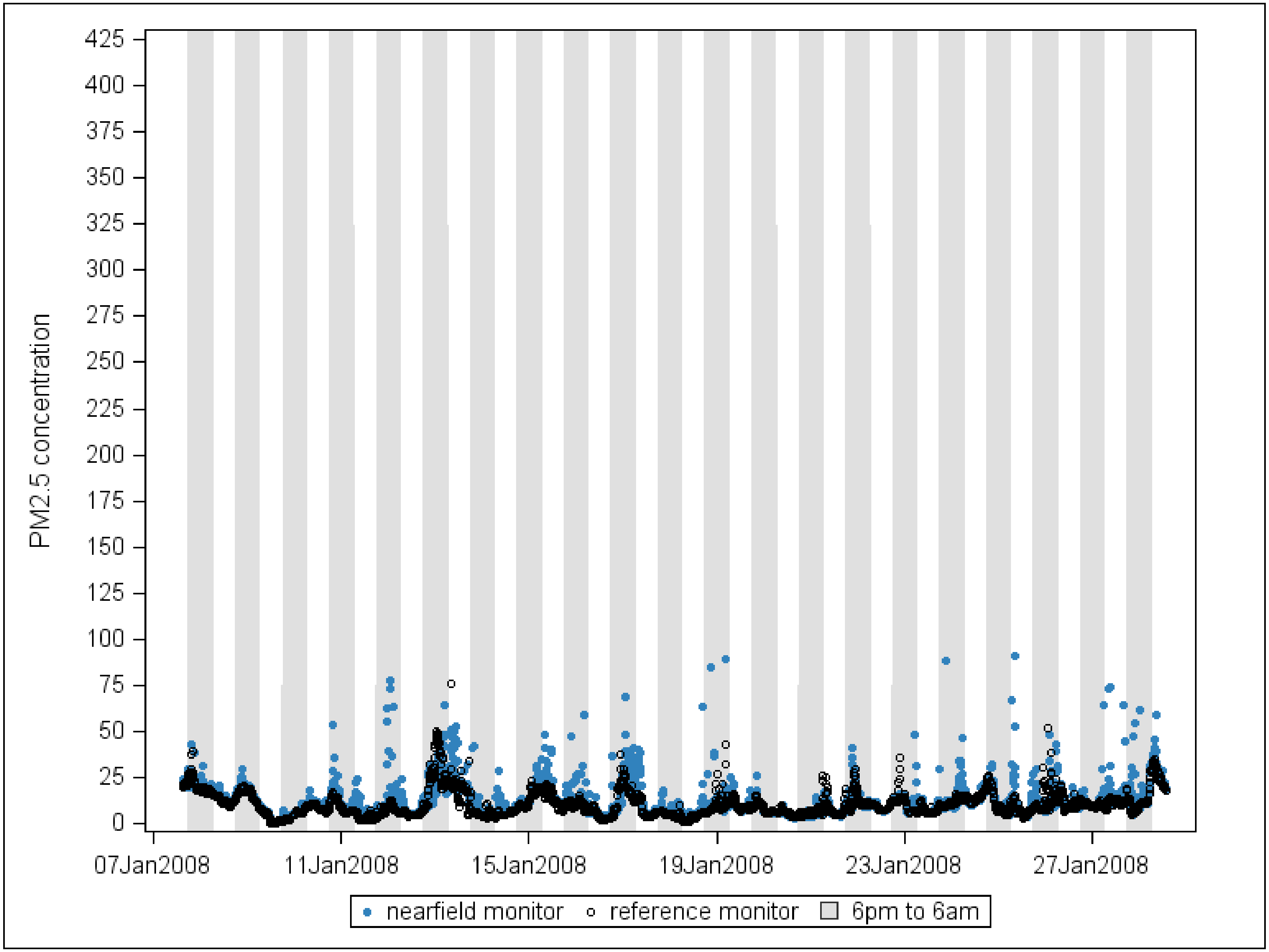


Figure A-12. Longitudinal Graph of $PM_{2.5}$ Concentrations - Site 6.

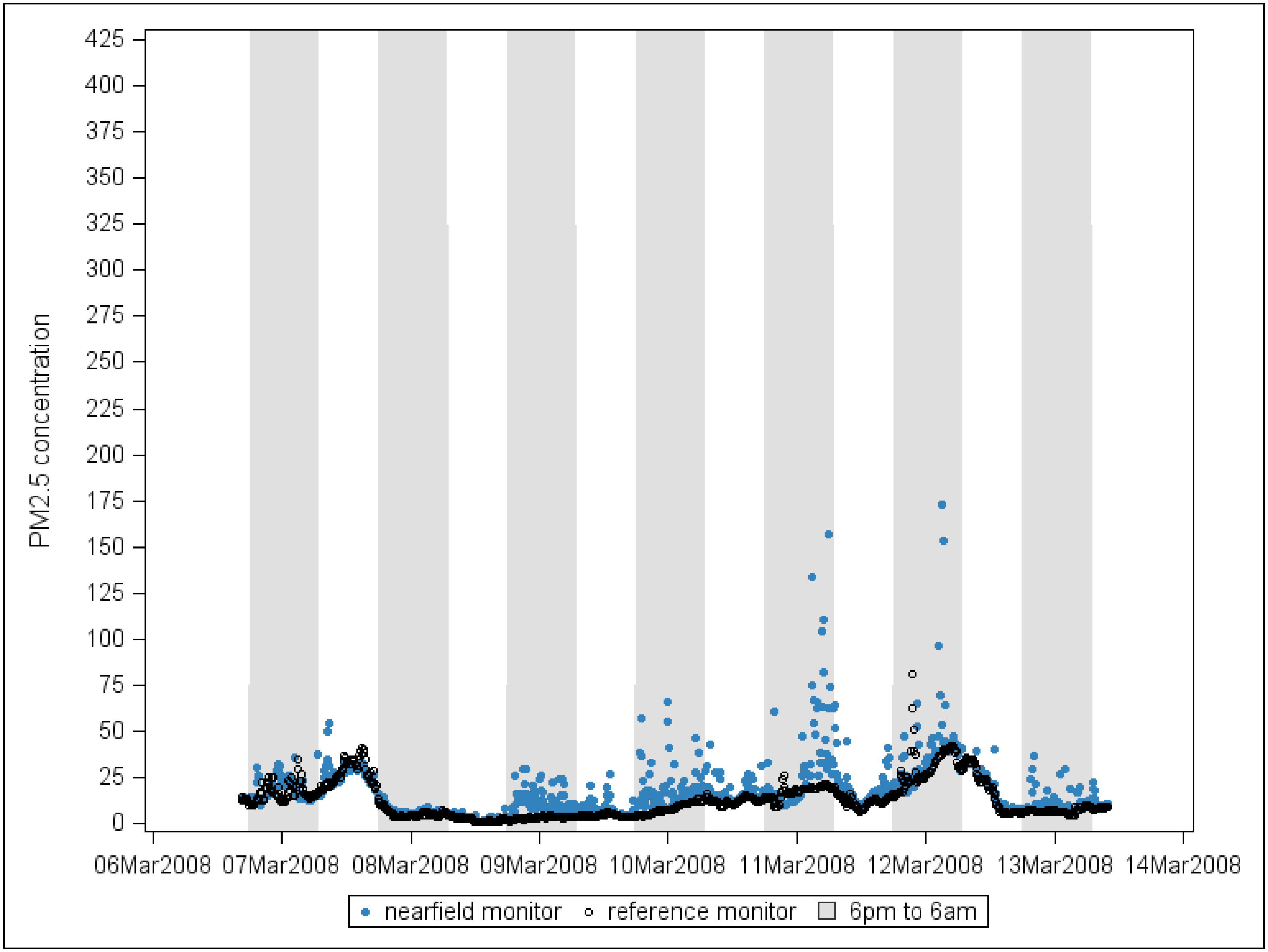


Figure A-13. Longitudinal Graph of $PM_{2.5}$ Differences - Site 1.

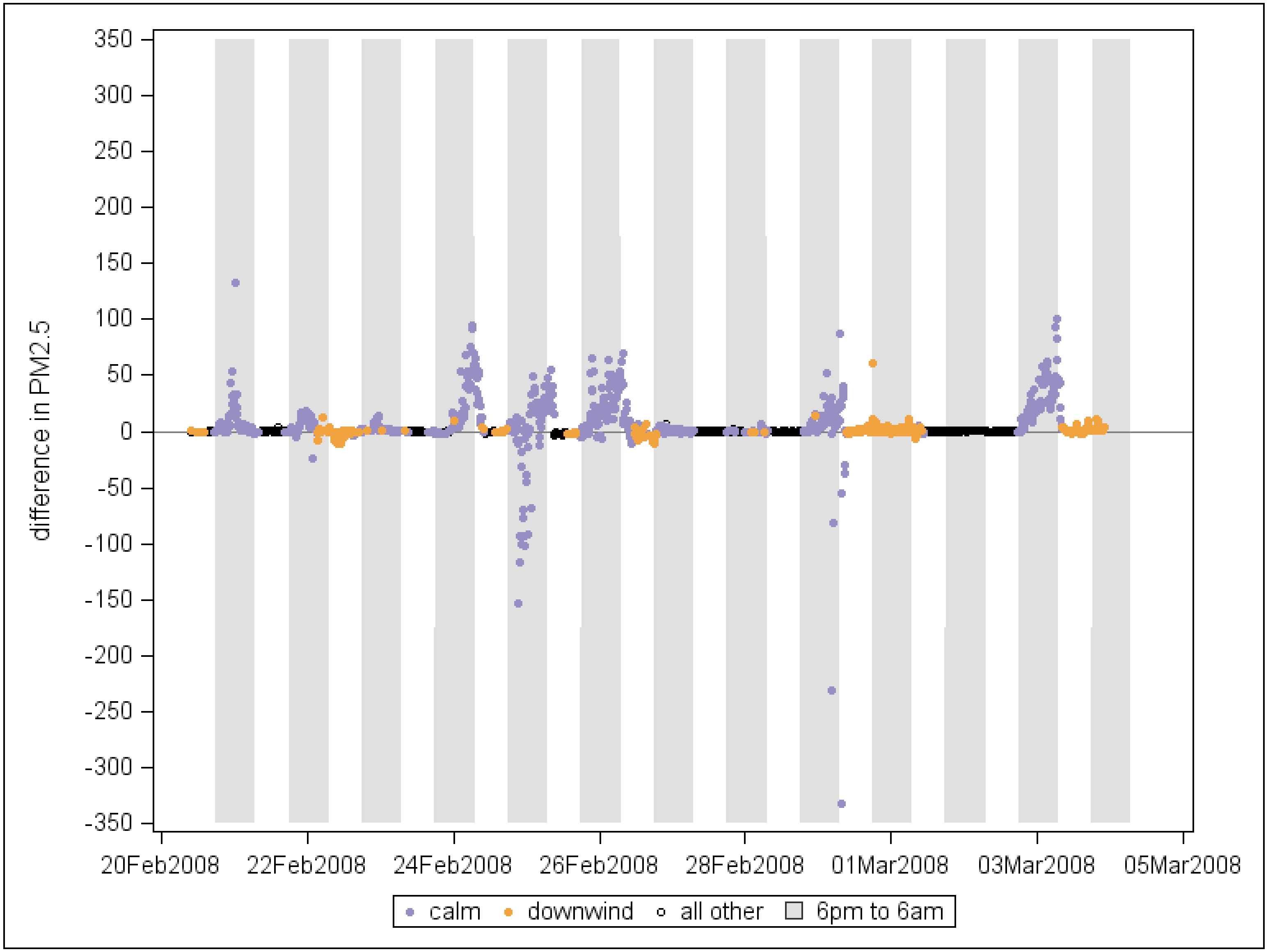


Figure A-14. Longitudinal Graph of $PM_{2.5}$ Differences - Site 2.

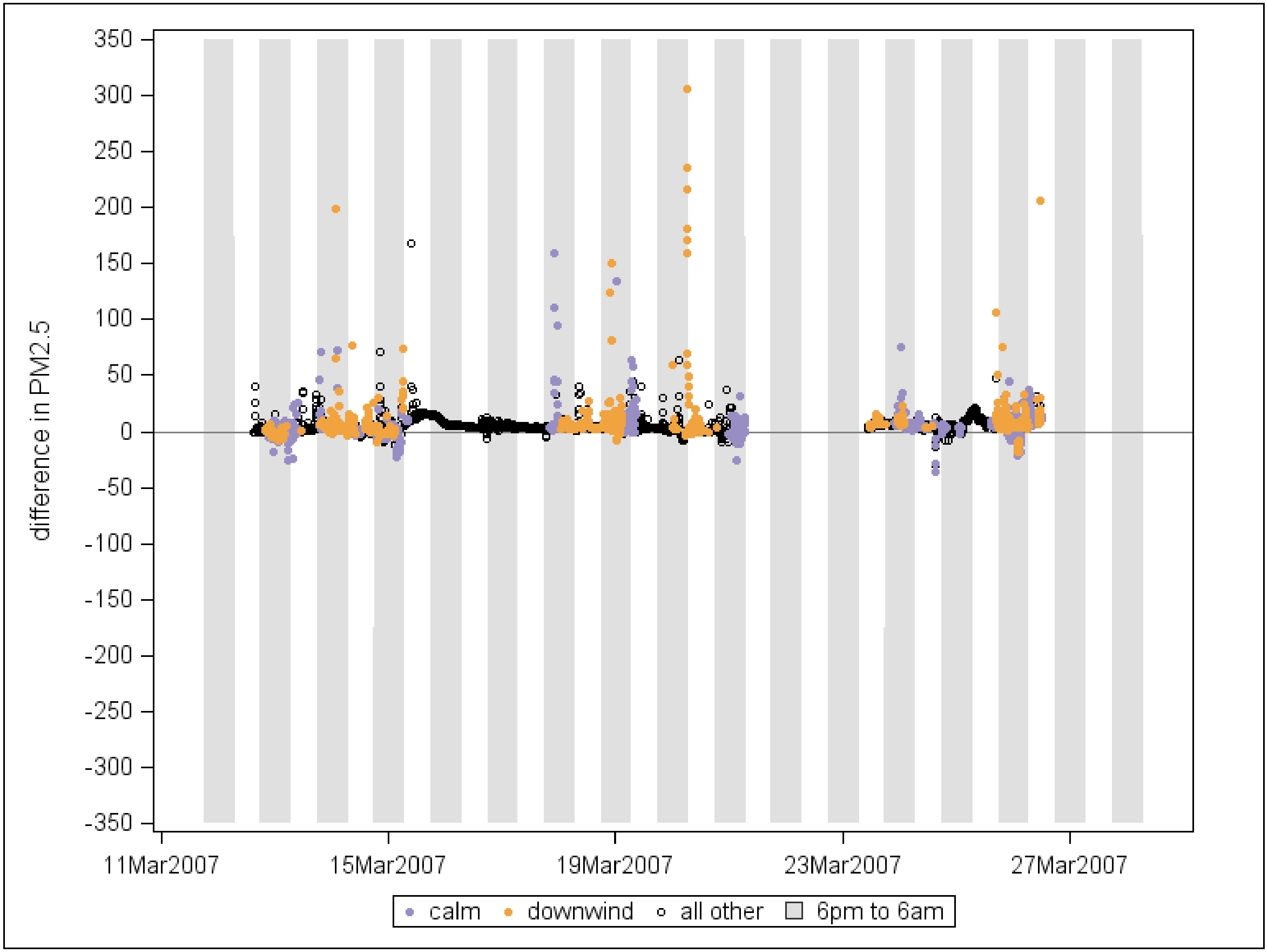


Figure A-15. Longitudinal Graph of $PM_{2.5}$ Differences - Site 3.

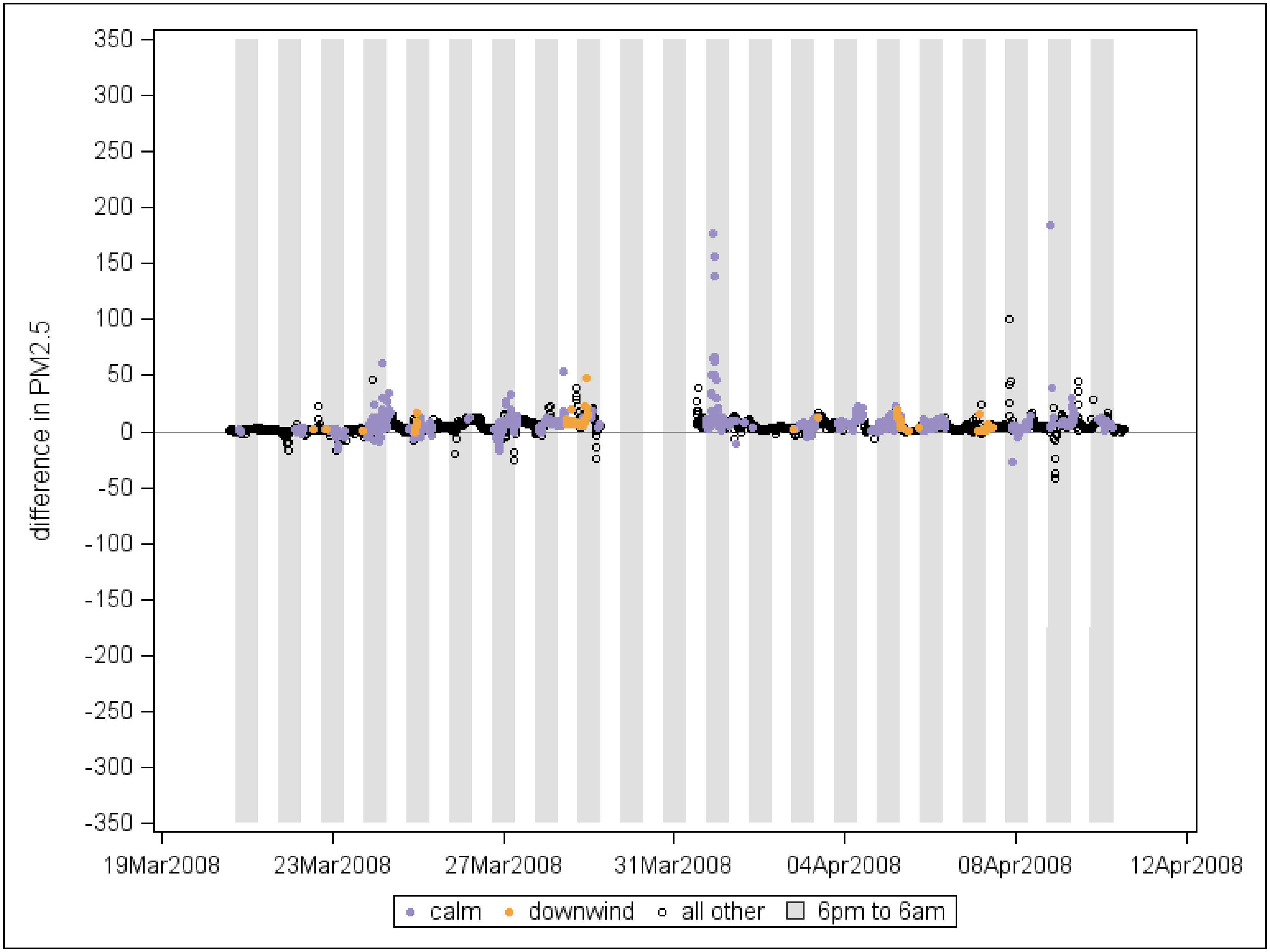


Figure A-16. Longitudinal Graph of $PM_{2.5}$ Differences - Site 4.

