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Measurement System Evaluation for Upwind/Downwind Sampling of Fugitive Dust Emissions

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ABSTRACT

Eight different PM_{10} samplers with various size-selective inlets and sample flow rates were evaluated for upwind/downwind assessment of fugitive dust emissions from two sand and gravel operations in southern California during September through October 2008. Continuous data were acquired at one-minute intervals for 24 hours each day. Integrated filters were acquired at five-hour intervals between 1100 and 1600 PDT on each day because winds were most consistent during this period. High-volume (hivol) size-selective inlet (SSI) PM_{10} Federal Reference Method (FRM) filter samplers were comparable to each other during side-by-side sampling, even under high dust loading conditions. Based on linear regression slope, the BGI low-volume (lovol) PQ200 FRM measured ~18% lower PM_{10} levels than a nearby hivol SSI in the source-dominated environment, even though tests in ambient environments show they are equivalent. Although the TSI DustTrak DRX PM_{10} concentrations did not equal those from the hivol SSI, both instruments were highly correlated ($R = 0.9$) at the two downwind sites. Multiple size ranges from the TSI DustTrak DRX and Grimm optical particle counters (OPC) allowed the identification of spatial non-uniformity for sources within and outside the facilities. Narrow dust plumes were only detected by some of the continuous instruments across the sampler array. Upwind PM_{10} concentrations at one of the locations were higher than the downwind concentrations owing to a high concentration of industrial and vehicular activities. The shorter-duration measurements and quantification of super-coarse (> 10 µm) particles with high deposition velocities available from optical particle counters is needed to evaluate the effects of local emissions on both upwind and downwind samples.

Keywords: Fugitive dust; Upwind/Downwind sampling; Fence line; Sand/Gravel operations; PM_{10}.

INTRODUCTION

Upwind/downwind sampling of total suspended particles (TSP) and particles with aerodynamic diameters < 10 µm (PM_{10}) has long been used to detect and quantify fugitive dust emissions from area sources such as unpaved roads, construction sites, mining and quarrying operations, and aggregate processing (Kinsey and Cowherd, 1992; Chow and Watson, 1992; Chow *et al.*, 1999; Gillies *et al.*, 1999; Watson *et al.*, 2000; Watson and Chow, 2000; Countess *et al.*, 2001; Cowherd, 2001). In this approach, particulate matter (PM) samplers (Chow, 1995; Watson and Chow, 2011) are located on the upwind side of a facility to quantify the PM flux entering the property. These upwind concentrations are subtracted from those measured at downwind samplers to estimate the incremental PM contributed by industrial activities. This method has been incorporated into regulations at the South Coast Air Quality Management District (SCAQMD) in southern California. SCAQMD (2005) states:

> *No person shall cause or allow PM_{10} levels to exceed 50 micrograms per cubic meter when determined, by simultaneous sampling, as the difference between upwind and downwind samples collected on high-volume particulate matter samplers [hivol] or other U.S. EPA-approved equivalent method for PM_{10} monitoring.*

While simple in concept, quantitative applications of

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upwind/downwind studies to estimate incremental emissions are costly and difficult to accurately implement. Wind-direction shifts may occur over the several hours required for integrated filter sampling, thereby obscuring the upwind or downwind designation of the monitoring sites. PM_{10} consists of many particle sizes with different deposition velocities (McMahon and Denison, 1979; Sehmel, 1980) that can cause large gradients in downwind concentration with distance from the emitters. Short-duration emissions of large particles from a nearby source within or outside the facility may dominate the integrated PM concentration (Watson and Chow, 2002), while PM concentrations reduce exponentially with increased distance from fugitive dust sources (Lee *et al.*, 2001; Tsai and Chang, 2002; Chang, 2004, 2006; Chang *et al.*, 2010). Although the hivol size-selective inlet (SSI) sampler is a U.S. EPA Federal Reference Method (FRM) for TSP and PM_{10} (U.S. EPA, 2011), it requires a large footprint and line power, making it difficult to locate in appropriate sampling sites. FRMs or Federal Equivalent Methods (FEMs) are required only for determining compliance with U.S. National Ambient Air Quality Standards (NAAQS; Bachmann, 2007; Chow *et al.*, 2007b; Chow and Watson, 2008).

The objectives of this study (Watson *et al.*, 2010) are to identify and characterize ambient air PM_{10} monitoring instruments and meteorological monitoring systems that can be effectively and economically applied for fence-line monitoring to estimate incremental PM_{10} concentrations contributed by facilities that generate fugitive dust.

Since sampling methods, siting criteria, and sampling durations for upwind/downwind monitoring are not subject to NAAQS compliance requirements (U.S. EPA, 1997; Chow *et al.*, 2002;), non-compliance alternatives can be considered. Upwind/downwind measurements should: 1) be rapidly deployable (light, durable, and self powered); 2) meet requirements for siting and security; 3) provide short-term average PM_{10} data that can be analyzed with respect to short-term average wind direction data; 4) capture PM_{10} mass loadings comparable (but not necessarily equivalent) to those from PM_{10} FRMs; and 5) have reasonable initial and operating costs.

