South Philadelphia Passive Sampler and Sensor Study: Interim Report

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Eben D. Thoma, Wan Jiao¹, Halley Brantley², Tai Wu, Bill Squier, and Bill Mitchell U.S. EPA, Office of Research and Development, National Risk Management Research Laboratory, 109 TW Alexander Drive, E343-02, Research Triangle Park, NC 27711, USA ¹Student services contractor; ² ORISE Fellow

Karen Oliver, Donald Whitaker, Shaibal Mukerjee, Maribel Colon, and Lilian Alston³ U.S. EPA, Office of Research and Development, National Exposure Research Laboratory, 109 TW Alexander Drive, E343-02, Research Triangle Park , NC 27711, USA ³ Senior Environmental Employment (SEE) Program

Carol Ann Gross-Davis, Howard Schmidt, and Ron Landy U.S. EPA, Region 3, 1650 Arch Street, Philadelphia, PA, 19103

Jason DeWees and Ray Merrill

U.S. EPA, Office of Air Quality Planning and Standards, 109 TW Alexander Drive, E143-02, Research Triangle Park, NC 27711, USA,

Elsy Escobar, M. Shahrooz Amin, and Mark Modrak

ARCADIS Inc., 4915 Prospectus Drive, Suite F, Research Triangle Park, NC 27713, USA

Tamira Cousett

Alion Science and Technology, 1000 Park Forty Plaza, Durham, NC 27713. USA

ABSTRACT

Starting in June 2013, the United States Environmental Protection Agency (U.S. EPA) and the City of Philadelphia Air Measurements Services began collaborative research on the use of passive samplers (PSs) and stand-alone air measurement (SAM) systems to improve information on the spatial distributions of air pollutant concentrations in south Philadelphia. The study uses draft U.S. EPA Method 325 time-integrated PSs, deployed in novel ways near facilities and in communities, along with sensor-based SAM technologies to help identify the origin of emissions. Following an overview of project elements, this presentation examines preliminary PS benzene results and provides an example of supporting SAM data. Related presentations in this conference will further detail PS and prototype SAM network deployments and data analysis. Considering all 17 PS sites and 28 (two-week nominal) deployment periods, the median and maximum PS benzene concentrations for this interim set were 0.51 ppbv and 3.13 ppbv, respectively (N = 854). Good co-deployed PS duplicate precision performance was found with an average percent difference of 5.8% for pairs with concentrations over 0.2 ppbv (N = 362). Preliminary data suggests a negative correlation between the sampling period minimum benzene concentrations and average temperature. Although no definite source attribution is offered in this interim report, benzene concentrations for PSs located in close proximity to facility fence lines were found to be consistently elevated by 1 ppby to 2 ppby in comparison to distant, incommunity sites. An examination of prevailing wind directions, spatial concentration gradients, and an example of time-resolved SAM data are also provided.

INTRODUCTION

Because most ducted and mobile sources have a definite emission point (a stack or tailpipe) and are usually amenable to fuel-based emission factors, methods to measure and model emissions from these sources have become relatively well-developed. In contrast, techniques to assess non-point source emissions are less advanced. Fugitive and area sources can be difficult to measure and model since emissions can exhibit significant spatial and temporal heterogeneity and can be profoundly affected by environmental or stochastic factors.¹ In air sheds that contain complex mixes of point, mobile, and non-point sources, the overall uncertainty in emissions and activity information can be significant, complicating assessment of local air quality impacts.

The Office of Research and Development (ORD) of the United States Environmental Protection Agency (U.S. EPA) conducts air pollutant source emissions and personal exposure research and collaborates with the U.S. EPA Office of Air and Radiation (OAR) to develop measurement methods and assess source emissions and impacts. Next generation air measurements (NGAM) approaches that incorporate new sampling, sensor, and informetric techniques are currently under investigation to help improve air quality knowledge. These techniques range from personal sensor systems to mobile inspection and fence line monitoring approaches. NGAM technologies are designed to provide improved understanding of air pollution exposure, and source emissions, help create safer working environments, and facilitate emissions reduction through advanced leak detection and other source mitigation strategies.²⁻⁵ In the future, NGAM approaches can help increase the density and responsiveness of measurements, facilitating both source attribution and exposure research.