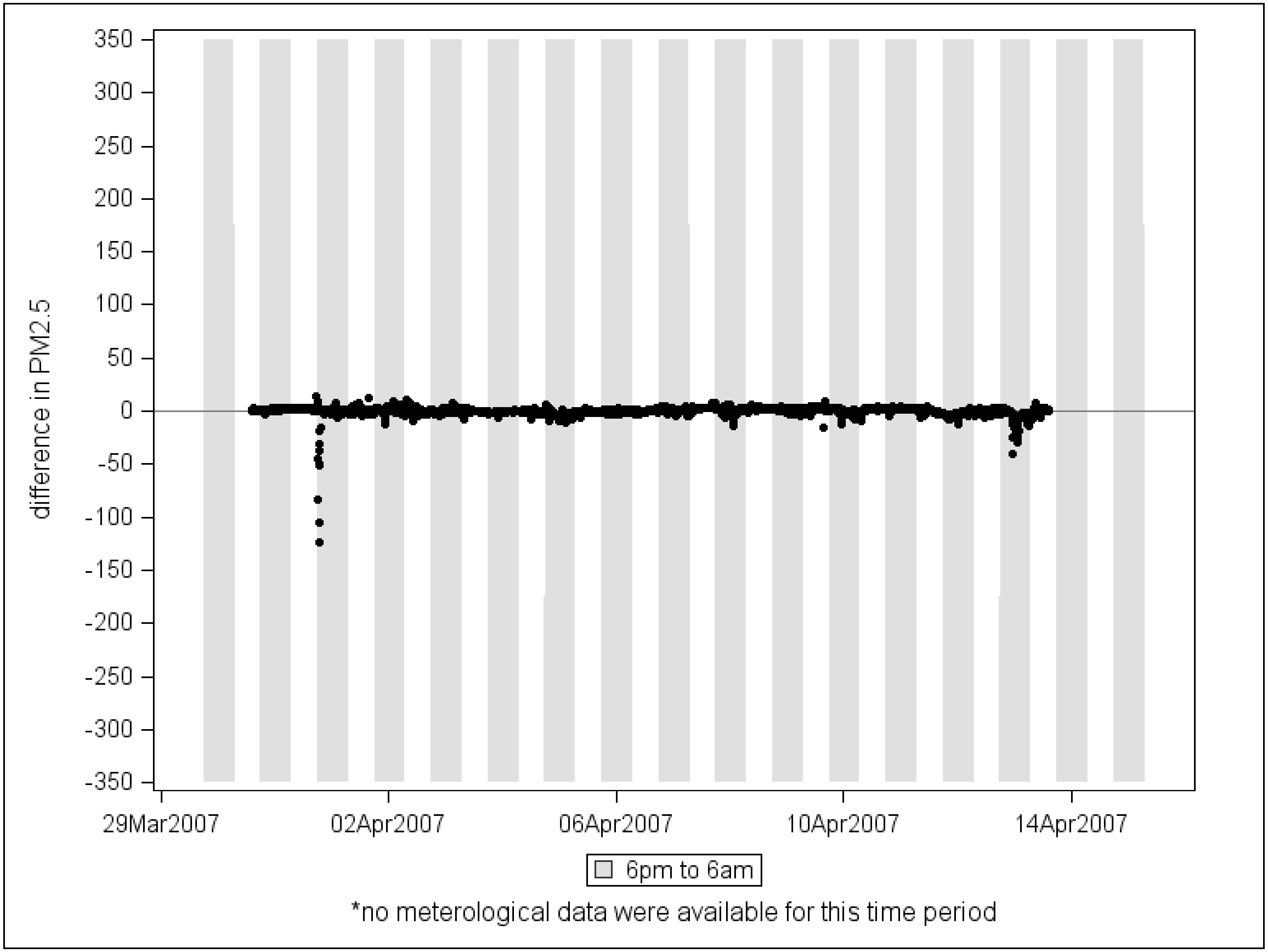


Figure A-17. Longitudinal Graph of $PM_{2.5}$ Differences - Site 5.

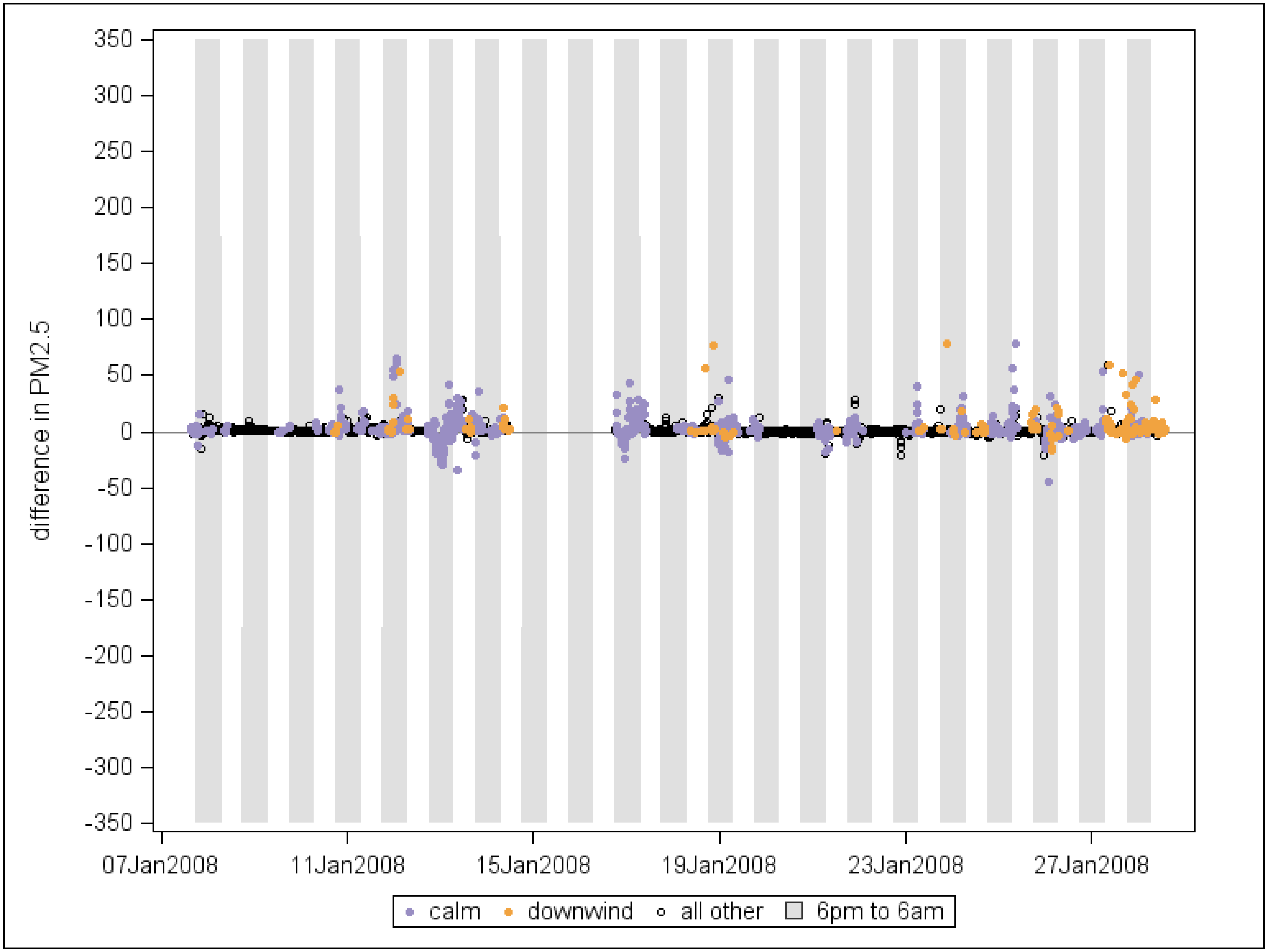


Figure A-18. Longitudinal Graph of $PM_{2.5}$ Differences - Site 6.

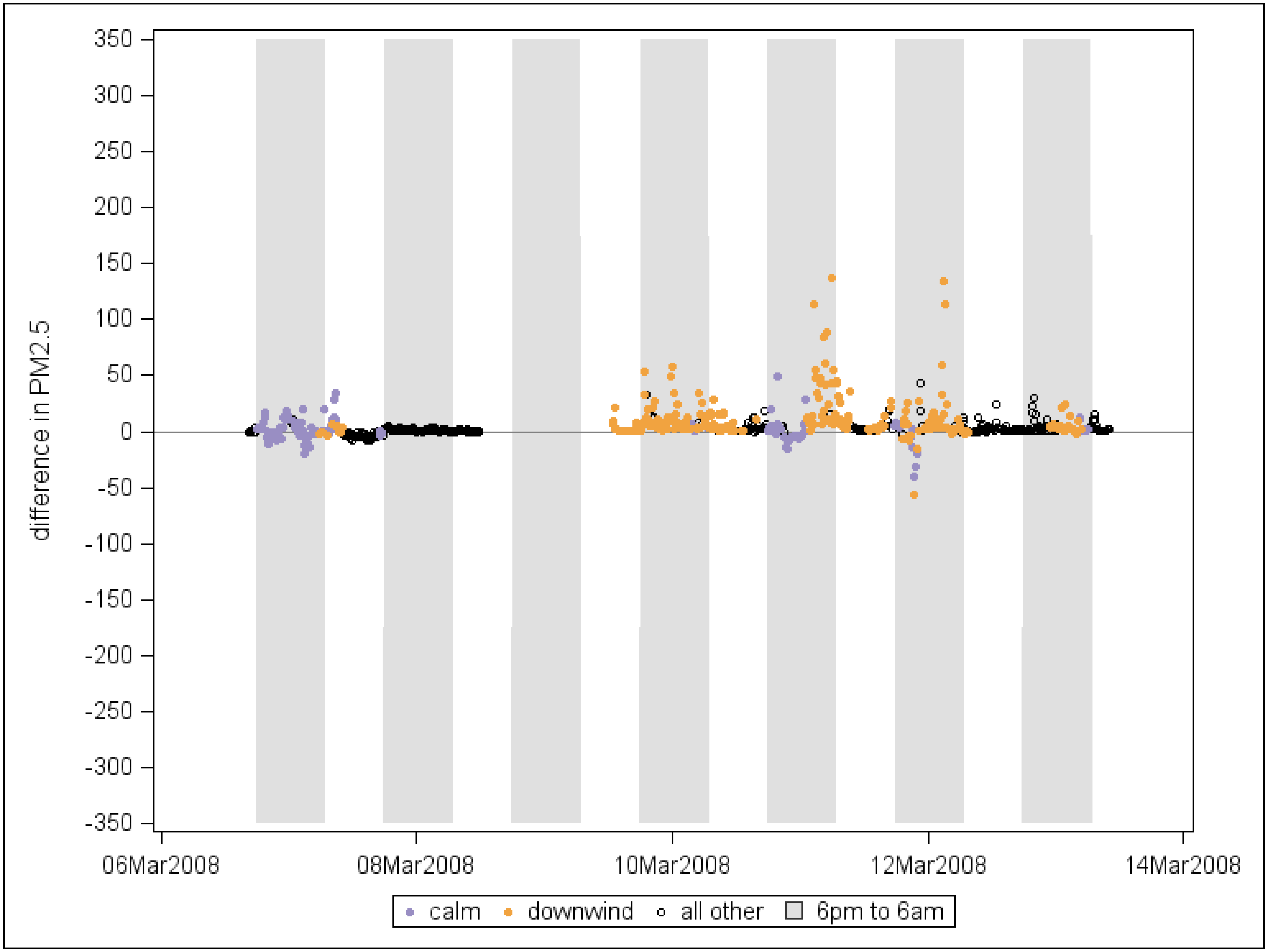


Figure A-19. Mean Difference in PM$_{2.5}$ by Wind Direction - Site 1.

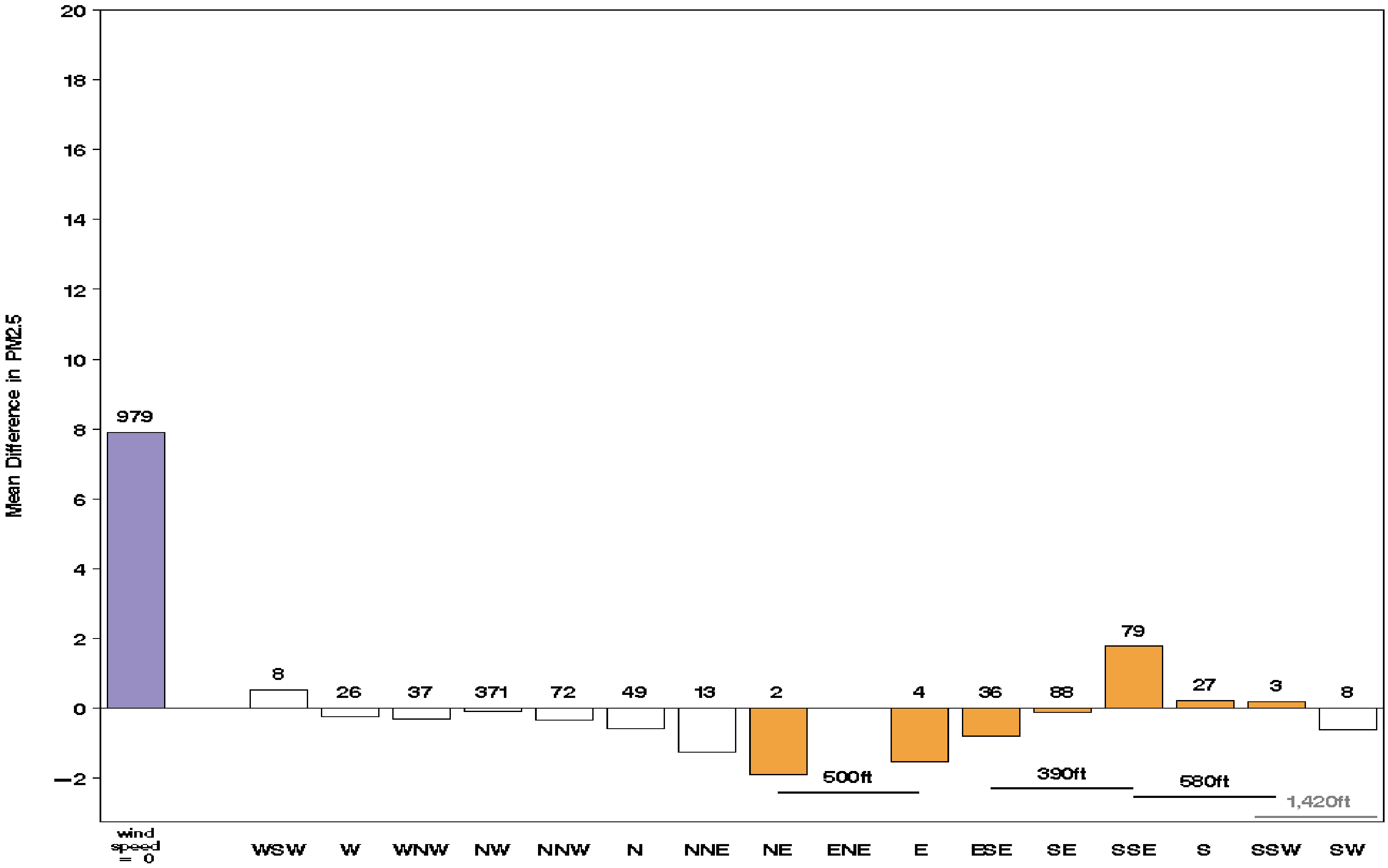


Figure A-20. Mean Difference in $PM_{2.5}$ by Wind Direction - Site 2.

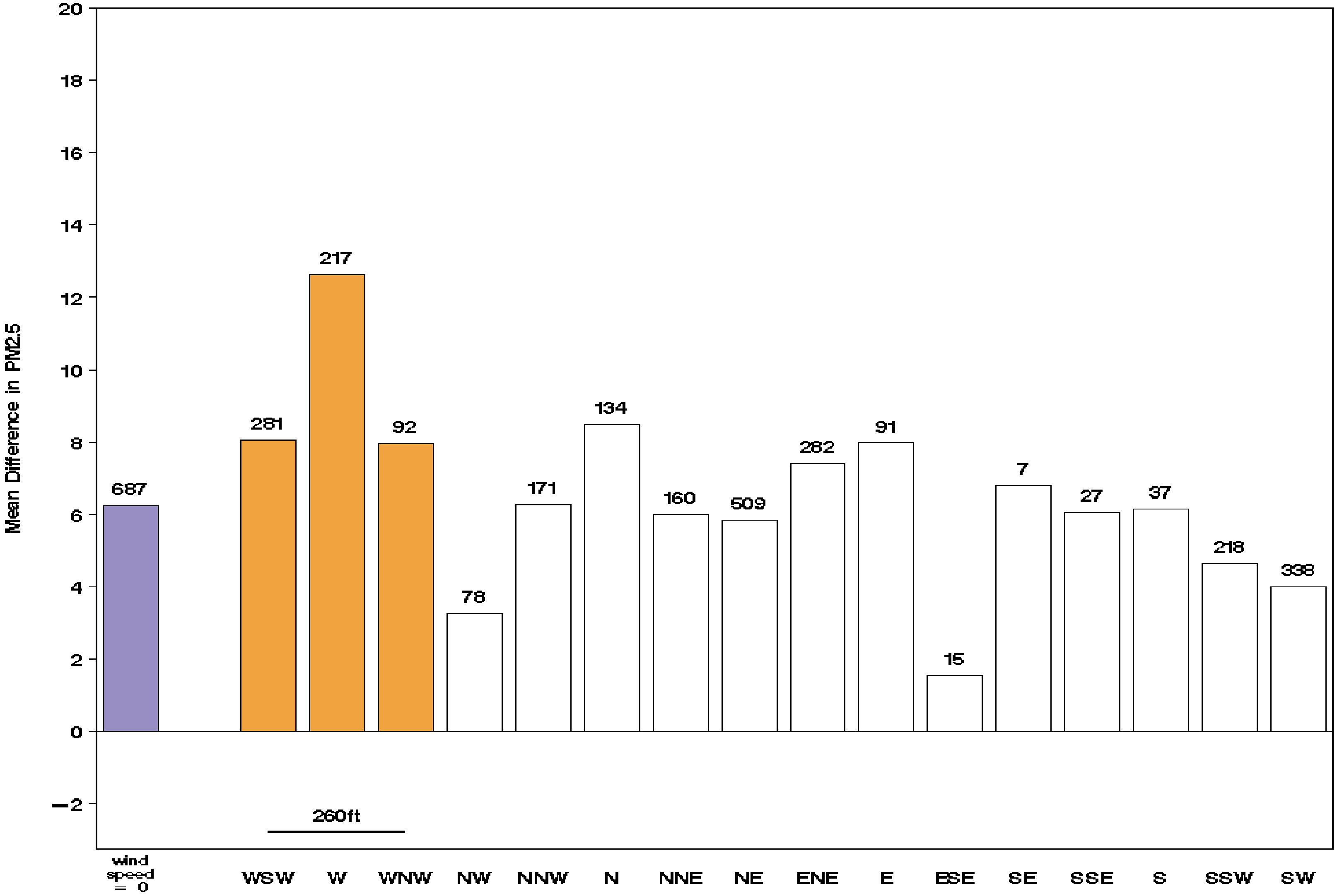


Figure A-21. Mean Difference in PM$_{2.5}$ by Wind Direction - Site 3.

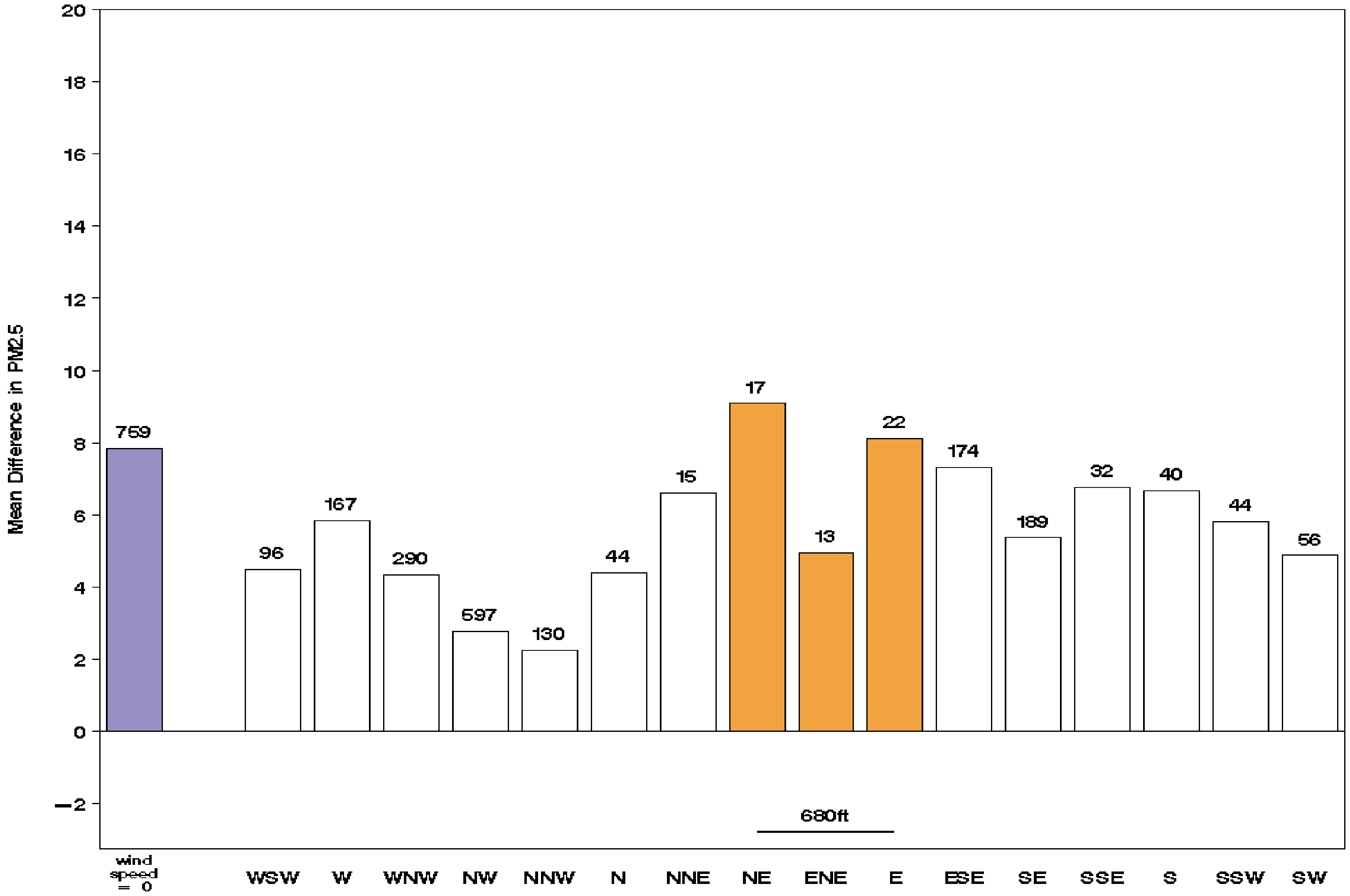


Figure A-22. Mean Difference in $PM_{2.5}$ by Wind Direction - Site 5.