In the South Philadelphia Passive Sampler and Sensor Study, the U.S. EPA ORD and OAR are collaborating with U.S. EPA Region 3 and the City of Philadelphia, Department of Public Health, Air Measurements Services (AMS) to investigate how passive samplers (PSs) and sensor-based, stand-alone air measurements (SAMs) can help improve information on air pollutant concentrations in areas with many potential sources (like south Philadelphia). The study, which began in June of 2013, uses a modified version of U.S. EPA method 325, timeintegrated PSs^{6,7} deployed in novel ways near facilities and in neighborhoods. The project also explores time-resolved SAM technologies that use passive photoionization detectors (PIDs) and wind measurements to help inform the origin of emissions. Another aspect of the project is AMS's deployment of open-path ultraviolet and near-infrared optical remote sensing systems in the area as part of a U.S. EPA OAR Communities-scale Grant. This interim report provides a brief overview of the project and explores preliminary results of the PS deployments for the compound benzene. Data on co-deployed PS duplicate comparisons are presented and spatial gradients of benzene are discussed along with a brief introduction to the SAM network data. Separate presentations and posters in this conference will further describe the PS analytical and deployment procedures and novel data analysis approaches from the prototype SAM network.⁸⁻¹³

EXPERIMENTAL METHODS

Sampling Locations:

The south Philadelphia sampling locations are shown in Figure 1A with the 17 numbered PS sites indicated. Sites 1, 2, 15, 16, and 17 are PS deployments in residential neighborhoods or parks located > 1 km from large facilities (including refineries or tank storage). PS Site 3 is located at the AMS Ritner Avenue air quality monitoring station. An expanded view (Figure 1B) shows sites 4, 5, and 7-11 along with the EPA SAM network system (yellow pins) consisting of the PID sensor pod (SPod) and Sentinel Base Station. The tanks on the left edge of Figure 1B belong to the Philadelphia Energy Solutions (PES) refinery, however there are several industrial facilities within the sampling area. The approximate deployment heights of the SAM network and PSs at sites 8-11 were 2 m while sites 1-5 and 15-17 were 3.6 m above the ground. The PSs at sites 12, 13, and 14 were 5.5 m, 9.1 m, and 7.3 m above the ground respectively. Seven of the PS sites (6, 7, 9, 11-14) were deployed using billboard infrastructure while the remainder of the PSs were mounted on light poles or attached to a fence or ground stakes. The billboards were either digital or mechanically-attached vinyl (no solvents or

Figure 1. Sampling locations (A) full view and (B) zoomed-in with SAM sites shown



glues used). PS Site 16 was discontinued after several months due to vandalism. Change-outs of the PS sets typically required six hours and was executed between the hours of 7:00 am and 1:00 pm. Meteorological data for the study is available from a combination of the SAM network, the AMS Ritner Ave. monitoring station, and the Philadelphia International Airport, located 4 km due south of PS Site 1. Period averages of hourly meteorological data from the airport are used here and are summarized in Supplemental Table 1, which also includes the sampling period number and period mid-point dates. Select time-resolved wind data from the SAM network is presented elsewhere.¹³

Passive Samplers:

The diffusive tube PSs used in this study were 89 mm long, 6.4 mm outer diameter stainless steel tubes, part # 28666-U, Supelco FLMTM Carbopack X SupelTMCoat (Sigma-Aldrich, St. Louis MO, USA), or equivalent, with 6.4 mm Brass Swagelok® fittings and plugs, one-piece Teflon® ferrules, and part # L4070207 diffusion caps (PerkinElmer, Shelton, CT, USA). For this study, the PSs were conditioned in the laboratory at 350°C for 1 hr while purging with 75 mL/min of helium and shipped to the site along with field blanks and field spikes in a cooler (no ice) to provide some thermal stability and physical protection. Following deployment documentation,

the plug on the sampling end of a PS was removed and replaced with a diffusion cap to expose the sorbent to ambient air. The PS was mounted in a protective housing (also called a sampling pod) using a convenient snap-in stainless steel holder designed by EPA ORD. The sampling pod was then attached to a previously installed mounting fixture at the site. After nominally two weeks of exposure, the PS was capped, registered in a chain of custody document, packaged and shipped in a cooler to the ORD (or commercial) laboratory for analysis. Analysis was by thermal desorption gas chromatograph mass spectrometry (GCMS) using a modified version of U.S. EPA Method 325B⁷. Due to the inherent benzene background on the Carbopack X tubes, the reported concentration values were analytically corrected for benzene using background subtraction techniques. Additionally, procedures were incorporated to correct for drift in instrument response. Specific details of these activities may be detailed in future work.

Figure 2. Three passive samplers in a (A) sampling pod, (B) with mounting fixture and (C) photos of several deployment locations for the current study



When a set of PSs were retrieved, a new unexposed set was usually deployed and this cycle repeated over time. Typically, multiple PSs were deployed in a single sampling pod at a given location for duplicate, field blank, and field spike quality control purposes or potentially to compare different sorbent materials or other factors. A group of three PSs with diffusion caps

installed in a sampling pod are shown in Figure 2A along with a mounting system (2B). This package is designed to hang from a hook that can be attached to various structures (such as a light pole about 3.5 m above the ground). For elevated deployments, a pole is used to retrieve the PS package for change-out. Figure 2C shows several example PS locations for this study.

General information on EPA's use of Carbopack X diffusive tube PSs for near source and personal exposure applications can be found in the literature,^{5,10,11} while additional details on PS analytical and deployment procedures for this study are presented in this conference.^{8,9} The field validation of the accuracy of PS data for benzene for one or two week deployments has been investigated through comparisons to automated gas chromatograph and canister measurments.^{5,11} This project primarily uses duplicates, field blanks, and field spikes as QC checks. In addition to deployments of PSs at the Philadelphia field sites, the project team also included participants from EPA Regions 3, 5, 6, and 8 who conducted simultaneous PS deployments around other sources in different areas of the U.S. providing additional duplicate performance data under different climatic and siting conditions (partially detailed in reference 12). Some comparisons to other sampling methods and to analysis performed by commercial laboratories are being conducted as part of the overall project and will be described in future reports.

Stand-Alone Monitors:

The EPA-built prototype SAM systems used in this study (Figure 3) are briefly described here with preliminary data analysis approaches and select results detailed elwhere.¹³ Based on passive PIDs, (white or blue label piD-TECH[®], Baseline-Mocon Inc. Lyons, CO, USA), these systems currently provide an un-calibrated measure of volatile organic compounds (VOCs) ionized by the 10.6 eV lamp, which includes benzene. Operating at a 1 Hz rate, the SAM VOC concentration

indicator can be combined with timesynchronized wind direction measurements to provide an indication of the origin of emissions. The "drop in place" SPod is solar powered and communicates to the Sentinel base station via a short range network. The land-powered Sentinel base station contains a model 81000V Ultrasonic Anemometers (R.M. Young, Inc., Traverse City, MI, USA) and communicates via a cell phone modem using a custom data acquisition program. In addition to the EPA SAM systems, the AMS open-path UV and near-IR systems (Figure 2B) have been operating since the spring of 2014 and will be described in future reports.

Figure 3. EPA-built prototype SAM system consisting of a SPod and Sentinel base



RESULTS AND DISCUSSION

Passive Samplers:

Deployments of PSs at the south Philadelphia sites began on June 18, 2013, and are expected to continue into 2015. This interim report presents preliminary analysis of PS benzene concentration data acquired through Sept 30, 2014, and consists of a total of 28 valid sampling periods. Twenty-six of the sampling periods were on nominally 14 days in duration. Due to

resource constraints, sampling periods 5 and 12 were extended in duration (20 days and 29 days respectively) and several deployment weeks were skipped during the October, 2013 U.S. Government shutdown. Sampling period 7 was invalidated due to instrument malfunction during analysis. A total of 854 PS data points from the Philadelphia sites including field samples and duplicates passed quality assurance checks and are part of this interim analysis. The average, median, minimum, and maximum benzene concentrations for this set were 0.72 ppbv, 0.51 ppbv,

Figure 4. PS duplicate comparisons (A) all sites, (B) Philadelphia sites only, with (N) indicating the number of duplicate pairs.



0.08 ppbv and 3.13 ppbv respectively. The method detection limit for the set was below 0.02 ppbv in all cases.