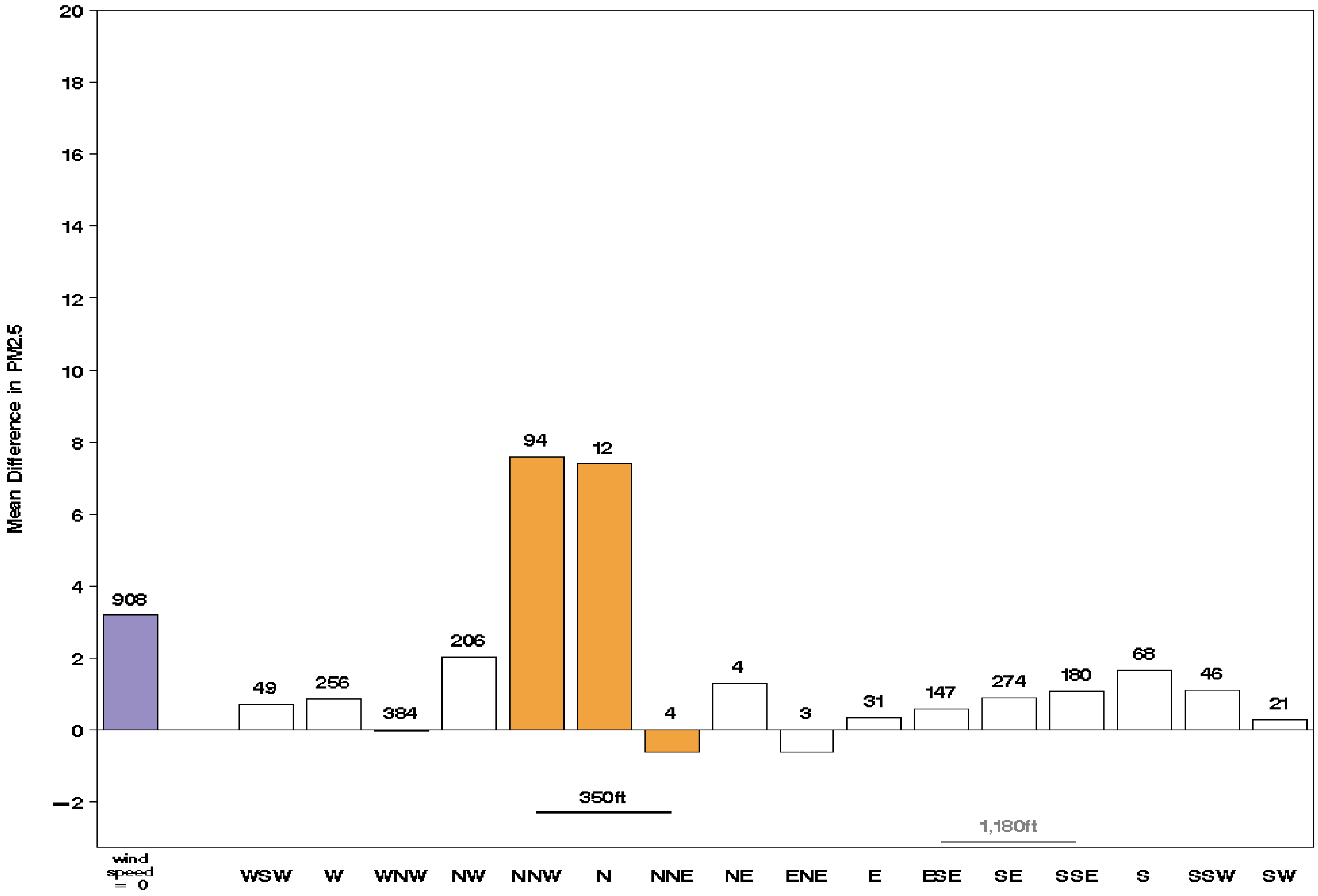


Figure A-23. Mean Difference in $PM_{2.5}$ by Wind Direction - Site 6.

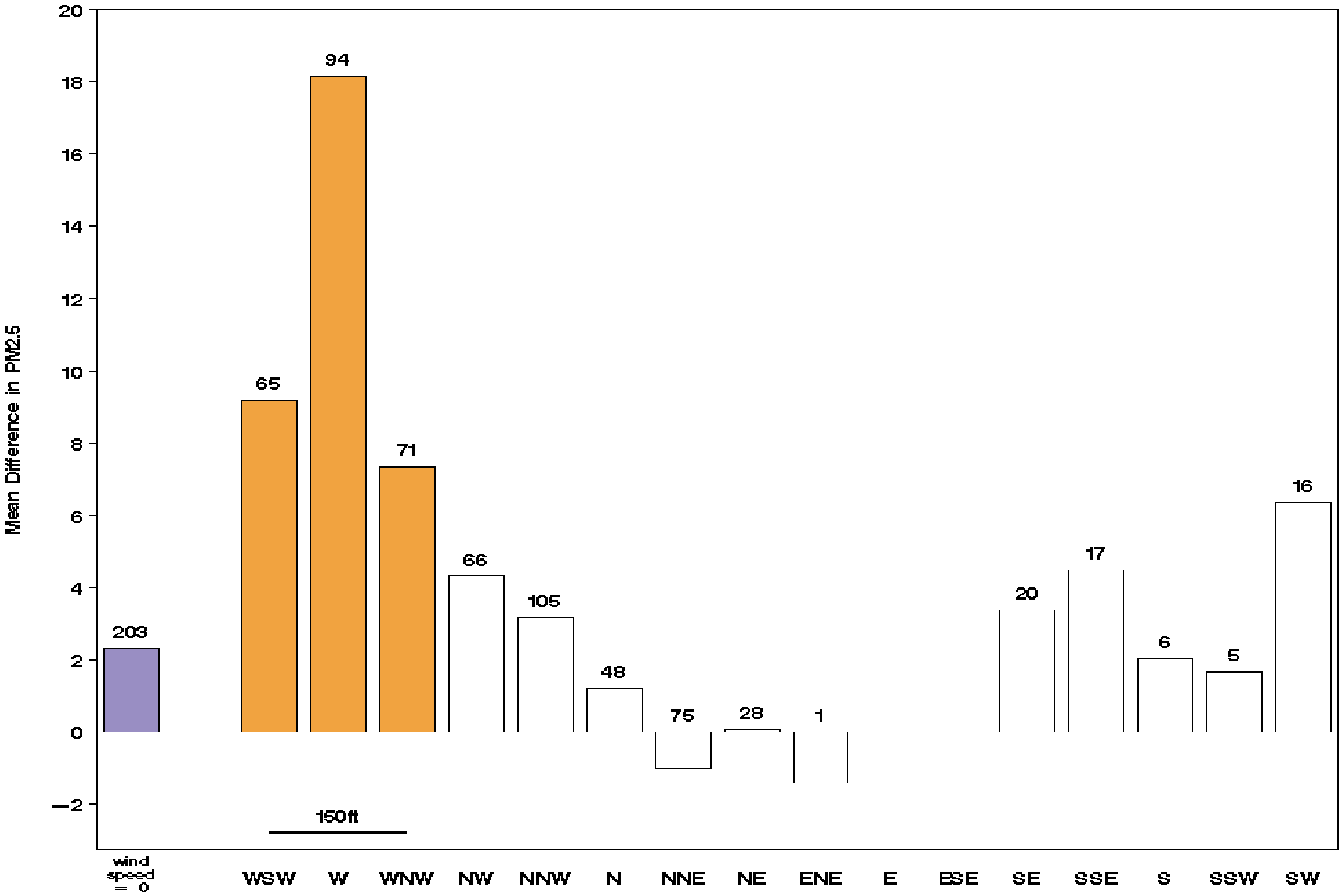
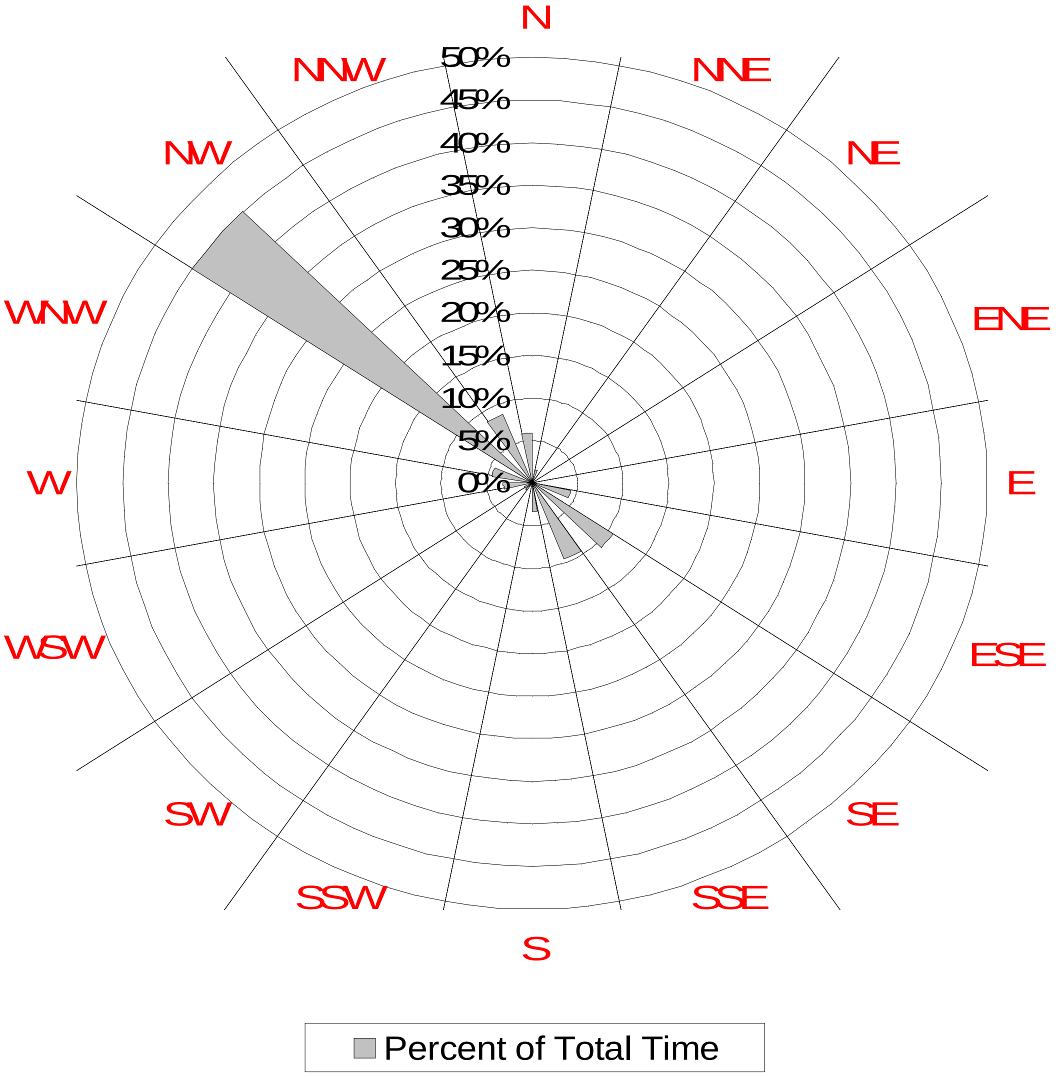
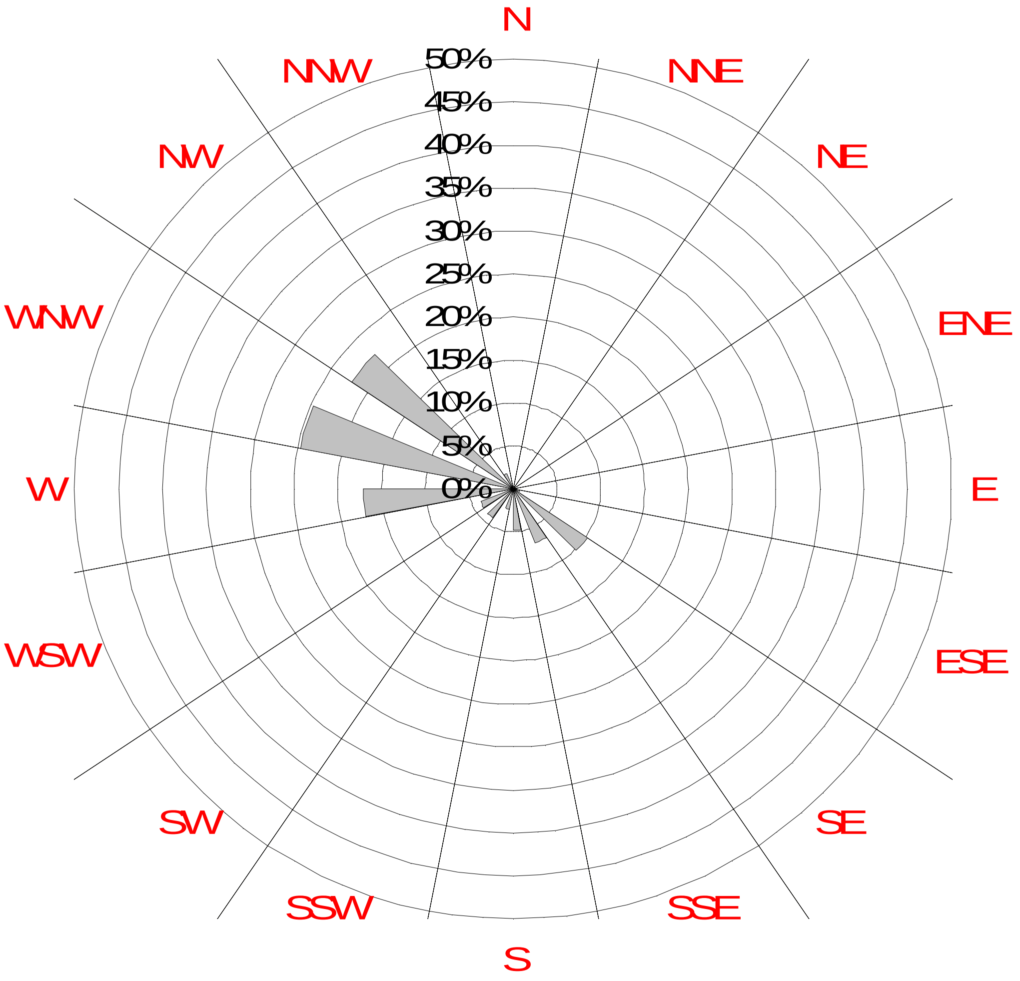


Figure A-24a. Wind Rose - N1.



NOTE: Wind speeds of zero (n=979), which comprised 54.33% of the data (n=1,802), were removed from the graph data.

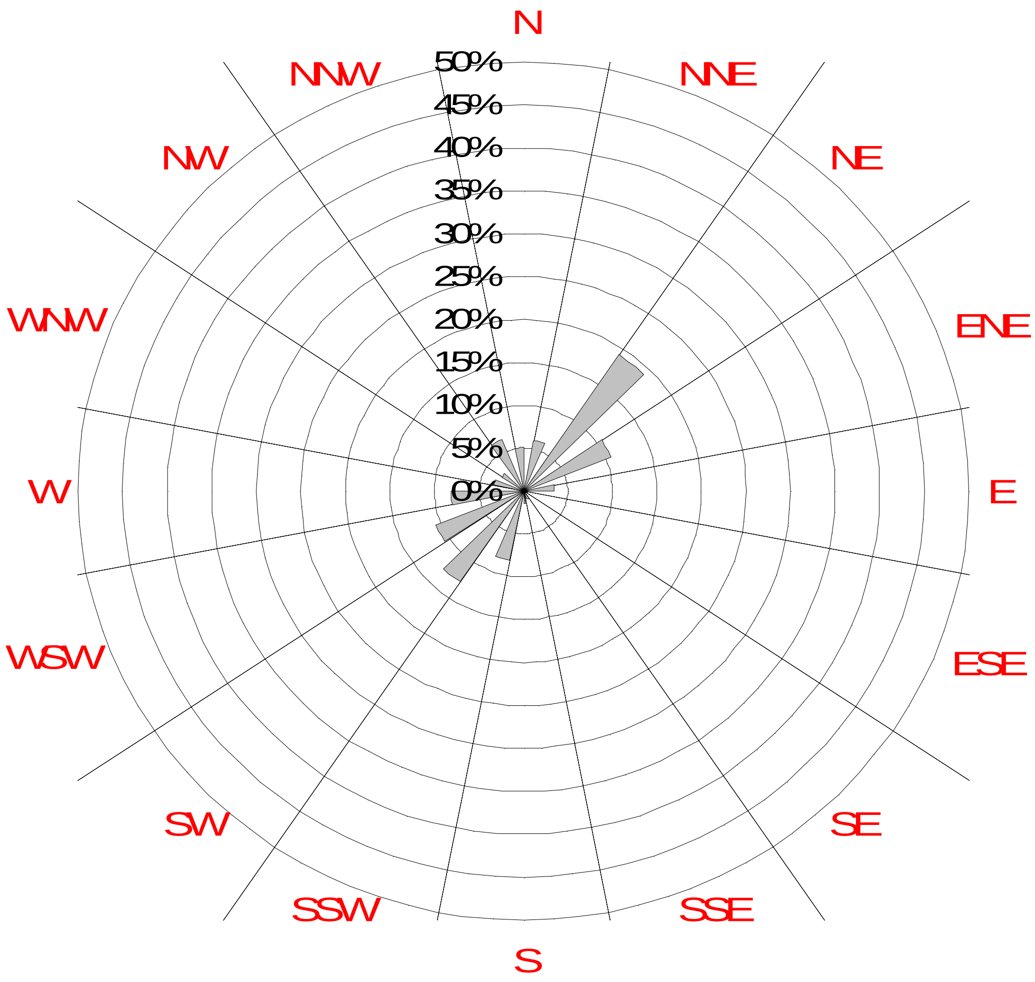
Figure A-24b. Wind Rose - R1.



▨ Percent of Total Time

NOTE: Wind speeds of zero (n=770), which comprised 42.73% of the data (n=1,802), were removed from the graph data.

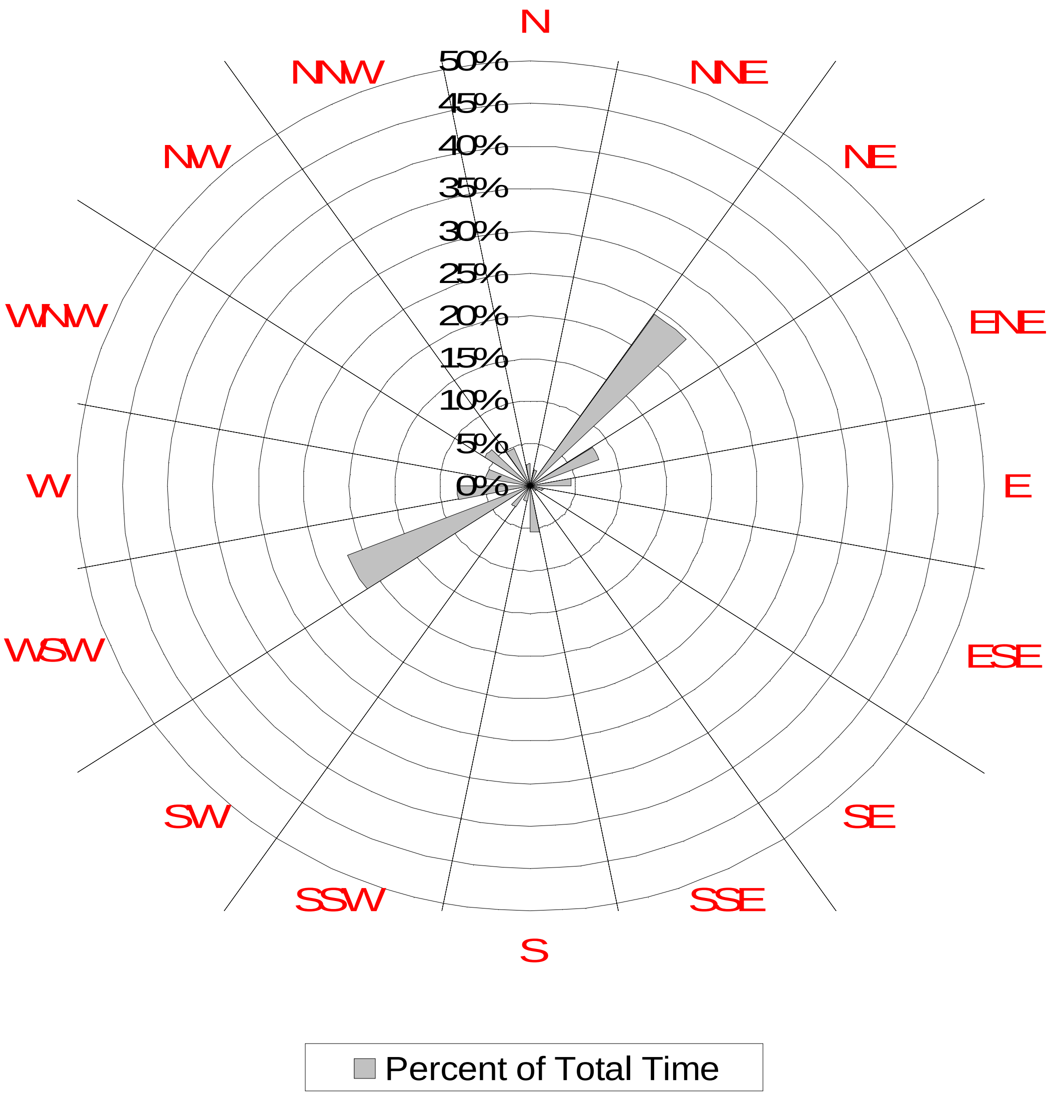
Figure A-25a. Wind Rose - N2.