The performance of the PSs are primarily evaluated in this study through use of co-deployed duplicate comparisons. Since the Philadelphia data set exhibits a relatively modest upper range, it is instructive to combine co-analyzed PS data from the EPA Regional deployments that are part of an overarching collaborative EPA project on use of PSs for near source appliations.¹² Figure 4A shows PS duplicate comparisons for benzene including both the EPA Region deployments and Philadelphia test sites whereas Figure 4B presents only the latter. The EPA Region deployments in many cases used multiple co-deployed duplicates in a single sampling pod while the Philadelphia test sites used only a single duplicate (not deployed in all cases). The interim Philadelphia PS data set consists of 449 valid field samples with 405 duplicate comparisons. As has been observed in previous two-week near source PS deployments,⁵ duplicate PS comparisons are relatively precise with an average percent difference of 5.8% and a maximum of 63.6% for pairs with concentrations over 0.2 ppbv (N=362). For subsequent discussion, co-deployed field and duplicate samples were averaged where available to produce a single value (N=449).

In addition to the duplicate comparisons, the performance of the PSs for the combined Regional and Philadelphia studies was assessed through evaluation of field blanks and field spikes. After correction for benzene artifact on all tubes, the mean for the field blanks was -0.005 ppbv ± 0.146 ppbv (N=135). The field spike recoveries were 100.1% $\pm 9.6\%$ (N=136).

Time-integrated PSs in fence line and community applications provide average pollutant concentration data acquired over a mix of source emission and atmospheric transport states. The meteorological conditions for this study are summarized in Supplemental Table 1 which also

provides the sampling period number and period mid-point dates. The prevailing wind for this area is from the southwest as is evident in the east-component of the resultant wind vector which is positive (winds from the west) for all periods.

In this complex urban air shed, any PS sampling location could be located near a source of benzene with emissions originating from mobile sources, heating oil, gas stations, local industry, etc. The largest potential source of benzene for this area is likely the PES refinery and other industry and tankage located to the west of sites 6 -14 (Figure 1). Sites 1, 2, 15, 16, 17, hereafter referred to as "in-community sites," are the farthest removed (> 1 km) from the PES refinery and neighboring facilities.

As this is a longer-term study, it is instructive to investigate trends in the minimum concentrations measured for each sampling period (Figure 5). In general, there is relatively little difference in the benzene concentration measured at the incommunity sites and the overall minimum for a given sampling period is usually associated with one of these locations. Minimum period concentrations are elevated in the December through March timeframe (periods 10-17). This is further explored in Figure 6 which plots the minimum period concentrations versus average period temperature. The variability in minimum period concentrations is likely due to a combination of seasonal source factors (e.g. mobile source fuel mix, cold starts, heating, etc.), atmospheric factors (mixing layer height and inversions), and potential environmental effects on PS performance characteristics. Additional information on these factors should be available for the conference presentation. With regard to the potential for ground-level inversions, periods 14 and 15 exhibited the largest period minimum concentrations and were recorded at the PS location 14, sited the highest above ground level at 7.3 m. Other than the in-community sites and site 14, the only other location to register a period minimum concentration was Site 12 (5.5 m elevation, 450 m due north of site 11) during





Figure 6. Minimum period benzene concentrations vs average temperature



period 27 which also possessed the lowest vector wind speed for the study, indicative of poor net transport conditions. Background correction for ambient air benzene levels can be helpful in

comparing relative PS concentrations among sites and across sampling periods. In subsequent discussion, the recorded minimum concentration for each sampling period is assigned as ambient benzene background value and is subtracted from the measured benzene concentrations at the remaining sites.

Figure 7. PS benzene data by site, combining all sampling periods. The box whiskers extend to the largest measurement < 1.5 times the interquartile range (IQR). Blue markers indicate means with 95 % confidence intervals calculated by non-parametric bootstrap.



Figure 7 summarizes atmospheric benzene background-corrected PS concentration data across all periods by sampling location. It is evident that the in-community sites (1, 2, 15-17) show consistently low benzene concentrations in comparison to the near-facility sites (7-11), Figure 1B. It is important to point out that although a local source of benzene is indicated at the nearfacility sites, the identity of the source(s) cannot be easily assigned. Sites 7-11 are close to a facility fence line (30 m to 40 m), a road way (26th Street) with significant traffic volume, and other potential industrial sources. By comparing the benzene values obtained at sites 7-11 to other sites, additional information on nearby sources can be potentially elucidated. Sites 12 and 6 are located ≈ 450 m to the north and south, respectively of sites 7 and 11, along the same section of 26th Street, which should, due to the lack of roadway exits, possess very similar traffic volume. Sites 6 through 12 are also similar distances to the neighboring facility fence line, although they are located adjacent to different parts of the facility. The lower benzene values at site 6 and at other sites located very near major roadways (e.g. sites 13, 14) would indicate that mobile source-generated benzene signal is likely not the most significant contributing factor for elevated readings at sites 7-11. The potential contributions of mobile source signal to the 7-11 group can be further investigated by looking at trends in other compounds measured on the PS, particularly the combustion-related compound 1,3 butadiene. Additional information on these comparisons should be available for presentation at the conference.

Although sites 7-11 are in relatively close proximity to each other (within 240 m) they show somewhat different responses. Sites 8 and 9 have similar medians, the largest mean values and are physically the closest together, at \approx 13 m apart. Sites 8 and 9 perhaps also have the least amount of nearby wind flow obstruction in the fence line group. It is important to note that the trees directly behind sites 6-12 likely affect wind flow and therefore registered concentrations in complex ways. This could include channeling of signal along 26th Street or urban canyon-like effects that could increase or decrease concentrations compared to the optimal free-flowing case. As shown in Figure 1B, sites 4 and 5 are due east of the 7-11 group and show elevated but decreasing concentrations as would be expected from a source to the west under the observed average transport (Supplemental Table 1). When considering this gradient, the signal at sites 4 and 5 are likely also affected by the trees and topography that separate these locations from the 7-11 group.

Figures 8A and 8B summarize PS benzene concentrations for subgroups formed by the in-community sites and fence line sites by sampling period. With period means typically less than 0.1 ppby, the incommunity sites show relatively small departures from the minimum registered period concentration that serves as the ambient benzene background correction factor (Figure 5). This relatively consistent behavior in the in-community site concentrations is indicative of a somewhat uniform air sheds with the general lack of strong proximate benzene sources. The period to period variability in PS benzene concentrations for the fence line group (Figure 8B) is pronounced in comparison (note order of magnitude scale change). It is likely the case that a portion of this variability is due to changes in nearby source emissions and part is due to changes in atmospheric conditions over time but it is clear that local sources are present.

Figure 9(A) further investigates this point by presenting PS concentration data by site as a function of distance from the nearest





facility fence line. Three regimes are evident with sites 6-12 within 50 m of the fence line, sites 13, 4, 3, 5, and 14 between 150 m and 750 m from the fence line and the in-community sites at distances exceeding 1 km. A general gradient in concentrations is evident with sites 1 and 2 on the predominately upwind side and 13 and 14 with positions offset to the north showing somewhat lower response as may be expected under an overall result wind vector, -0.2 m/s north, 1.1 m/s east (Supplemental Table 1).

From Figure 9B, the sites 7-11(average), 4, 5 and 16 define a due east gradient which is explored in a preliminary fashion in Figure 9(B). Here the gradient in PS concentrations is fitted to a simple power law expression and compared to normalized concentration gradients that would be produced from a single ground level source, due west, at 200 m and 300 m inside of the fence line under Pasquill-Gifford atmospheric stability classes¹⁴ A and C respectively, using the simple Gaussian dispersion equation [concentration = $Q^*/\pi u\sigma_y\sigma_z$,] with u equal to the easterly component of the mean wind vector (1.1 m/s) and the source emission rate (Q*) set to match the measured average concentration at the 7-11 site, 36.6 m east of the fence line.





In Figure 9 the PS data are combined across all 28 periods and the error bars represent 95% confidence intervals in the mean calculated by non-parametric bootstrap. This is indeed a very large combination of measurements, atmospheric conditions, and likely local source strengths. It is interesting that this broad combination could produce a fairly reasonable concentration gradient, under simple assumptions of the sources to the west. It is hoped that the conference presentation associated with this interim report will contain further analysis in this regard by looking at the transport characteristics of individual sampling periods.

Example of SAM Data:

Although PS data can provide a cost-effective means to investigate average benzene concentrations around facilities and in local air sheds, the time-integrated nature of the sampling limits source attribution power. As part of the EPA NGAM research program, a growing number of lower cost custom-built and commercially available SAM systems are being investigated that use new air pollutant and wind measurement sensors and data analysis approaches. These next generation systems can effectively support PS deployments by providing

additional information on the origin of source emissions in areas where consistently high PS readings are observed.