▨ Percent of Total Time

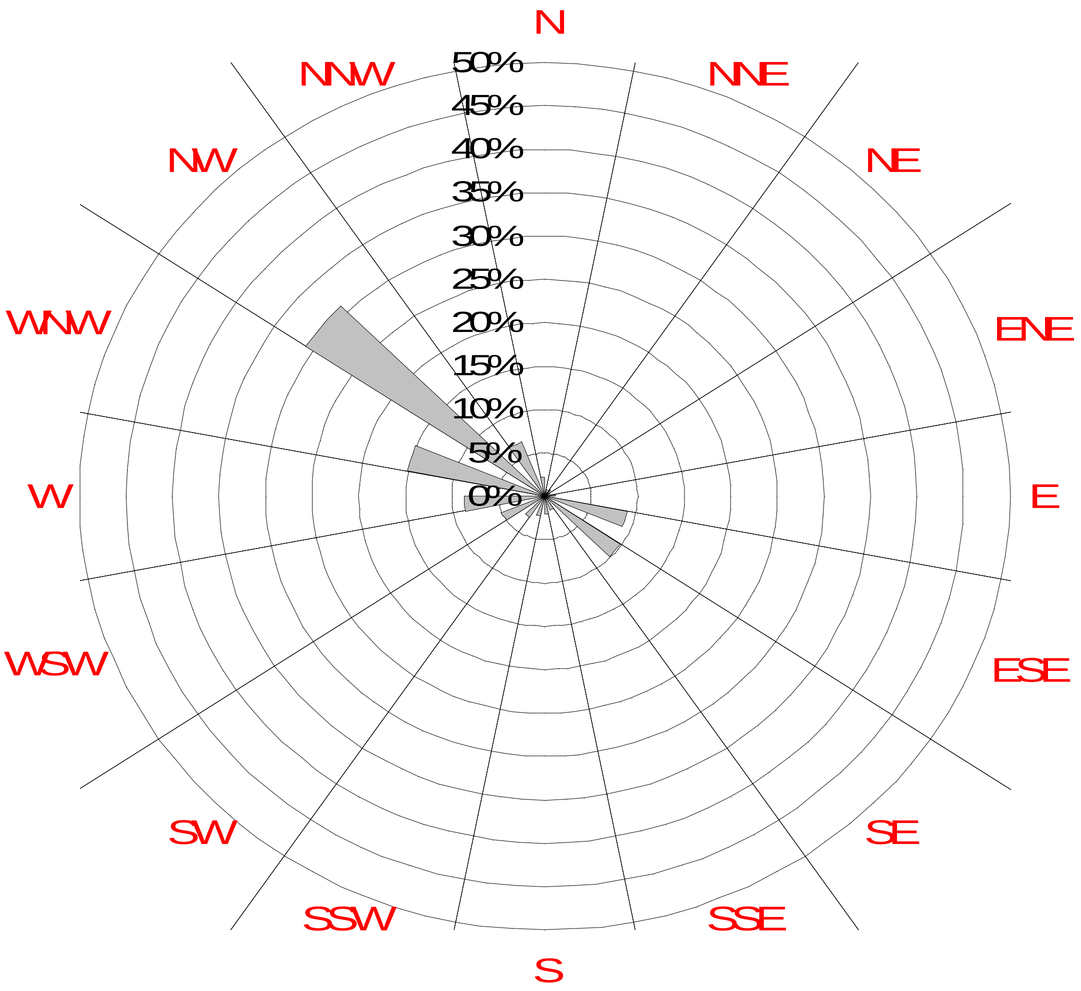
NOTE: Wind speeds of zero (n=687), which comprised 20.54% of the data (n=3,344), were removed from the graph data.

Figure A-25b. Wind Rose - R2.



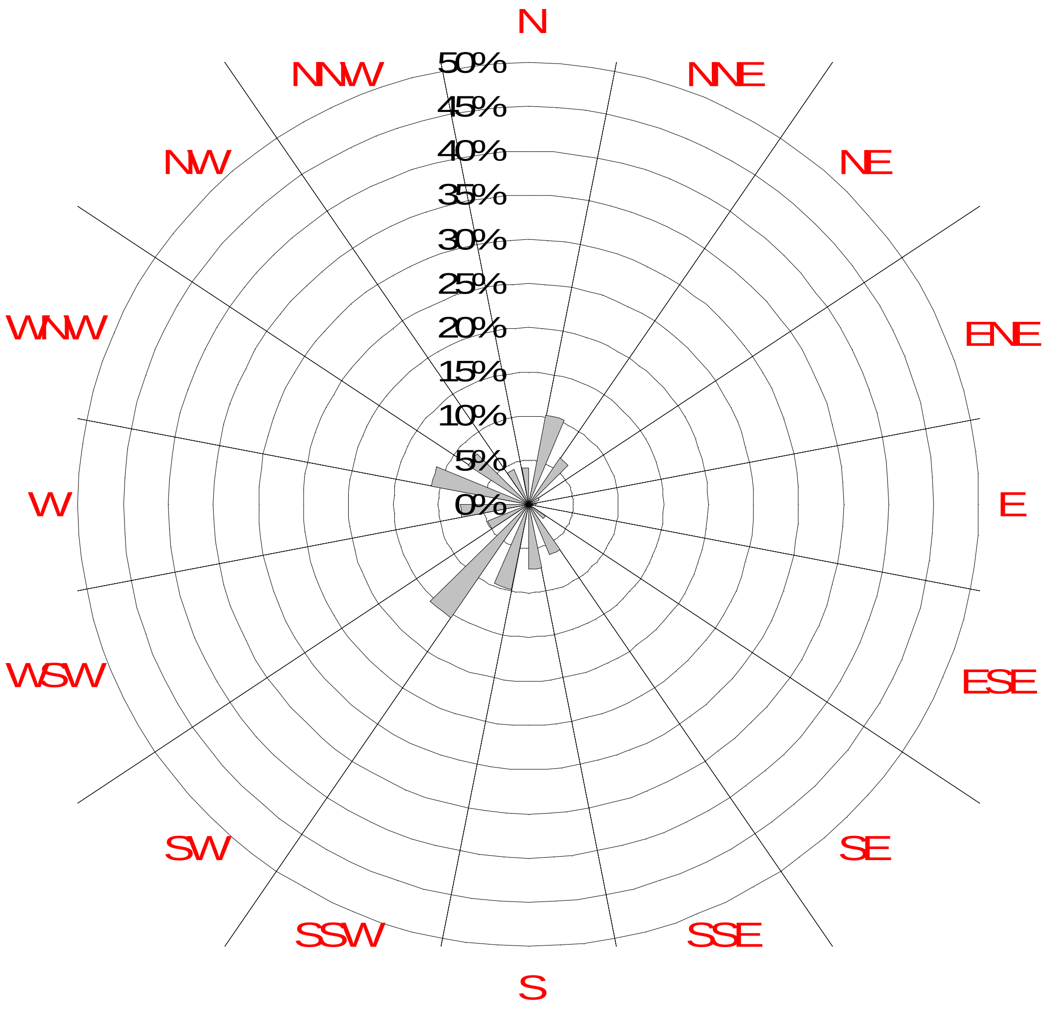
NOTE: Wind speeds of zero (n=826), which comprised 24.70% of the data (n=3,344), were removed from the graph data.

Figure A-26a. Wind Rose - N3.



NOTE: Wind speeds of zero (n=759), which comprised 28.27% of the data (n=2,685), were removed from the graph data.

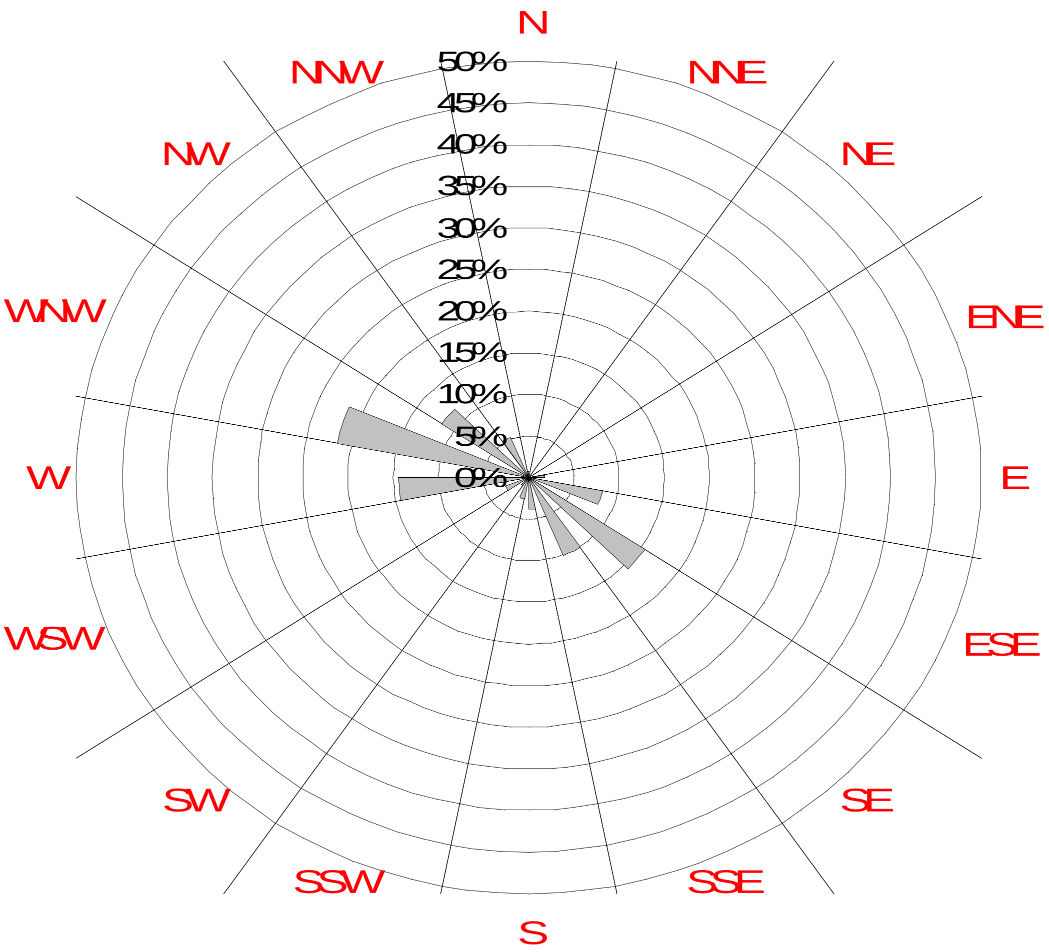
Figure A-26b. Wind Rose - R3.



▨ Percent of Total Time

NOTE: Wind speeds of zero (n=1,368), which comprised 50.95% of the data (n=2,685), were removed from the graph data.

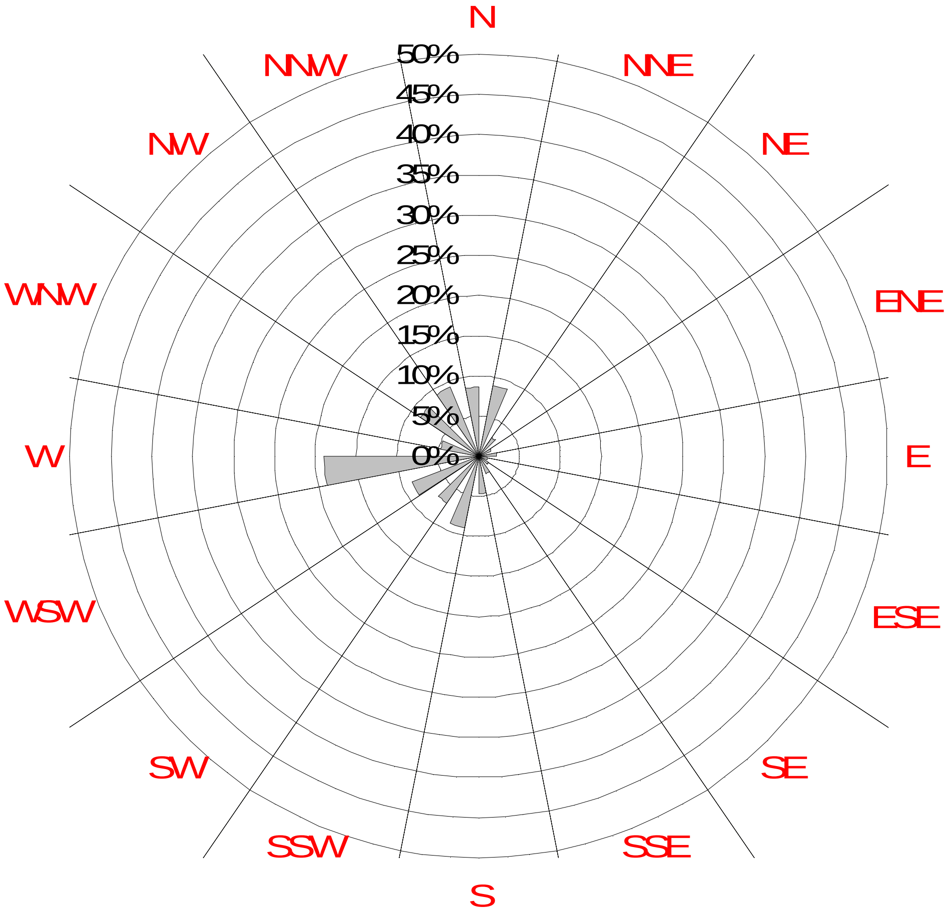
Figure A-27a. Wind Rose - N5.



▨ Percent of Total Time

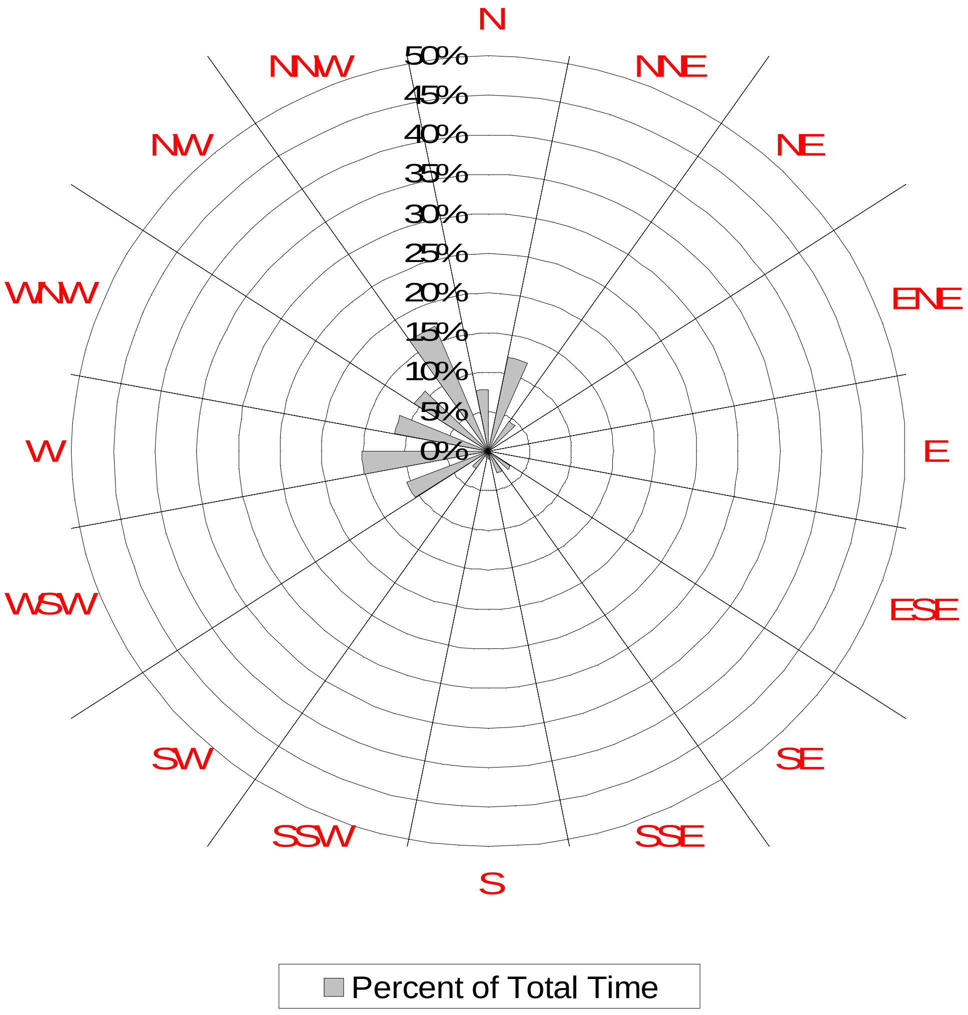
NOTE: Wind speeds of zero (n=908), which comprised 33.79% of the data (n=2,687), were removed from the graph data.

Figure A-27b. Wind Rose - R5.



NOTE: Wind speeds of zero (n=1,256), which comprised 46.74% of the data (n=2,687), were removed from the graph data.

Figure A-28. Wind Rose - N6 and R6.



NOTE: Wind speeds of zero (n=203), which comprised 24.8% of the data (n=820), were removed from the graph data.

Appendix B. Field Test Summaries

Initial field tests were conducted to confirm the feasibility of using different models of fine particulate ($PM_{2.5}$) monitors to measure $PM_{2.5}$ levels near an OWB. Information from these initial tests supported selection of the DataRAM Model DR-4000 as the preferred $PM_{2.5}$ monitor. Additional field tests were conducted to confirm that the two DataRAM Model DR-4000 units employed during these investigations responded similarly to $PM_{2.5}$.

Feasibility Studies

Feasibility studies were performed in April, 2006, and then again during Winter 2006/2007, at a location within a narrow valley approximately 1,000 feet downhill from an OWB (Figure B-1). Figures B-2 through B-10 are examples of time series plots indicating trends in $PM_{2.5}$ concentrations reported by one of the DataRAM Model DR-4000 units during the Winter 2006/2007. Table B-1 is a homeowner log of observations recorded during the same monitoring period. $PM_{2.5}$ levels were usually between 1 and 20 $\mu g/m^3$ without strong pine smoke odors, but were substantially higher during periods of pine smoke odors. Outdoor air pollution due to smoke was most obvious during calm conditions in the early evenings, night time and early morning hours, when the atmosphere was more stable and ground level air movement tended to flow southward with topography.

Figure B-1. View from Monitors Deployed Approximately 1,000 Feet from an OWB.

The OWB is located out of view to the left. The OWB smoke plume is visible in front of the treeline.

Figure B-2. Fine Particulate Matter ($PM_{2.5}$) Concentrations November 6-14, 2006.