In addition to PSs, the South Philadelphia project includes deployments of lower-cost prototype SAM systems built by EPA ORD and an AMS-deployed open-path ultra violet differential optical absorption spectroscopy system capable of time-resolved speciated measurements of benzene and other compounds (with minimum detection limits currently estimated at \approx 5ppbv). The AMS system is located to the north of PS sites 4 and 5, in close proximity to (directly south of) the heavily-traveled Schuylkill Expressway (Figure 1B) and will be described in future reports. Preliminary data from AMS indicates very few (if any) confirmed detections of benzene. This finding would seem to agree with the generally low (sub ppbv) benzene concentrations at sites 4 and 5.

The EPA prototype SENTINEL and SPod systems (Figure 2), along with preliminary data analysis approaches, are detailed in a separate presentation.¹³ A brief example of time-resolved data from a first prototype SPod system during an eight-hour period in late October, 2013 is provided in Figure 10. This early system operated at a 1 Hz measurement rate and produced an un-calibrated measure of volatile organic compounds (VOCs), including benzene, using a passive 10.6 eV PID sensor, time-synchronized with a wind direction measurement from a 3-D sonic anemometer. In Figure 10(A), the SPod signal (blue trace, left ordinate) is offset by 0.1 V for ease of viewing. The direction from which the wind was blowing is indicated by the dashed line (right ordinate). Winds from due north are from 360° with increasing values indicating winds from east of north. Here the 1 Hz data are expressed as a moving five minute average. By visual inspection, there is an apparent wellcorrelated increase in the SPod signal above baseline as the wind direction moves into and through the shaded





region ($\approx 310^{\circ}$ to 340°). A rudimentary back trajectory projection of the shaded region in Figure 10(A) defines the yellow lines of Figure 10(B) indicating the likely direction of the origin of emissions. By providing real time information on potential source locations, low cost SAM systems, like the "drop-in-place" SPod may in the future support time-integrated PS approaches.

SUMMARY

The South Philadelphia Passive Sampler and Sensor study is a collaborative research project investigating how PSs and SAM systems can help improve information on air pollutant concentrations in areas with many potential sources. In addition to a project overview and meteorological summary, preliminary analysis of PS benzene data from June 2013 through September 2014 and a brief example of SAM data are provided. Analysis of co-deployed duplicate pairs for the current study, in conjunction with results from the EPA Regional sister study, indicate relatively robust precision performance for the utilized PSs. Although the effects of metrological variables on PS data are still being explored, preliminary data suggests a negative correlation between the period minimum benzene concentrations and average temperature. Although no definite source attribution is offered, benzene concentrations for PS located in proximity to facility fence lines are consistently elevated by 1-2 ppbv in comparison to distant, in-community sites. An examination of prevailing wind directions (easterly) along with spatial gradients in concentration and an example of time-resolved SAM data support the notion of a benzene source to the west of sites 7-11. The conference presentation associated with this December 2014 interim report should include additional findings of interest for the study. The presentation will also explore the general advancement of NGAM technologies by the study and the potential for these systems to assist in a range of future air quality management decisions.

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KEYWORDS

Fugitive Emission, Fence line Monitoring, Sensors, Passive Samplers, Method 325A and 325B

Winds From SE (%)	21.7	7.0	20.4	16.5	12.0	8.3	7.9	7.3	6.6	2.1	7.5	2.8	4.9	3.8	8.8	6.7	10.5	15.1	12.5	18.0	9.0	15.5	27.5	12.8	13.2	24.7	17.2	16.7	12.0	11.2	9.9	2.1
Winds From NE (%)	5.6	18.6	10.2	7.6	13.6	4.4	18.2	3.5	20.6	22.6	14.4	8.1	15.7	22.7	19.9	25.3	23.8	20.3	21.5	22.7	12.8	22.9	10.4	7.6	12.6	10.2	20.1	19.9	15.6	17.0	9.9	3.5
Winds From NW (%)	6.8	16.3	34.7	24.7	24.5	46.3	26.8	37.2	32.1	34.8	23.3	43.4	40.4	33.7	37.8	42.4	39.0	24.4	44.2	29.4	25.4	33.1	19.9	22.1	34.0	31.1	28.9	21.3	30.6	31.6	9.3	6.8
Winds From SW (%)	52.9	53.8	25.1	38.8	41.6	31.9	32.1	43.9	22.5	30.7	42.1	40.0	27.6	31.7	24.9	21.5	21.5	31.7	19.2	23.5	43.7	21.4	36.0	54.9	33.6	25.9	23.9	37.1	33.3	31.8	10.4	19.2
Lulls (%)	13.0	4.4	9.6	12.5	8.2	9.1	15.0	8.1	18.1	9.8	12.7	5.6	11.3	8.1	8.5	4.1	5.2	8.4	2.6	6.4	0.6	7.0	6.3	2.6	6.6	8.1	6.6	5.0	8.4	8.2	3.6	2.6
Resultant Wind Vector (east)	1.0	1.2	6.0	1.0	6.0	12	1.4	2.7	13	1.5	1.9	2.8	1.1	1.7	1.0	1.6	6.0	0.7	1.1	0.4	1.0	0.4	9.0	1.7	0.9	0.2	0.4	0.4	1.1	1.0	0.6	0.2
Kesultant Wind Vector (north)	1.6	0.7	0.0	0.5	0.3	-0.7	-0.2	0.0	-0.8	-1.2	0.3	-0.7	-1.2	-1.0	-13	-15	-1.4	0.5	-13	0.2	0.2	-0.4	1.1	1.3	0.0	0.2	-0.1	0.2	-0.2	0.0	0.9	-1.5
Vector Wind Speed (m/s)	1.9	1.4	6.0	1.2	6.0	1.4	1.4	2.7	1.5	1.9	1.9	2.9	1.7	1.9	1.7	22	1.7	0.8	1.7	0.4	1.0	9.0	13	22	0.9	0.3	0.5	0.5	1.4	1.4	0.7	0.3
Scalar Wind Speed (m/s)	3.0	3.7	33	2.9	33	33	3.6	4.4	3.5	4.0	3.9	4.9	3.2	4.4	3.9	5.4	4.9	4.7	4.9	3.7	3.4	3.4	3.4	4.4	3.6	3.1	3.0	3.6	3.8	3.6	0.7	2.9
Total Rainfall (cm)	8.9	11.8	24.4	6.2	10.2	3.5	0.8	0.6	5.9	8.8	9.4	0.9	7.1	5.8	1.2	2.8	<mark>8.3</mark>	1.9	13.8	4.3	2.8	10.7	3.8	5.9	4.4	4.6	1.5	3.3	6.2	5.2	5.1	0.6
Relative Humidity (%)	69.5	66.7	64.2	66.0	66.0	62.7	59.1	53.7	56.5	68.4	64.9	53.9	58.1	59.9	49.1	47.1	59.0	49.7	48.8	60.8	60.2	62.2	58.3	59.4	58.4	64.7	64.3	66.7	59.9	60.1	6.2	47.1
Temprature (°C)	24.3	28.4	23.2	23.8	23.5	18.5	10.9	0.6	4.5	1.9	2.9	-3.7	-2.0	1.5	0.5	4.3	8.6	13.3	14.0	18.5	19.8	22.9	25.1	25.8	24.1	23.8	23.1	24.5	14.8	18.5	10.2	-3.7
Atmos. Pressure (mbar)	1014.4	1015.8	1016.0	1018.1	1016.4	1017.3	1020.4	1021.4	1023.7	1021.3	1019.3	1014.7	1023.9	1015.7	1019.2	1015.4	1015.2	1019.9	1014.0	1019.3	1017.2	1013.8	1016.4	1015.0	1015.8	1017.6	1015.5	1018.5	1017.5	1016.8	2.8	1013.8
Period Mid-point (mm/dd/yy)	06/24/13	07/16/13	07/30/13	08/14/13	08/31/13	09/17/13	10/29/13	11/12/13	11/27/13	12/11/13	01/02/14	01/22/14	02/04/14	02/18/14	03/04/14	03/18//14	04/01/14	04/15/14	04/29/14	05/13/14	05/27/14	06/10/14	06/25/14	07/09/14	07/23/14	08/05/14	08/19/14	09/02/14	N/A	N/A	N/A	N/A
Sampling Period Number	1	5	3	4	5	9	8	6	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	Average	Median	StdDev.	Minimum

Supplemental Table 1: Sampling period numbers, mid-point dates, and average meteorological conditions