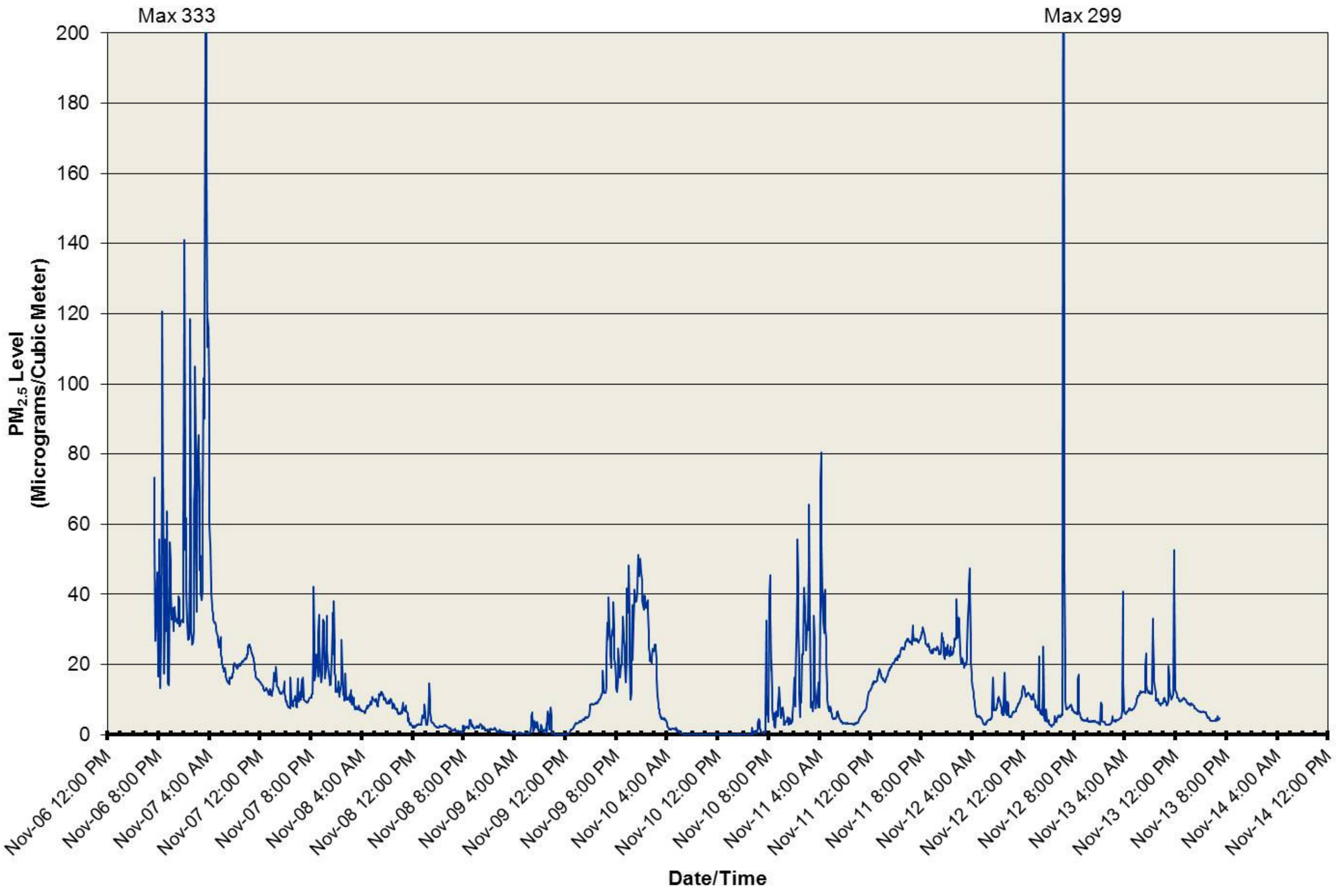


Figure B-3. Fine Particulate Matter ($PM_{2.5}$) Concentrations November 20-27, 2006.

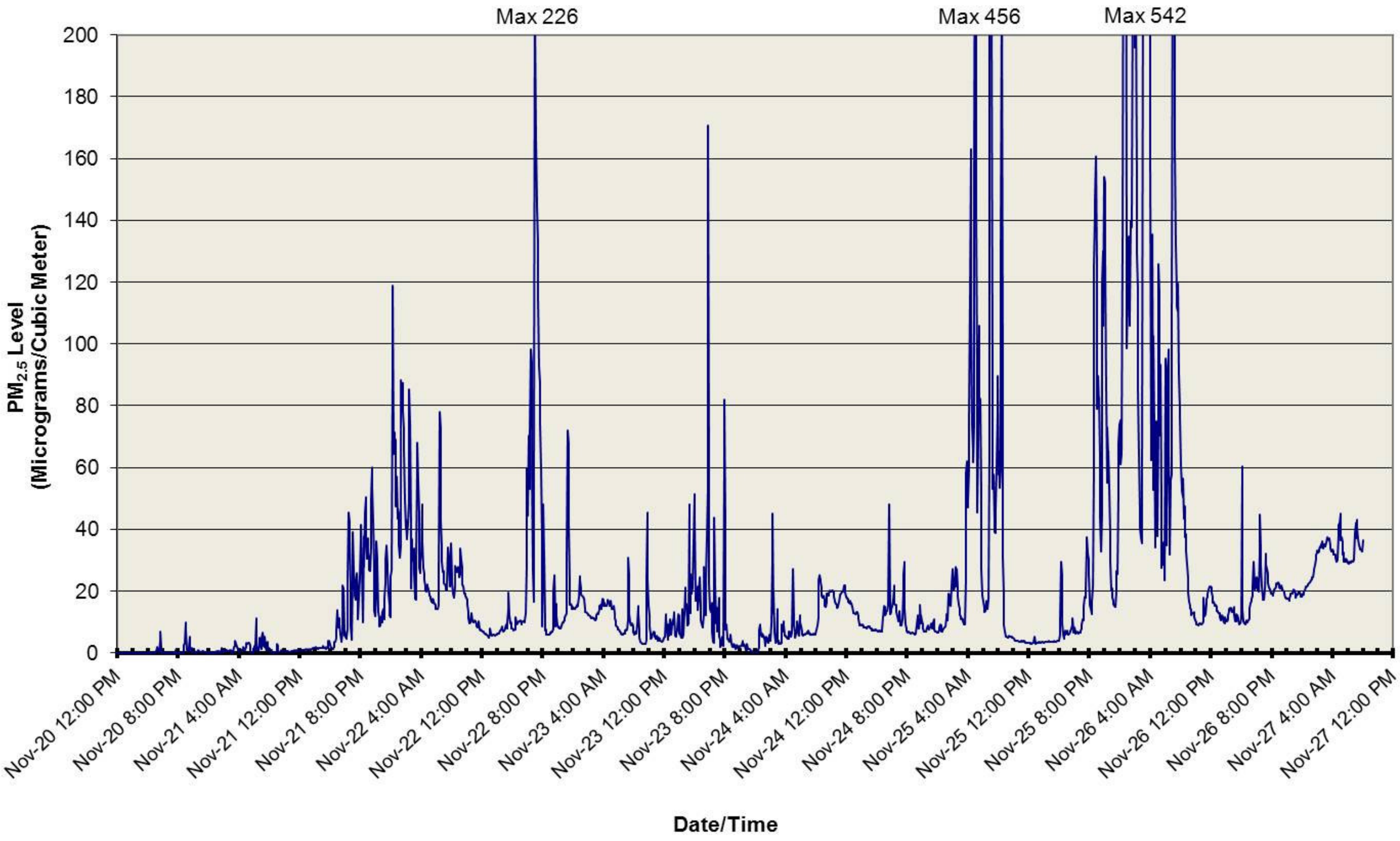


Figure B-4. Fine Particulate Matter ($PM_{2.5}$) Concentrations December 7-14, 2006.

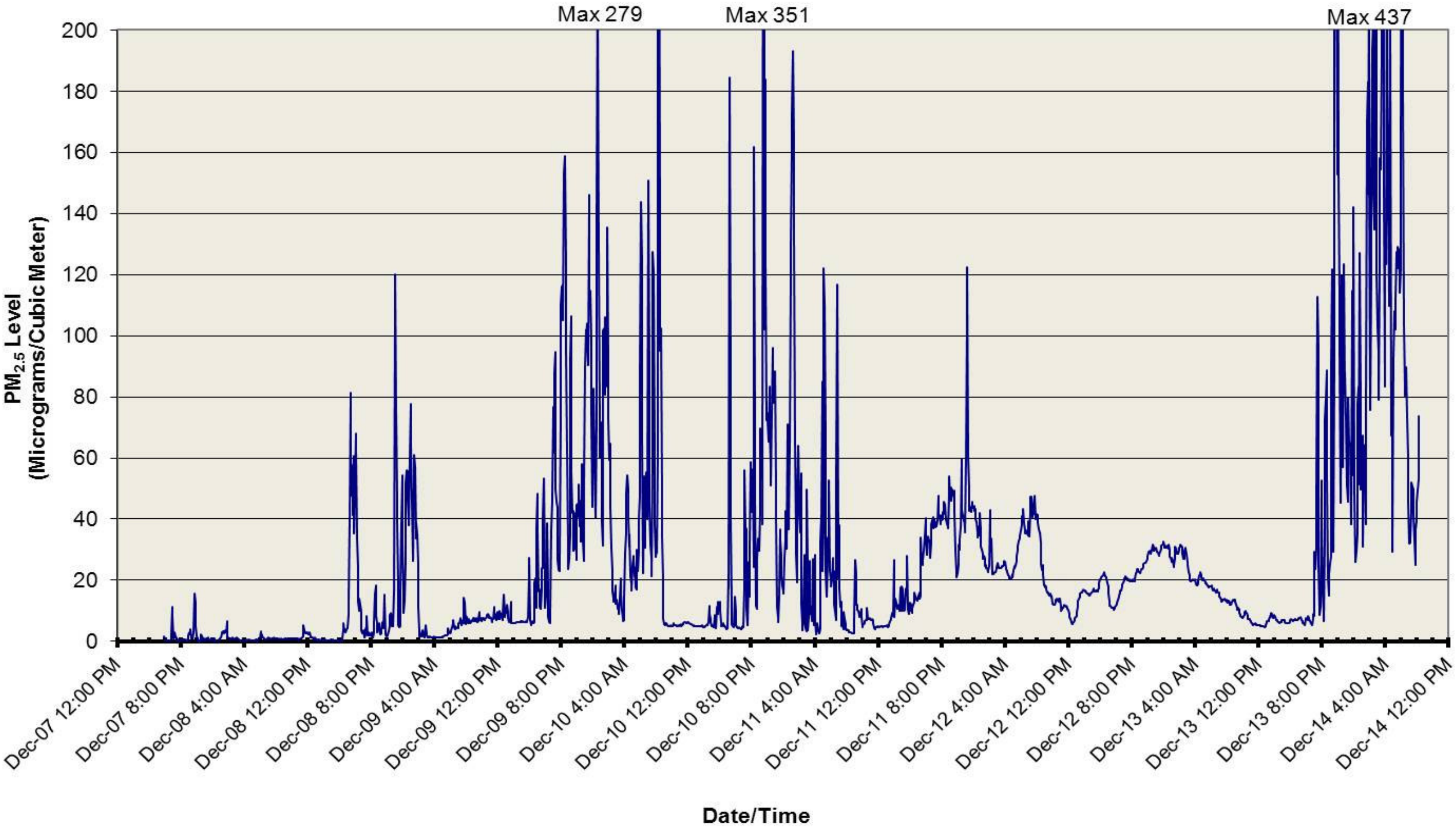


Figure B-5. Fine Particulate Matter ($PM_{2.5}$) Concentrations December 15-26, 2006.

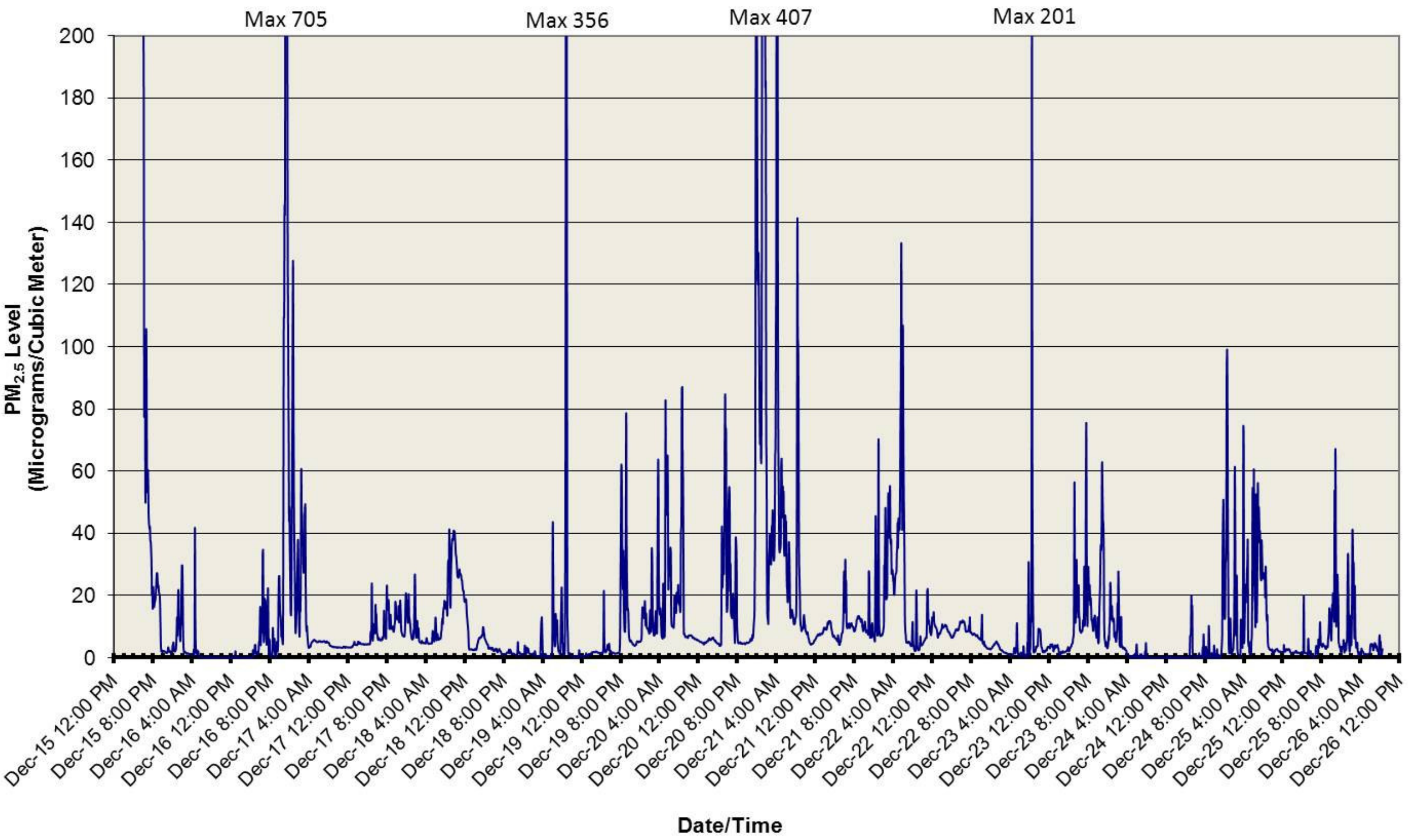


Figure B-6. Fine Particulate Matter ($PM_{2.5}$) Concentrations December 28, 2006 - January 4, 2007.

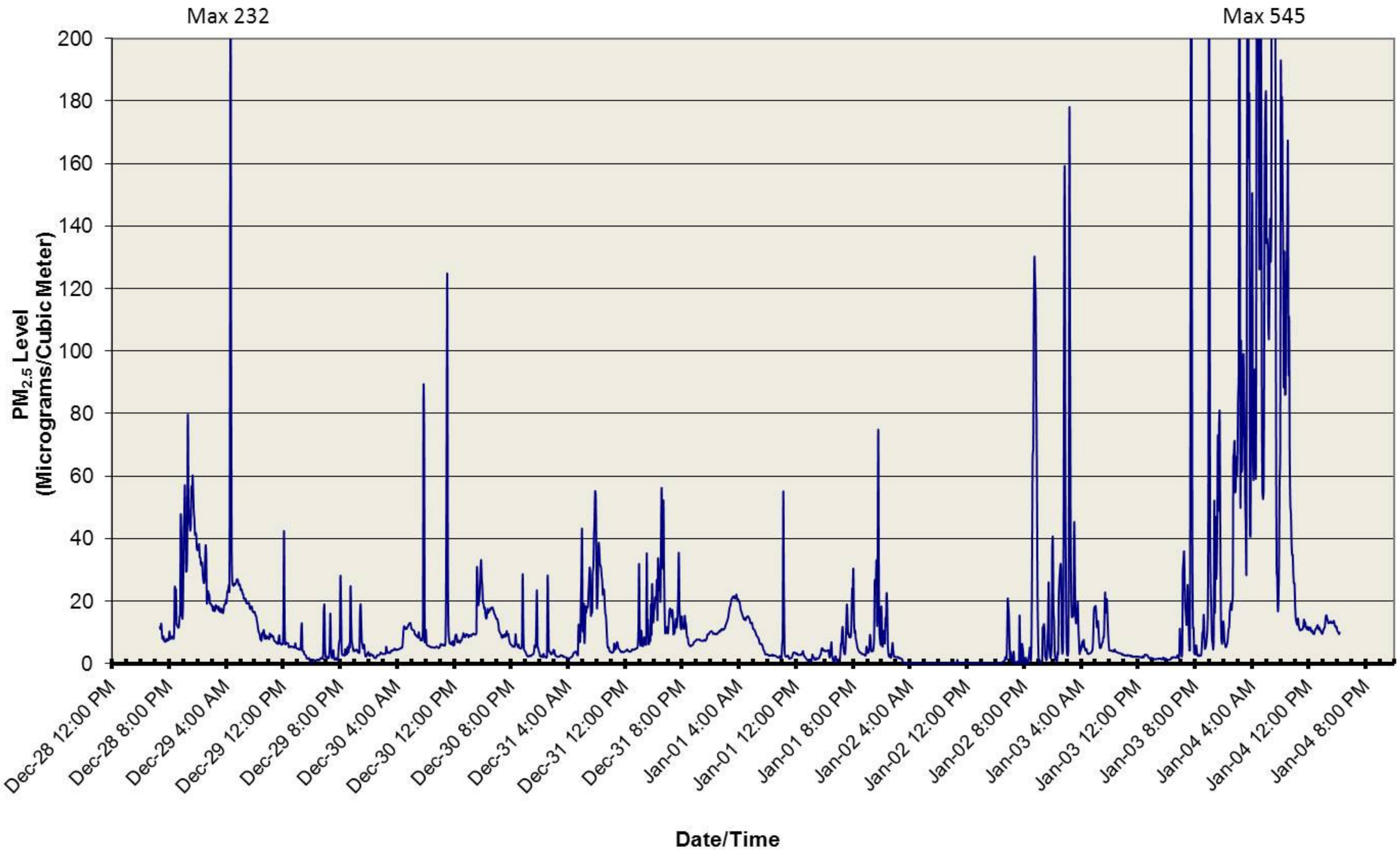


Figure B-7. Fine Particulate Matter ($PM_{2.5}$) Concentrations January 4-13, 2007.

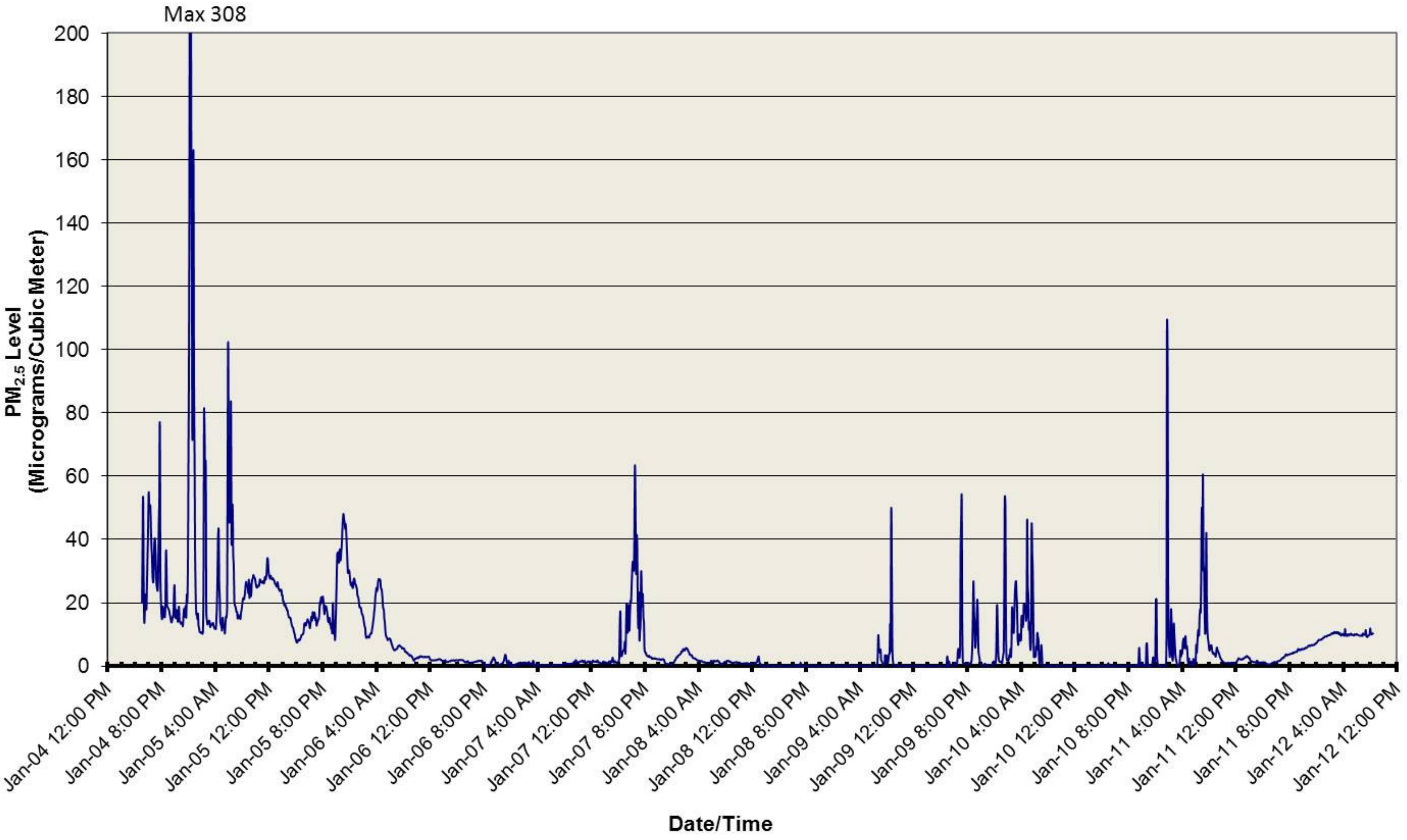


Figure B-8. Fine Particulate Matter ($PM_{2.5}$) Concentrations January 21-29, 2007.

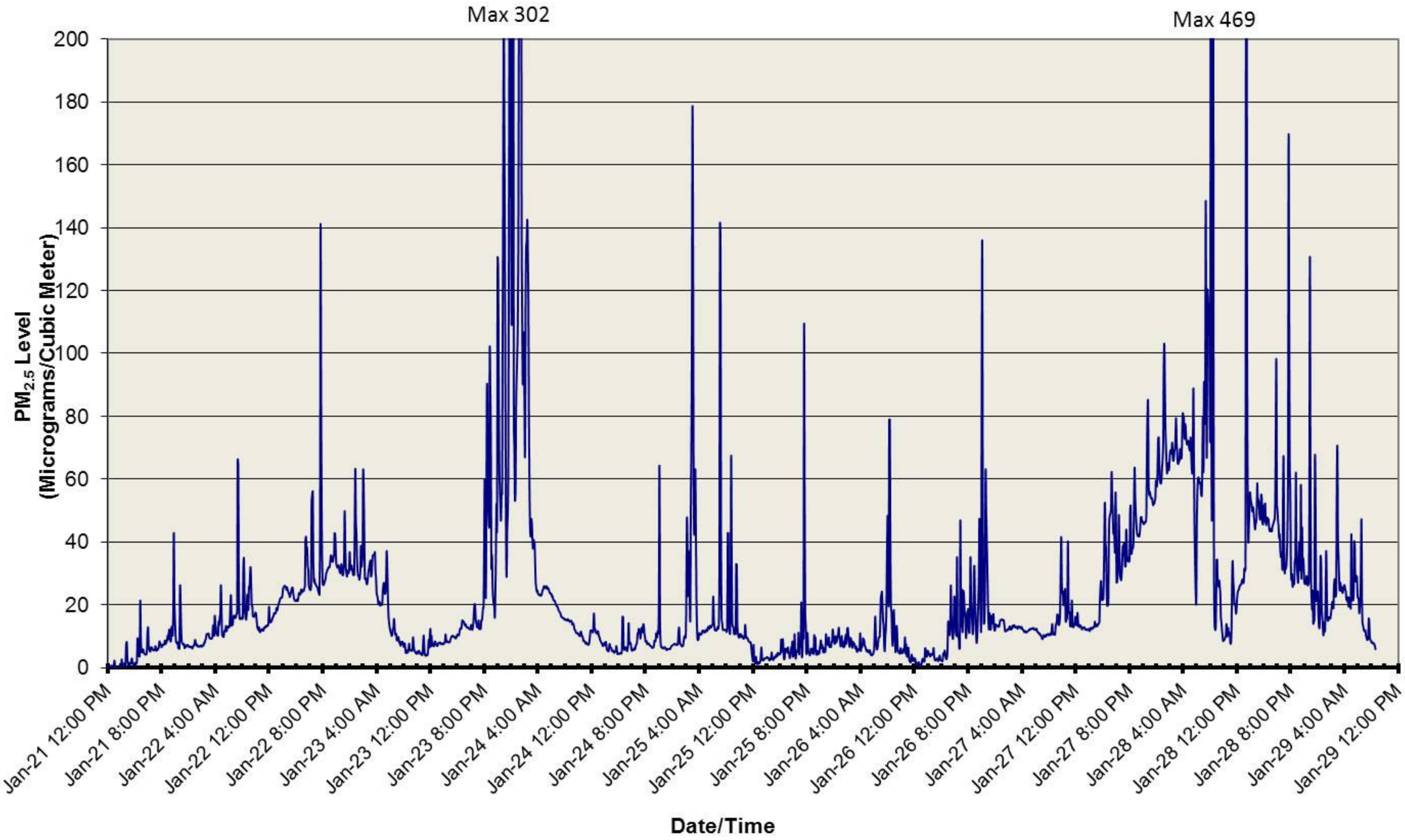


Figure B-9. Fine Particulate Matter ($PM_{2.5}$) Concentrations January 30 - February 2, 2007.

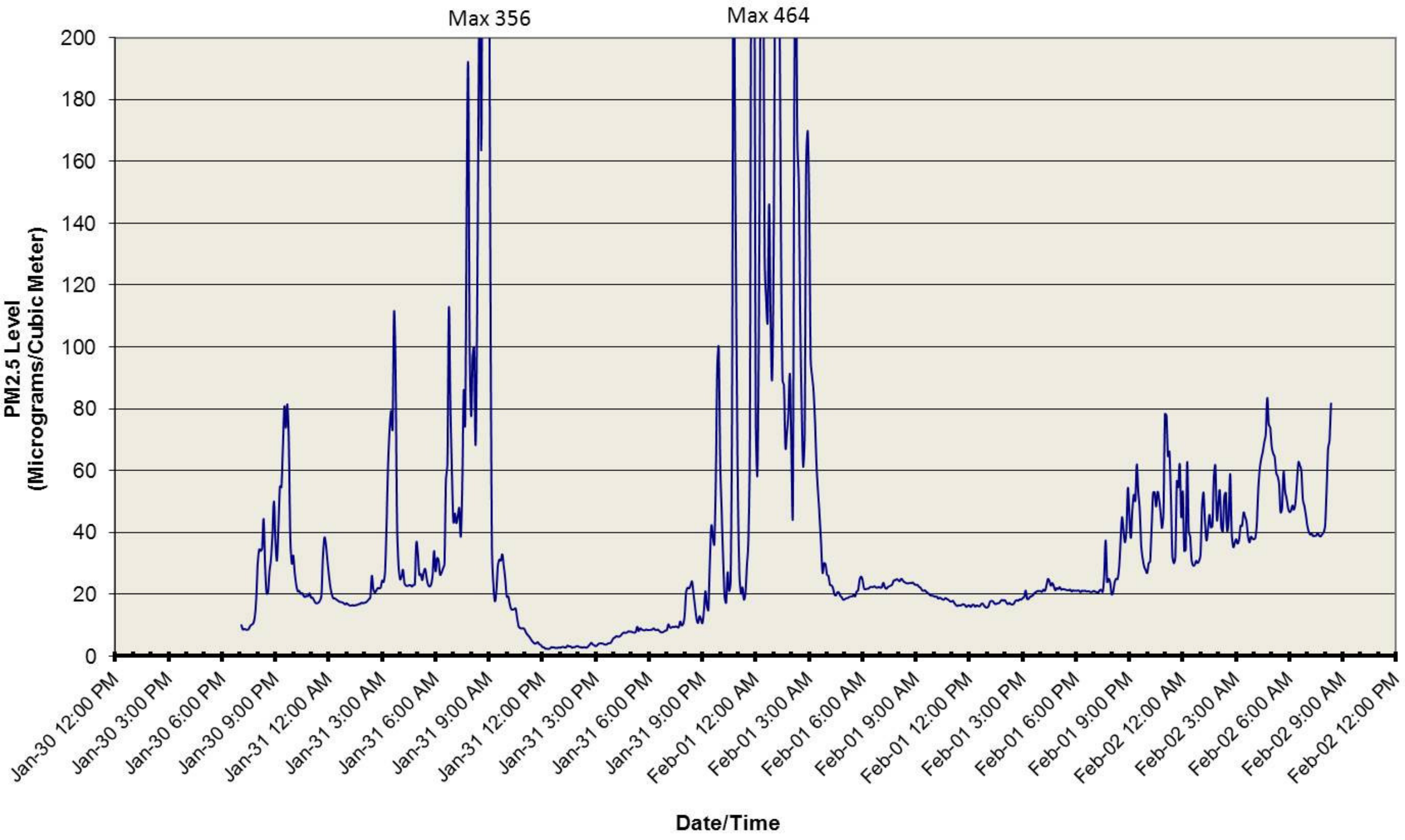


Figure B-10. Fine Particulate Matter ($PM_{2.5}$) Concentrations February 3-7, 2007.

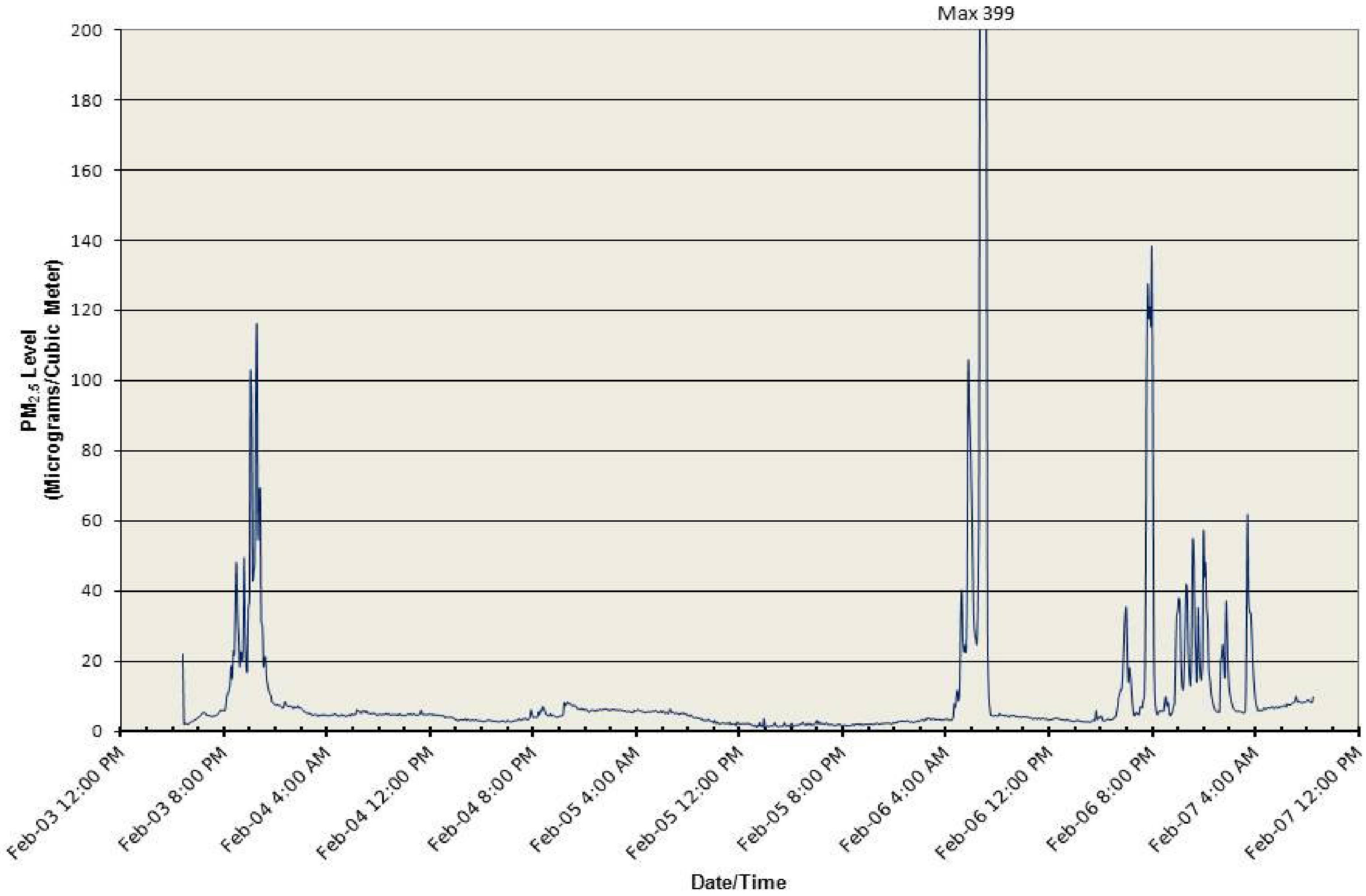


Table B-1. Homeowner Log of Observations

Nov. 6, 2006	18:15	slight pine smoke[1] odor, Deployed 2 DataRAMs, , DR 4000 with inlet heater, 2 Dustracks, all 5 minute logging intervals
Nov. 7	5:00	no odors, mild. Checked DR 4000, heater was off, adjusted power supply, heater on
	6:00	slight pine odor
	18:00	no odors , south wind
	20:00	cooked on grill, raining out
Nov. 8	6:00	no odors, raining
	21:30	no odors, still raining
Nov. 9	5:00	no odors, cloudy, calm, mild
	10:00	no odors, breezy mild
	13:30 to 14:30	used diesel tractor in driveway to smooth some stone
	18:00	slight pine smoke odor, cool and calm
	21:00	slight wafting pine smoke odor, very light
Nov. 10	5:00	no odors, breezy
	9:00	no odors, windy
Nov. 11	all day	no odors, windy and mild
Nov. 12	all day	intermittent slight odor if any, rainy, variable wind
Nov. 13	all day	intermittent slight odor if any, rainy, variable wind
Nov. 17, 2006	13:00	deployed 2 DataRAMs, no inlet heater, 2 Dustracks slight pine smoke odor
	20:50	accidentally reset DR-4000
Nov. 18	19:10	no odors, DR-4000 was off, plugged in meter and restarted, windy all day
	19:45	cooked on grill
Nov. 19	all day	no odors, windy
Nov. 20	12:00 – 13:00	neighbor shooting off fireworks
	21:00	cooked on grill
Nov. 21	18:00	slight pine smoke odor, OWB neighbor called to say burning fire in nearby driveway. I spoke with him, mostly wood, some plywood. He agreed to not burn any construction related material anymore.
	21:00	pine smoke odor.
Nov. 22	6:00	pine smoke odor, clear, calm, cold night
	19:00	strong pine smoke odor
Nov. 23	12:10 – 20:00	Thanksgiving Day, had fire in my fireplace, detected fireplace odor on porch near instruments, breezy
Nov. 24	12:00	no odors, mild with variable south wind.
Nov. 25	8:00	strong pine smoke odor, clear and cold last night
	night	strong pine smoke odor
Nov. 26	15:30	wife had fire in driveway
	19:00	pine smoke odor
Dec. 7, 2006	18:00	no odors, windy, setup DR 4000 w/ inlet heater, 2 dustracks and 2 R&P Dustscans
Dec. 8, 2006	8:00	no odors, 1 Dustrack was off, adjusted power cord and restarted.
Dec. 8	17:30	pine smoke odor, cold and calm
	18:30	started my fireplace and ran it until December 10, 21:00
Dec. 9	5:30	no odors
	18:00	pine smoke odor
Dec. 10	7:00	pine smoke odor
	8:20	very strong pine smoke odor, took pictures of smoke looking toward pond and of DataRAM
	10:00	no odors, took second picture of pond, clear morning
	16:00	no odors, clear and cooling down
	17:30	pine smoke odor

Dec. 11	morning	pine smoke odor
	13:30 – 24:00	had fire in fireplace
Dec. 12	6:00	no odors
	7:45	slight pine smoke odor
Dec. 13	all day	no odors, mild, windy and rainy
Dec. 14	3:30	strong pine smoke odor, let cat out
	6:00	strong pine smoke odor
	8:30	took meters in for data dump.
Dec. 15, 2006	18:00	strong pine smoke odor, setup DR 4000 w/ inlet heater, 2 dustracks and 2 R&P Dustscans
	19:00	cooked on grill, started getting rainy and windy
Dec. 16 and 17		no information recorded
Dec. 18	9:00	slight pine smoke odor
Dec. 19	8:00	pine smoke plume down entire valley, took pictures and video, odors got strong soon after, made complaint to DEC Reg. 4 Officer Young.
Dec. 20	8:00	slight pine smoke odor
	18:00	pine smoke odor, clear and cool
Dec. 21	4:00	very strong pine smoke odor, let cat out
	6:00	strong pine smoke odor, let dog in, stinks like pine smoke
	8:30	pine smoke odor, told OWB owner that smoke adversely affects my house and life. He pointed to the 4 houses across the road that burn wood. **Told him that I smell his unseasoned pine smoke.**
Dec. 22	8:00	no odors
Dec. 23	16:50	cooked on grill, lit fire in fireplace and ran it until Dec. 24, 10 AM
	21:50	smelled fireplace fire on porch
Dec. 24	2:00	tended my fire and went to bed.
	10:00	fireplace out
	23:45	pine smoke odor
Dec. 25	12:00	had fire in fireplace until 21:00
	21:00	fireplace out
Dec. 26	8:30	took meters in for data dump.
Dec. 28, 2006	18:30	setup DR 4000 w/ inlet heater, 2 dustracks and 2 R&P Dustscans
	20:00	pine smoke odor
Dec. 31	14:00	wife starts campfire outside
	20:30	slight pine smoke odor
Jan. 3, 2007	18:00	slight pine smoke odor
	22:00	strong pine smoke odor
Jan. 4	7:00	strong pine smoke odor
Jan. 7	14:50.	wife starts campfire outside
	18:00	Fire out. Pine smoke odor on porch
	20:00	No odors on porch
Jan. 8	8:00	Rainy, windy, no odors
	18:30 to 19:00	grilled outside, windy
January 9	7:00	slight smoke odor, maybe not pine
	8:00	pine smoke odor
	18:00	Started DR 2000 with filter, no odors
	18:30	grilled
	19:00	pine smoke odor, snowing
Jan. 10	6:30	pine smoke odor
	18:00	windy, no odors
Jan. 11	8:00	pine smoke odor, cold and calm outside
	19:30	grilled
Jan. 12	9:00	slight pine smoke odor
January 22, 2007		
Jan. 23	21:00	strong pine smoke odor

Jan. 24	19:15	grilled
Jan. 25	19:00	started my fireplace, went out overnight
	22:00	smelled my fire on porch, cold and breezy
Jan. 26	7:00	pine smoke odor
	9:00	pine smoke odor, cold and calm
	17:00	started 2 dustscans, Dustscan 1 had operational problems
	18:00	started my fireplace, ran through Jan 28
Jan. 27	20:00	pine smoke odor
Jan. 28	8:00	dense pine smoke, took pictures,
Jan. 29	20:00	strong pine smoke odor
Jan. 30	6:00	pine smoke odor
	18:30	grilled
	21:30	pine smoke odor
Jan. 31	6:45	pine smoke odor
	20:00	pine smoke odor
Feb. 1	midnight	pine smoke odor
Feb. 2	3:00 to 8:00	pine smoke odor, no meters operating
Feb. 3	16:30	re-deployed meters
	22:15	pine smoke odor
Feb. 4	9:00	no odors
	22:30	no odors, breezy and cold
Feb. 5	8:00	no odors, breezy and cold

1 –OWB was observed being fired with freshly cut white pine for entire heating season. Pine smoke odors are indicative of OWB smoke.

Although the initial study protocol called for the use of both DataRAM Model DR-4000 and Dustscan $PM_{2.5}$ monitors, feasibility studies provided information in support of the investigators' decision to designate the DataRAM Model DR-4000, rather than the Dustscan, as the primary instrument for $PM_{2.5}$ measurement. The reasons for this decision are summarized below.

- During a pilot study that compared $PM_{2.5}$ concentrations reported by four collocated monitors (two DataRAM Model DR-4000 units and two Dustscan units) deployed near an active OWB, one of the Dustscan monitors demonstrated relatively poor sensitivity at the low end of the observed $PM_{2.5}$ concentration range. This was considered unacceptable because it was anticipated that low $PM_{2.5}$ concentrations would be common, especially at reference monitors, and the investigators did not wish to impute values for a large number of observations.

- The investigators experienced difficulties when downloading data from the Dustscan instruments, and when reading Dustscan output files directly into statistical analysis software. These problems were not encountered with the DataRAM Model DR-4000. Additionally, data output from the DataRAM Model DR-4000 required less re-formatting prior to statistical analysis.

- The Dustscan model employed during these investigations is no longer marketed or serviced by the manufacturer, which made attaining technical support and instrument repairs difficult. In contrast, DataRAM products are still marketed and supported.

- Staff from the New York State Department of Environmental Conservation (NYS DEC) indicated that the DataRAM Model DR-4000, when employed as a single-wavelength instrument, may be superior to the Dustscan for monitoring woodsmoke-related $PM_{2.5}$ levels.

- The Dustscan backup battery is short-lived compared with that of the DataRAM Model DR-4000, which raised concerns with regard to the potential for data loss during power interruptions.

- The investigators noted that the Dustscan sometimes experienced operational difficulties, such as failure of the readout screen, at low air temperatures.

- Only the DataRAM Model DR-4000 accommodates an analytical filter, potentially supporting gravimetric analyses.[4]

DataRAM Model DR-4000: Field Comparison of Real-Time $PM_{2.5}$ Levels

Prior to study initiation, the two DataRAM Model DR-4000 $PM_{2.5}$ monitors employed during these investigations (DR1 and DR2) were co-deployed side-by-side on a residential porch in the Town of Coeymans, New York. Monitors were separated by a distance of two feet and faced east, sheltered from the direct line of site to an active OWB installed at a neighboring residence. Real-time $PM_{2.5}$ concentrations were recorded at five-minute intervals from February 7 through February 13, 2007.

A total of 1,558 time-matched $PM_{2.5}$ observations were recorded by each monitor, and these were evaluated using quantile analyses of relative percent $PM_{2.5}$ concentration differences, paired $PM_{2.5}$ concentration differences and raw $PM_{2.5}$ concentrations. In addition, a Pearson's product moment correlation coefficient (*r*) was calculated for the correlation between natural log-transformed time-matched $PM_{2.5}$ levels reported by monitor DR1 and corresponding levels reported by DR2.[5]

Relative percent differences (RPDs) for time-matched $PM_{2.5}$ concentrations were calculated using equation 1 before conversion into absolute values:

$$RPD = 100\frac{DR1 - DR2}{\left(DR1 + DR2\right)/2} \qquad \textbf{Eq. 1}$$

where: *DR1* and *DR2* are time-matched $PM_{2.5}$ concentrations reported by monitors DR1 and DR2, respectively.

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[4] Although gravimetric analyses were originally planned, they were ultimately abandoned due to technical problems.

[5] Log-transformation was required to better approximate Gaussian (normal) data distributions.

Paired $PM_{2.5}$ concentration differences were the differences of time-matched *DR1* and *DR2*. Raw $PM_{2.5}$ concentrations were simply the $PM_{2.5}$ levels reported by each monitor.

Tables B-2, B-3 and B-4 provide percentile values for RPDs, paired $PM_{2.5}$ concentration differences, and raw $PM_{2.5}$ concentrations, respectively. Table B-5 lists all relatively large RPDs (≥ 20 percent) and corresponding $PM_{2.5}$ concentration differences. Figure B-11 is a scatter plot that compares DR1 and DR2 raw $PM_{2.5}$ concentrations.

The median (50th percentile) RPD was 10.0 percent, suggesting that monitors DR1 and DR2 generally reported similar $PM_{2.5}$ levels. Paired $PM_{2.5}$ concentration differences ranged from -4.1 to 28.5 $\mu g/m^3$, and the central tendency was -0.2 $\mu g/m^3$, confirming good correspondence. Relatively large RPDs were nearly always associated with low $PM_{2.5}$ concentrations (<10 $\mu g/m^3$) and small concentration differences (-4.1 to 3.2 $\mu g/m^3$). A substantial discordance was observed on February 9 at 10:38 p.m., when an RPD of 142.1 percent and a paired $PM_{2.5}$ concentration difference 28.5 $\mu g/m^3$ was observed. The cause of this discordance was not determined.

Distributions of raw $PM_{2.5}$ concentrations reported by monitors DR1 and DR2 were similar. A correlation coefficient (*r*) of 0.983 (Fisher's z transformed 95 percent CI 0.981, 0.984) was calculated for the correlation between time-matched $PM_{2.5}$ levels reported the two monitors, indicating a strong correlation.

In summary, field test data provided substantial evidence that, under the conditions of the test, the two DataRAM Model DR-4000 $PM_{2.5}$ monitors responded similarly to outdoor air $PM_{2.5}$.

Table B-2. Distribution of relative percent differences (%).

	Minimum	1	5	25	50	75	95	99	Maximum
RPD	0	0	0	4.5	10.0	18.5	33.0	45.2	142.1

Table B-3. Distribution of paired $PM_{2.5}$ concentration differences ($\mu g/m^3$).

	Minimum	1	5	25	50	75	95	99	Maximum
Difference (*DR1-DR2*)	-4.1	-2.1	-1.6	-0.9	-0.2	0.3	3.2	9.4	28.5

Table B-4. Distributions of raw $PM_{2.5}$ concentrations ($\mu g/m^3$).

Monitor	Minimum	1	5	25	50	75	95	99	Maximum
DR1	0.8	1.6	2.0	4.0	5.2	9.4	36.2	75.9	252.7
DR2	1.1	1.8	2.1	4.2	6.0	9.7	33.9	71.0	224.7

Figure B-11. Scatterplot of time-matched $PM_{2.5}$ concentrations.

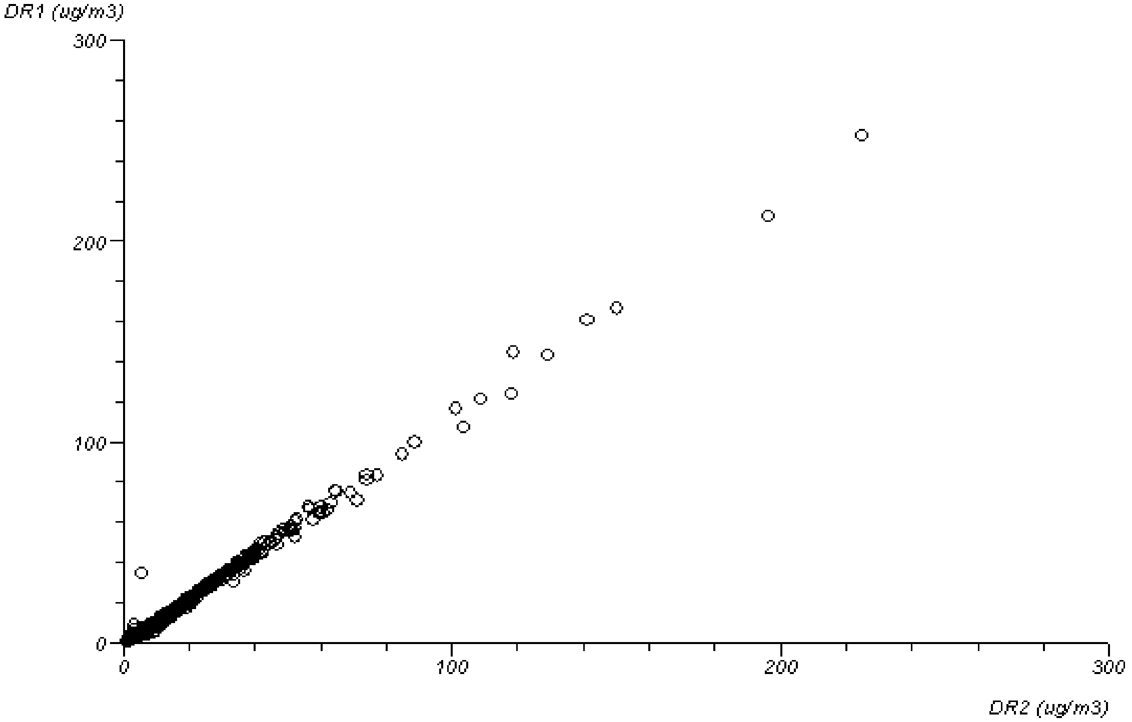

Table B-5. Time-matched observations with RPD greater than 20 percent.

DATE/TIME	DR1 MASS (μg/m^3)	DR2 MASS (μg/m^3)	DIFFERENCE (μg/m^3)	RPD(%)
2/9/2007 22:38	34.3	5.8	28.5	142.1
2/9/2007 11:48	8.8	3.2	5.6	93.3
2/9/2007 8:08	0.9	2.0	-1.1	75.9
2/9/2007 12:48	6.7	3.5	3.2	62.7
2/9/2007 9:33	0.8	1.5	-0.7	60.9
2/9/2007 7:43	4.2	2.3	1.9	58.5
2/8/2007 18:18	4.1	7.4	-3.3	57.4
2/13/2007 8:23	5.3	9.4	-4.1	55.8
2/9/2007 5:23	5.1	8.6	-3.5	51.1
2/9/2007 5:28	5.1	8.5	-3.4	50.0
2/9/2007 9:38	1.3	2.1	-0.8	47.1
2/12/2007 23:28	3.8	6.1	-2.3	46.5
2/9/2007 7:18	4.8	3.0	1.8	46.2
2/7/2007 22:53	2.2	3.5	-1.3	45.6
2/9/2007 7:53	1.2	1.9	-0.7	45.2
2/9/2007 7:58	1.2	1.9	-0.7	45.2
2/9/2007 8:28	1.9	1.2	0.7	45.2
2/7/2007 23:48	2.8	4.4	-1.6	44.4
2/7/2007 23:58	2.8	4.4	-1.6	44.4
2/8/2007 1:03	3.0	4.7	-1.7	44.2
2/8/2007 0:28	2.9	4.5	-1.6	43.2
2/7/2007 22:48	2.2	3.4	-1.2	42.9
2/9/2007 8:03	1.5	2.3	-0.8	42.1
2/8/2007 4:13	3.8	5.8	-2.0	41.7
2/8/2007 23:28	2.1	3.2	-1.1	41.5
2/7/2007 22:38	2.3	3.5	-1.2	41.4
2/7/2007 23:38	2.7	4.1	-1.4	41.2
2/8/2007 0:43	3.1	4.7	-1.6	41.0
2/8/2007 1:58	3.5	5.3	-1.8	40.9
2/8/2007 3:38	3.9	5.9	-2.0	40.8
2/8/2007 0:13	2.8	4.2	-1.4	40.0
2/7/2007 22:43	2.2	3.3	-1.1	40.0
2/8/2007 2:58	3.6	5.3	-1.7	38.2

DATE/TIME	DR1 MASS ($\mu g/m^3$)	DR2 MASS ($\mu g/m^3$)	DIFFERENCE ($\mu g/m^3$)	RPD(%)
2/9/2007 18:38	1.7	2.5	-0.8	38.1
2/8/2007 0:53	3.2	4.7	-1.5	38.0
2/9/2007 8:23	2.2	1.5	0.7	37.8
2/13/2007 8:03	5.0	7.3	-2.3	37.4
2/8/2007 1:38	3.5	5.1	-1.6	37.2
2/8/2007 1:48	3.5	5.1	-1.6	37.2
2/8/2007 1:18	3.3	4.8	-1.5	37.0
2/8/2007 0:33	3.1	4.5	-1.4	36.8
2/8/2007 0:58	3.1	4.5	-1.4	36.8
2/8/2007 1:08	3.1	4.5	-1.4	36.8
2/9/2007 14:28	2.9	2	0.9	36.7
2/8/2007 0:18	2.9	4.2	-1.3	36.6
2/7/2007 23:18	2.7	3.9	-1.2	36.4
2/8/2007 6:13	4.3	6.2	-1.9	36.2
2/8/2007 1:23	3.4	4.9	-1.5	36.1
2/8/2007 1:53	3.4	4.9	-1.5	36.1
2/13/2007 4:03	4.8	6.9	-2.1	35.9
2/8/2007 0:48	3.2	4.6	-1.4	35.9
2/9/2007 10:33	2.3	1.6	0.7	35.9
2/9/2007 10:43	1.6	2.3	-0.7	35.9
2/8/2007 2:08	3.9	5.6	-1.7	35.8
2/8/2007 3:13	3.9	5.6	-1.7	35.8
2/8/2007 3:18	3.9	5.6	-1.7	35.8
2/8/2007 0:03	3.0	4.3	-1.3	35.6
2/8/2007 2:23	3.7	5.3	-1.6	35.6
2/8/2007 3:33	4.0	5.7	-1.7	35.1
2/8/2007 1:13	3.3	4.7	-1.4	35.0
2/8/2007 1:28	3.3	4.7	-1.4	35.0
2/7/2007 22:58	2.6	3.7	-1.1	34.9
2/8/2007 2:33	3.8	5.4	-1.6	34.8
2/9/2007 16:58	2.7	1.9	0.8	34.8
2/13/2007 8:18	5.0	7.1	-2.1	34.7
2/8/2007 1:33	3.4	4.8	-1.4	34.1
2/9/2007 11:58	1.7	2.4	-0.7	34.1
2/8/2007 3:03	3.9	5.5	-1.6	34.0

DATE/TIME	DR1 MASS (μg/m^3)	DR2 MASS (μg/m^3)	DIFFERENCE (μg/m^3)	RPD(%)
2/8/2007 6:23	4.4	6.2	-1.8	34.0
2/13/2007 8:08	4.4	6.2	-1.8	34.0
2/13/2007 5:13	4.9	6.9	-2.0	33.9
2/13/2007 6:03	5.4	7.6	-2.2	33.8
2/8/2007 2:48	3.7	5.2	-1.5	33.7
2/8/2007 7:03	4.2	5.9	-1.7	33.7
2/12/2007 23:43	5.5	7.7	-2.2	33.3
2/8/2007 5:43	4.5	6.3	-1.8	33.3
2/9/2007 8:33	1.0	1.4	-0.4	33.3
2/8/2007 5:08	4.3	6.0	-1.7	33.0
2/8/2007 2:28	3.8	5.3	-1.5	33.0
2/13/2007 7:43	5.6	7.8	-2.2	32.8
2/8/2007 4:33	4.1	5.7	-1.6	32.7
2/13/2007 6:43	5.4	7.5	-2.1	32.6
2/8/2007 6:33	4.4	6.1	-1.7	32.4
2/8/2007 3:28	3.9	5.4	-1.5	32.3
2/8/2007 5:48	4.7	6.5	-1.8	32.1
2/13/2007 8:13	4.7	6.5	-1.8	32.1
2/8/2007 3:23	4.2	5.8	-1.6	32.0
2/7/2007 23:28	2.9	4.0	-1.1	31.9
2/7/2007 23:33	2.9	4.0	-1.1	31.9
2/8/2007 0:08	2.9	4.0	-1.1	31.9
2/13/2007 6:38	5.3	7.3	-2.0	31.7
2/8/2007 2:53	4.0	5.5	-1.5	31.6
2/13/2007 5:18	5.1	7.0	-1.9	31.4
2/8/2007 3:58	4.3	5.9	-1.6	31.4
2/8/2007 4:48	4.3	5.9	-1.6	31.4
2/9/2007 7:13	4.8	3.5	1.3	31.3
2/8/2007 2:03	3.8	5.2	-1.4	31.1
2/8/2007 8:08	4.9	6.7	-1.8	31.0
2/13/2007 7:23	4.9	6.7	-1.8	31.0
2/7/2007 23:43	3	4.1	-1.1	31.0
2/8/2007 4:58	4.1	5.6	-1.5	30.9
2/8/2007 7:48	4.4	6.0	-1.6	30.8
2/9/2007 9:28	1.1	1.5	-0.4	30.8

DATE/TIME	DR1 MASS (μg/m^3)	DR2 MASS (μg/m^3)	DIFFERENCE (μg/m^3)	RPD(%)
2/8/2007 8:28	4.7	6.4	-1.7	30.6
2/8/2007 1:43	3.6	4.9	-1.3	30.6
2/9/2007 8:13	2.5	3.4	-0.9	30.5
2/9/2007 21:03	2.5	3.4	-0.9	30.5
2/8/2007 4:38	4.2	5.7	-1.5	30.3
2/8/2007 5:18	4.5	6.1	-1.6	30.2
2/8/2007 5:58	4.5	6.1	-1.6	30.2
2/8/2007 6:03	4.5	6.1	-1.6	30.2
2/7/2007 23:53	3.1	4.2	-1.1	30.1
2/8/2007 0:23	3.1	4.2	-1.1	30.1
2/9/2007 18:33	1.7	2.3	-0.6	30.0
2/9/2007 18:43	1.7	2.3	-0.6	30.0
2/9/2007 19:28	1.7	2.3	-0.6	30.0
2/13/2007 7:58	5.7	7.7	-2.0	29.9
2/8/2007 2:38	4.0	5.4	-1.4	29.8
2/8/2007 3:48	4.3	5.8	-1.5	29.7
2/8/2007 5:28	4.6	6.2	-1.6	29.6
2/8/2007 22:33	2.6	3.5	-0.9	29.5
2/9/2007 11:18	3.5	2.6	0.9	29.5
2/13/2007 6:13	5.5	7.4	-1.9	29.5
2/8/2007 22:13	2.9	3.9	-1.0	29.4
2/8/2007 22:18	2.9	3.9	-1.0	29.4
2/9/2007 8:48	2.9	3.9	-1.0	29.4
2/13/2007 7:48	7.3	9.8	-2.5	29.2
2/8/2007 4:18	4.1	5.5	-1.4	29.2
2/13/2007 2:43	4.1	5.5	-1.4	29.2
2/8/2007 4:53	4.4	5.9	-1.5	29.1
2/8/2007 6:08	4.4	5.9	-1.5	29.1
2/8/2007 6:53	4.4	5.9	-1.5	29.1
2/13/2007 4:13	5.6	7.5	-1.9	29.0
2/13/2007 4:18	5.6	7.5	-1.9	29.0
2/8/2007 0:38	3.3	4.4	-1.1	28.6
2/13/2007 3:23	4.8	6.4	-1.6	28.6
2/13/2007 7:08	6.3	8.4	-2.1	28.6
2/8/2007 8:58	5.1	6.8	-1.7	28.6

DATE/TIME	DR1 MASS (µg/m^3)	DR2 MASS (µg/m^3)	DIFFERENCE (µg/m^3)	RPD(%)
2/9/2007 9:53	1.5	2.0	-0.5	28.6
2/9/2007 16:18	3.6	2.7	0.9	28.6
2/8/2007 3:08	4.2	5.6	-1.4	28.6
2/8/2007 23:23	2.1	2.8	-0.7	28.6
2/13/2007 5:33	5.2	6.9	-1.7	28.1
2/8/2007 8:53	4.9	6.5	-1.6	28.1
2/8/2007 5:33	4.6	6.1	-1.5	28.0
2/8/2007 5:38	4.6	6.1	-1.5	28.0
2/8/2007 6:18	4.6	6.1	-1.5	28.0
2/8/2007 4:08	4.3	5.7	-1.4	28.0
2/8/2007 6:48	4.3	5.7	-1.4	28.0
2/8/2007 7:08	4.3	5.7	-1.4	28.0
2/8/2007 2:18	4.0	5.3	-1.3	28.0
2/9/2007 6:53	3.4	4.5	-1.1	27.8
2/8/2007 23:53	2.5	3.3	-0.8	27.6
2/9/2007 10:38	3.3	2.5	0.8	27.6
2/8/2007 9:43	4.7	6.2	-1.5	27.5
2/8/2007 10:23	4.7	6.2	-1.5	27.5
2/13/2007 4:08	6.6	8.7	-2.1	27.5
2/8/2007 4:43	4.4	5.8	-1.4	27.5
2/8/2007 7:13	4.4	5.8	-1.4	27.5
2/8/2007 7:53	4.4	5.8	-1.4	27.5
2/8/2007 15:43	2.9	2.2	0.7	27.5
2/9/2007 12:18	2.2	2.9	-0.7	27.5
2/13/2007 7:28	6.3	8.3	-2.0	27.4
2/8/2007 2:13	3.8	5.0	-1.2	27.3
2/8/2007 8:03	4.5	5.9	-1.4	26.9
2/8/2007 4:28	4.2	5.5	-1.3	26.8
2/8/2007 2:43	3.9	5.1	-1.2	26.7
2/13/2007 6:08	6.2	8.1	-1.9	26.6
2/13/2007 3:53	4.9	6.4	-1.5	26.5
2/8/2007 5:13	4.6	6.0	-1.4	26.4
2/8/2007 5:23	4.6	6.0	-1.4	26.4
2/8/2007 6:58	4.6	6.0	-1.4	26.4
2/9/2007 12:38	3.0	2.3	0.7	26.4

DATE/TIME	DR1 MASS (μg/m^3)	DR2 MASS (μg/m^3)	DIFFERENCE (μg/m^3)	RPD(%)
2/9/2007 14:53	2.3	3.0	-0.7	26.4
2/10/2007 14:03	6.6	8.6	-2	26.3
2/13/2007 7:03	8.6	11.2	-2.6	26.3
2/9/2007 4:58	5.0	6.5	-1.5	26.1
2/7/2007 23:08	3.0	3.9	-0.9	26.1
2/8/2007 22:08	3.0	3.9	-0.9	26.1
2/8/2007 8:23	4.7	6.1	-1.4	25.9
2/9/2007 3:28	4.7	6.1	-1.4	25.9
2/13/2007 6:48	6.4	8.3	-1.9	25.9
2/8/2007 19:13	2.7	3.5	-0.8	25.8
2/8/2007 3:53	4.4	5.7	-1.3	25.7
2/9/2007 8:38	1.7	2.2	-0.5	25.6
2/13/2007 6:18	6.8	8.8	-2.0	25.6
2/8/2007 10:48	5.1	6.6	-1.5	25.6
2/9/2007 3:58	4.8	6.2	-1.4	25.5
2/13/2007 5:53	5.5	7.1	-1.6	25.4
2/8/2007 5:03	4.5	5.8	-1.3	25.2
2/8/2007 7:28	4.5	5.8	-1.3	25.2
2/8/2007 7:38	4.5	5.8	-1.3	25.2
2/9/2007 2:48	4.5	5.8	-1.3	25.2
2/9/2007 22:33	4.5	5.8	-1.3	25.2
2/13/2007 5:08	5.2	6.7	-1.5	25.2
2/13/2007 3:08	5.6	7.2	-1.6	25.0
2/13/2007 7:18	5.6	7.2	-1.6	25.0
2/8/2007 3:43	4.2	5.4	-1.2	25.0
2/9/2007 1:13	3.5	4.5	-1.0	25.0
2/9/2007 2:03	4.2	5.4	-1.2	25.0
2/8/2007 9:08	4.9	6.3	-1.4	25.0
2/9/2007 3:33	4.9	6.3	-1.4	25.0
2/13/2007 3:58	4.9	6.3	-1.4	25.0
2/13/2007 6:33	6.0	7.7	-1.7	24.8
2/8/2007 7:43	4.6	5.9	-1.3	24.8
2/8/2007 11:23	4.6	5.9	-1.3	24.8
2/8/2007 15:48	3.2	2.5	0.7	24.6
2/8/2007 22:43	2.5	3.2	-0.7	24.6

DATE/TIME	DR1 MASS (µg/m^3)	DR2 MASS (µg/m^3)	DIFFERENCE (µg/m^3)	RPD(%)
2/8/2007 22:53	2.5	3.2	-0.7	24.6
2/8/2007 5:53	5.0	6.4	-1.4	24.6
2/8/2007 9:38	5.0	6.4	-1.4	24.6
2/9/2007 2:33	4.3	5.5	-1.2	24.5
2/13/2007 2:28	4.3	5.5	-1.2	24.5
2/11/2007 8:53	5.4	6.9	-1.5	24.4
2/11/2007 15:28	4.6	3.6	1.0	24.4
2/9/2007 14:48	1.8	2.3	-0.5	24.4
2/9/2007 18:18	1.8	2.3	-0.5	24.4
2/9/2007 18:53	1.8	2.3	-0.5	24.4
2/9/2007 19:13	1.8	2.3	-0.5	24.4
2/13/2007 7:13	6.5	8.3	-1.8	24.3
2/8/2007 8:13	4.7	6.0	-1.3	24.3
2/7/2007 23:23	2.9	3.7	-0.8	24.2
2/8/2007 8:38	5.1	6.5	-1.4	24.1
2/9/2007 5:43	5.1	6.5	-1.4	24.1
2/8/2007 20:58	3.3	4.2	-0.9	24.0
2/9/2007 0:58	3.3	4.2	-0.9	24.0
2/10/2007 1:08	5.5	7.0	-1.5	24.0
2/13/2007 3:13	5.5	7.0	-1.5	24.0
2/13/2007 3:43	5.5	7.0	-1.5	24.0
2/9/2007 8:53	2.2	2.8	-0.6	24.0
2/8/2007 8:33	4.8	6.1	-1.3	23.9
2/8/2007 8:43	4.8	6.1	-1.3	23.9
2/9/2007 4:43	4.8	6.1	-1.3	23.9
2/8/2007 23:43	2.6	3.3	-0.7	23.7
2/8/2007 23:48	2.6	3.3	-0.7	23.7
2/9/2007 1:38	4.1	5.2	-1.1	23.7
2/8/2007 4:03	4.5	5.7	-1.2	23.5
2/9/2007 2:53	4.5	5.7	-1.2	23.5
2/9/2007 7:48	1.9	1.5	0.4	23.5
2/11/2007 4:28	3.4	4.3	-0.9	23.4
2/9/2007 12:53	2.4	1.9	0.5	23.3
2/9/2007 8:58	1.9	2.4	-0.5	23.3
2/9/2007 9:18	1.9	2.4	-0.5	23.3

DATE/TIME	DR1 MASS (µg/m^3)	DR2 MASS (µg/m^3)	DIFFERENCE (µg/m^3)	RPD(%)
2/13/2007 5:03	5.7	7.2	-1.5	23.3
2/13/2007 5:58	6.1	7.7	-1.6	23.2
2/13/2007 2:23	4.2	5.3	-1.1	23.2
2/8/2007 6:38	4.6	5.8	-1.2	23.1
2/8/2007 7:23	4.6	5.8	-1.2	23.1
2/8/2007 10:33	4.6	5.8	-1.2	23.1
2/9/2007 2:38	4.6	5.8	-1.2	23.1
2/11/2007 9:33	4.6	5.8	-1.2	23.1
2/11/2007 9:53	4.6	5.8	-1.2	23.1
2/8/2007 9:53	5.0	6.3	-1.3	23.0
2/9/2007 0:38	3.1	3.9	-0.8	22.9
2/13/2007 4:23	7.4	9.3	-1.9	22.8
2/9/2007 1:33	3.9	4.9	-1.0	22.7
2/8/2007 4:23	4.3	5.4	-1.1	22.7
2/9/2007 7:23	4.3	5.4	-1.1	22.7
2/8/2007 7:58	4.7	5.9	-1.2	22.6
2/8/2007 8:18	4.7	5.9	-1.2	22.6
2/8/2007 9:13	5.1	6.4	-1.3	22.6
2/8/2007 9:58	5.1	6.4	-1.3	22.6
2/9/2007 5:18	5.1	6.4	-1.3	22.6
2/11/2007 8:43	5.1	6.4	-1.3	22.6
2/11/2007 9:08	5.1	6.4	-1.3	22.6
2/7/2007 23:03	2.8	3.5	-0.7	22.2
2/9/2007 7:33	2.8	3.5	-0.7	22.2
2/9/2007 2:43	4.8	6.0	-1.2	22.2
2/9/2007 4:48	4.8	6.0	-1.2	22.2
2/11/2007 9:23	4.8	6.0	-1.2	22.2
2/13/2007 5:23	7.6	9.5	-1.9	22.2
2/12/2007 23:38	5.0	4.0	1.0	22.2
2/8/2007 17:58	2.0	2.5	-0.5	22.2
2/9/2007 19:53	2.0	2.5	-0.5	22.2
2/11/2007 3:08	3.6	4.5	-0.9	22.2
2/9/2007 1:43	4.0	5.0	-1.0	22.2
2/9/2007 12:23	1.6	2.0	-0.4	22.2
2/11/2007 5:08	3.2	4.0	-0.8	22.2

DATE/TIME	DR1 MASS (μg/m^3)	DR2 MASS (μg/m^3)	DIFFERENCE (μg/m^3)	RPD(%)
2/9/2007 22:58	4.4	5.5	-1.1	22.2
2/10/2007 0:33	4.4	5.5	-1.1	22.2
2/13/2007 6:58	8.1	10.1	-2.0	22.0
2/8/2007 9:18	5.3	6.6	-1.3	21.8
2/8/2007 6:43	4.9	6.1	-1.2	21.8
2/8/2007 9:03	4.9	6.1	-1.2	21.8
2/13/2007 3:48	4.9	6.1	-1.2	21.8
2/8/2007 11:53	4.5	5.6	-1.1	21.8
2/8/2007 12:08	4.5	5.6	-1.1	21.8
2/11/2007 9:28	4.5	5.6	-1.1	21.8
2/10/2007 2:33	6.6	8.2	-1.6	21.6
2/7/2007 23:13	2.9	3.6	-0.7	21.5
2/9/2007 11:53	2.9	3.6	-0.7	21.5
2/13/2007 5:43	5.8	7.2	-1.4	21.5
2/13/2007 3:03	5.4	6.7	-1.3	21.5
2/11/2007 3:58	2.5	3.1	-0.6	21.4
2/8/2007 8:48	5.0	6.2	-1.2	21.4
2/8/2007 9:28	5.0	6.2	-1.2	21.4
2/8/2007 10:08	5.0	6.2	-1.2	21.4
2/8/2007 11:03	5.0	6.2	-1.2	21.4
2/9/2007 3:48	5.0	6.2	-1.2	21.4
2/13/2007 2:13	5.0	6.2	-1.2	21.4
2/9/2007 2:08	4.6	5.7	-1.1	21.4
2/11/2007 8:58	5.5	6.8	-1.3	21.1
2/13/2007 1:58	5.5	6.8	-1.3	21.1
2/9/2007 7:38	1.7	2.1	-0.4	21.1
2/9/2007 14:58	1.7	2.1	-0.4	21.1
2/11/2007 4:53	1.7	2.1	-0.4	21.1
2/8/2007 11:18	4.7	5.8	-1.1	21.0
2/8/2007 21:08	3.0	3.7	-0.7	20.9
2/8/2007 22:48	2.6	3.2	-0.6	20.7
2/8/2007 23:38	2.6	3.2	-0.6	20.7
2/9/2007 13:23	2.6	3.2	-0.6	20.7
2/9/2007 5:33	5.2	6.4	-1.2	20.7
2/13/2007 7:53	7.4	9.1	-1.7	20.6

DATE/TIME	DR1 MASS (µg/m^3)	DR2 MASS (µg/m^3)	DIFFERENCE (µg/m^3)	RPD(%)
2/8/2007 10:28	4.8	5.9	-1.1	20.6
2/11/2007 7:38	4.8	5.9	-1.1	20.6
2/9/2007 7:03	3.5	4.3	-0.8	20.5
2/10/2007 3:53	6.6	8.1	-1.5	20.4
2/9/2007 16:48	2.7	2.2	0.5	20.4
2/8/2007 23:13	2.2	2.7	-0.5	20.4
2/8/2007 13:38	4.4	5.4	-1.0	20.4
2/9/2007 2:18	4.4	5.4	-1.0	20.4
2/9/2007 5:13	5.3	6.5	-1.2	20.3
2/8/2007 20:43	3.1	3.8	-0.7	20.3
2/11/2007 20:08	7.1	8.7	-1.6	20.3
2/8/2007 10:18	4.9	6.0	-1.1	20.2
2/9/2007 4:23	4.9	6.0	-1.1	20.2
2/11/2007 7:43	4.9	6.0	-1.1	20.2
2/11/2007 9:48	4.9	6.0	-1.1	20.2
2/8/2007 11:08	7.1	5.8	1.3	20.2
2/9/2007 17:03	2.2	1.8	0.4	20.0
2/9/2007 17:08	2.2	1.8	0.4	20.0
2/9/2007 18:48	1.8	2.2	-0.4	20.0
2/11/2007 4:48	1.8	2.2	-0.4	20.0
2/8/2007 18:13	3.6	4.4	-0.8	20.0
2/13/2007 2:38	4.5	5.5	-1.0	20.0

Appendix C. Detailed Descriptions of Air Monitor Deployments.

Site 1

Nearfield Monitor		Reference Monitor	
Inlet Height	**Groundcover**	**Inlet Height**	**Groundcover**
43.5" (3.6ft) [cooler (16.5"), inlet heater (15"), porch (12"]	$PM_{2.5}$ monitors were placed on a wooden front porch deck (where the power source was located). The equipment was protected by a roof, which covered the entire porch. The house was surrounded by trees that were approximately 40ft in height. The property was heavily wooded. The terrain was generally flat with minor undulations.	95.5" (8ft) [cooler (16.5"), inlet heater (15"), porch (60"), pallet (4"]	$PM_{2.5}$ monitors were set up on a wooden front porch deck, next to the external power source, and were placed on a 4-inch pallet. The porch was not covered, so instruments were exposed to the elements. The house was located on a mildly slope. Trees (about 50-70 feet tall) surrounded the house. The property around the home was heavily wooded. The front of the home was single story ranch style and approximately 18 feet high. The back of the home was double story.

Site 2

Nearfield Monitor		Reference Monitor	
Inlet Height	**Groundcover**	**Inlet Height**	**Groundcover**
39.5" (3.3ft) [cooler (16.5"), inlet heater (15"), 2 pallets (2 x 4")]	$PM_{2.5}$ monitors were placed on two pallets at the front of the house, 55 feet east from the road, and 6 feet west of the house. The monitors were surrounded by snow covered ground (10" of snow). However the monitors were placed directly on frozen grass (on a little area where the snow was cleared). There was a line of trees west of the house (approximately 30 feet in height) bordering the road in front of the house. The property was located on the cusp of a residential area where most houses were within 500 feet of each other. It was bordered by a large field to the west, and the terrain was relatively flat. There was a row of trees in front of the house, and there were small clusters of trees throughout the neighborhood.	39.5" (3.3ft) [cooler(16.5'), inlet heater (15"), 2 pallets (2 x 4”)]	$PM_{2.5}$ monitors were set up approximately 20 feet north of the house and 15 feet south of the driveway, in a relatively flat area. The monitors were set up east/northeast of a group of 6 trees (5 in a line parallel with the front of the house and the road, and another closer to the house and along the driveway). The closest tree was approximately 20 feet from the monitors. The trees were all approximately 45 feet in height, and the house was about 30 feet high. The monitors were placed on 2 pallets situated atop a small incline leading from the house down to a State Route. The house was located amidst agricultural fields. It was situated on a small hill and surrounded by relatively flat terrain. There was another home approximately 300-400 feet north of the residence, but there were no homes across the street from the home, and the closest home to the southwest was over 1,900 feet away. There was a housing development about 1,200 feet to the east of the residence that bordered the back of the property. There was a line of trees bordering the road at the front of the property and brush to the south of the house along the hillside. There was also a cluster of trees on the back of the property, as well as a treeline defining the eastern and southern borders of the agricultural field behind the residence.

Site 3

Nearfield Monitor		Reference Monitor	
Inlet Height	**Groundcover**	**Inlet Height**	**Groundcover**
39.5" (3.3ft) [cooler (16.5"), inlet heater (15"), 2 pallets (2 x 4")]	$PM_{2.5}$ monitors were placed on two 4-inch high pallets on the side of the house, approximately 2 feet from the house. The equipment location was chosen because of its close proximity to external power sources (located on a nearby porch). There was a gradual downward slope in the terrain from the west of the property to the east end of the parcel, and downgradient toward the OWB. There was a small stream running through the property (west to east). There was a shed located approximately 15 feet north of the back of the house, and a garage was located approximately 25 feet east of the shed (and 33 feet north northeast of the back of the house). There was a dog kennel housing about 6 dogs located approximately 138 feet north of the shed. There was a line of trees approximately 45 feet in height lining the western boundary of the property. The northeastern quadrant of the property was also heavily wooded. With the exception of the driveway most of the property was covered with approximately 5 inches of snow.	39.5" (3.3ft) [cooler (16.5"), inlet heater (15"), 2 pallets (2 x 4")]	$PM_{2.5}$ monitors were deployed at the back of the house, next to the external power source. They were placed on two 4-inch pallets. The ground was covered with approximately 5 inches of snow at set-up. The monitors were approximately 88 feet east/southeast of a road. The terrain was mostly flat. The house was located at the bottom of the hollow. There was a gradual incline from the road eastwards to the end of the property. There were 4 trees (30 feet high) evenly spaced approximately 30 feet apart at the western side of the property, which bordered the road. There was a line of 9 trees approximately 188 feet east of the road in the middle of the property. There was a little water well (possibly ornamental) approximately 60 feet southeast of the back of the house.

Site 4

Nearfield Monitor		Reference Monitor	
Inlet Height	**Groundcover**	**Inlet Height**	**Groundcover**
71.5" (6ft) [cooler (16.5"), inlet heater (15"), deck (36"), pallet (4")]	$PM_{2.5}$ monitors were placed on a 4-inch high pallet on a backyard wooden deck adjacent to the kitchen. The monitor was approximately 650 feet from a road. The deck was not covered. At the back of the house there was an above-ground pool 10 feet from the deck, a trampoline (10 feet high) 15 feet from the deck, and a well approximately 20 feet from the deck. The terrain sloped downward from the back of the property toward the road. There were numerous trees surrounding the house, which were approximately 50 feet tall. There was approx 2 inches of snow on the ground around the deck	39.5" (3.3ft) [cooler (16.5"), inlet heater (15"), 2 pallets (2 x 4")]	$PM_{2.5}$ monitors were set up approximately 30 feet east of the house alongside a fenced-in enclosure in the backyard. The location was nearly flat, with access to a power source. The monitors were set up west/northwest of a few separate lines/clusters of trees, all of which were approximately 30 feet in height. The monitors sat on 2 pallets approximately 135 feet east of State Route 40. The nearest tree was approximately 30 feet from the monitors. There was also a lone tree along the north side of the house that measured about 40 feet in height. The home itself was about 20 feet high. There was approximately 2 inches of snow on the surrounding ground.

Site 5

Nearfield Monitor		Reference Monitor	
Inlet Height	**Groundcover**	**Inlet Height**	**Groundcover (control)**
39.5" (3.3ft) [cooler (16.5"), inlet heater (15"), 2 pallets (2 x 4")]	The $PM_{2.5}$ monitors were placed on a 4-inch-high pallet next to a large bush situated between the house and the garage. There was approx 2 inches of snow on the ground. The monitors were approximately 40 feet from a road. The terrain was generally flat with a gentle downward slope from the front of the property (which was by a road) to the back of the property. There were 6 clusters of bushes around the front of the house with few trees. The back of the property was open, with a 30-foot tree in the middle of the property.	71.5" (6ft) [cooler (16.5"), inlet heater (15"), pallet (4"), deck (36")]	$PM_{2.5}$ monitors were deployed on a backyard wooden deck attached to the kitchen. The monitors were placed on a 4 inch pallet. There was approx 2 inches of snow on the ground. The terrain was hilly, and the house was situated at the top of a hill. The land sloped downward, moving away from the house toward a road. There were at least ten trees in the backyard within 10 feet of the house, and woods were within 20 feet of the house. There was a large bush about 4 feet southeast of the monitoring equipment. There was a swing set about 10 feet from the back porch. Behind the swing set there was a small shed about 8 feet tall, located approximately 20 feet from the back porch. There was a detached garage and shed southwest of the back porch.

Site 6

Nearfield Monitor		Reference Monitor	
Inlet Height	**Groundcover**	**Inlet Height**	**Groundcover**
31.5" (2.6ft) [cooler (16.5"), inlet heater (15")]	The $PM_{2.5}$ monitor was placed on the ground in the backyard approximately 6 feet behind and South of the house. The distance was approximately 90 feet South of a road. The terrain was generally flat. There was no snow on the ground near the monitor, but snow depth in the general area ranged from a dusting to 3 inches. There was a 6ft-tall fence approximately 50 feet to the West on the property line between the OWB and the monitor.	91.5" (7.6ft) [cooler (16.5"), inlet heater (15"), porch (24"), picnic table (36")]	The $PM_{2.5}$ monitor was placed on a picnic table located on a wooden front porch. The porch was protected by a roof, which covered the entire porch. The monitor was approximately 225 feet east of a road. The terrain was sloping down towards the north and east. Snow depth in the general area ranged from a dusting to 3 inches. There were several scattered trees and ornamental shrubs around the property. The property is heavily wooded to the south and east and generally open to the north and west.

Appendix D. Data Summary Table.

Table D-1. Time-matched $PM_{2.5}$ concentrations ($\mu g/m^3$).

	Site 1		Site 2		Site 3		Site 4		Site 5		Site 6	
	N1	***R1***	***N2***	***R2***	***N3***	***R3***	***N4***	***R4***	***N5***	***R5***	***N6***	***R6***
N	1914		3373		2689		4004		3001		970	
Geometric Mean	11.5	9.8	15.8	9.1	6.6	2.3	3.2	4.4	9.8	8.5	13.3	9.1
Minimum	1.6	1.8	3.2	0.3	0.4	0.1	0.3	0.05	0.2	0.3	0.8	0.7
5th percentile	3.7	3.8	6.7	1.7	1.9	0.6	1.4	0.05	3.4	2.7	3.4	2.5
25th percentile	6.0	5.7	10.4	5.8	4.0	1.4	3.1	1.4	6.3	5.9	8.0	4.7
Median	9.4	8.7	14.7	8.8	6.9	2.3	4.5	3.6	9.9	8.8	13.7	9.9
75th percentile	19.0	14.0	22.4	15.9	10.7	3.9	6.2	7.1	15.2	12.8	23.2	17.8
95th percentile	70.4	42.9	50.6	41.9	18.4	8.1	12.6	14.4	29.9	23.1	42.7	34.4
99th percentile	101.5	65.5	82.9	56.5	34.8	14.9	18.0	20.5	48.0	34.6	74.3	40.9
Maximum	144.2	407.8	320.8	66.7	188.1	49.1	28.7	125.2	91.2	75.4	172.5	80.9
Geometric Mean (combined)	10.6		12.0		3.9		3.2		9.1		11.0	
Median (combined)	9.1		12.0		3.9		4.1		9.4		12.1	
95th percentile (combined)	56.3		46.9		15.6		13.5		26.2		37.9	
>95th percentile (number of obs)	150 (7.8%)	42 (2.2%)	234 (6.9%)	107 (3.2%)	251 (9.3%)	22 (0.8%)	167 (4.2%)	242 (6.0%)	210 (7.0%)	92 (3.1%)	71 (7.3%)	26 (2.7%)
99th percentile (combined)	93.5		65.9		25.3		18.6		42.3		62.9	
>99th percentile (number of obs)	27 (1.4%)	14 (0.7%)	67 (2.0%)	2 (0.1%)	47 (1.8%)	7 (0.3%)	33 (0.8%)	51 (1.3%)	46 (1.5%)	15 (0.5%)	19 (2.0%)	1 (0.1%)
mean paired difference	4.28		6.5732		5.42		0.21		1.95		5.21	
variance	341.4		215.4		83.3		20.9		53.3		165.1	
lag	27		14		30		78		21		19	
adjusted variance	5358.9		1490.4		1035.6		596.9		426.2		1651.5	
Student's *t*	10.1		26.0		30.8		2.9		14.7		12.6	
adjusted *t*	2.6		9.9		8.7		0.5		5.2		4.0	
p-value	<0.0001		<0.0001		<0.0001		0.004		<0.0001		<0.0001	
adjusted *p*-value	0.01		<0.0001		<0.0001		0.59		<0.0001		<0.0001	

N w/ meteorological data	1802	3344	2685	0	2687	820