EXPERIMENTAL PROCEDURES

Upwind/downwind sampling was conducted at two southern California aggregate processing operations (Facilities A and B) to evaluate the eight PM_{10} monitoring instruments and two meteorological systems described in Table 1. Figs. 1 and 2 show the locations of the sampling sites at the two facilities, which are similar to hundreds of sand and gravel operations throughout the world (Richards and Palm, 2000; Lee *et al.*, 2001; Shiraki and Holmen, 2002; Chang, 2006; Trzepla-Nabaglo *et al.*, 2006; Semple *et al.*, 2008; Pimonsree *et al.*, 2009; Richards *et al.*, 2009; Chang *et al.*, 2010) that support asphalt and concrete construction projects.

To avoid the autumn rain storms, the study was conducted during the September through October 2008 period. Since the samplers were operated unattended (except for daily maintenance and sample changing), it was necessary to locate the sampling sites within the property boundaries. The site selection is primarily based on the prevailing wind direction at each facility and the availability of space, power, and security within the fence line. Monitors were closer to dust-generating activities than would be the case for a test conducted outside the fence line. Therefore, fugitive dust source contributions and PM_{10} levels for this study are expected to be higher than concentrations outside of the fence line.

Downwind Site A-1 (Fig. 1) was located on a concrete pad near the northeast fence line. An unpaved turnout was just southwest of the pad which was blocked from traffic during the study. A truck wash station on the main paved road through the facility was within 10 m south of the site. The paved road within the facility carried heavy-duty truck traffic during weekdays and was swept regularly with a vacuum sweeper. Conveyors and storage piles were 10 to 30 m southeast of the site. A heavily-travelled interstate highway was within 100 m to the east, while a flood control area was located to the north.

Upwind Site A-2 was located on a graded area ~400 m to the southwest of Site A-1, just inside the fence line at the southwest corner of the facility, which is at the northeast corner of two heavily-travelled paved roads. The southern boundary road was being repaired to the west of this corner during the study. The main raw material conveyor was immediately (< 3 m) to the north of the monitors. Intense diesel truck traffic was observed throughout the sampling period along the boundary roads. A construction material dump site was in operation within a spent gravel pit on the south side of the southern boundary road.

Downwind Site B-1 (Fig. 2) was located on a concrete patio west of the employee lunchroom and weigh station. Dust was cleaned from the patio and nearby areas prior to locating the samplers. The truck scales were located within 5 m south of the monitors and experienced heavy diesel traffic. Employee cars were parked to the immediate north and west of the patio. The area to the north was flat and unpaved, but regularly watered. This area was frequently traversed by large (75 ton haul) trucks and maintenance vehicles within 5 to 25 m north of the samplers. Loading, dumping, and grading took place ~30 m northeast of the monitors.

Upwind Site B-2 was located in a large sandy plain ~160 m to the southwest of Site B-1. Monitors were within 400 m of an interstate highway to the southeast and south. Heavy truck traffic on unpaved surfaces near the site was occasional, but increased near the end of the measurement period when a storage pile ~50 m east of the site was being moved to another location.

PM_{10} inlets were located 2 m above ground level (agl) and at least 2 m from each other to avoid cross-interference in sampling from the same intake air flow. Even so, samplers were at different distances from nearby sources which might affect their particle collection. Anemometers and wind vanes were installed on masts

Table 1. PM and meteorological monitors used in upwind/downwind sampling.

System/Manufacturer (Number of units used) (Reference)	Description (website)	Specifications
General Metal Works (now Tisch Environmental, Cincinnati, OH, USA) HIVOL-SSI FRM (hivol) (Two units) (Ecotech, 2011; Thermo Scientific, 2011; Tisch, 2011; Watson and Chow, 2011) 	• PM_{10} FRM sampler draws air into a G1200 inlet (anodized spun aluminum with a single stage of opposing jet) at 1133 L/min with a cut point of 9.7 ± 1.5 µm • A carbon-vane blower is used to pull air through a 20.32 × 25.4 cm QMA (Whatman Clifton, NJ, USA) quartz-fiber filter • The inlet housing consists of a clamshell that can be opened to grease and clean the impaction plate • The sampler is switched on and off with a timer http://www.tisch-env.com/	• Weight: ~40 kg • Dimensions[a]: 38 × 48 × 107 • Operates at 110V AC line power at ~8 amps (a portable generator is used for sampling at remote locations) • A platform on leg extensions is needed to place the inlet 2 m above ground level (agl)
BGI PQ200 Air Sampler (lovol; Waltham, MA, USA) (One unit) (Tolocka *et al.*, 2001; Kenny *et al.*, 2005) 	• BGI FRM louvered PM_{10} inlet; machined aluminum with one impactor tube and three vertical elutriator tubes • Modification of flat top SA-246 inlet with a top that curves over the inlet bug screen to minimize interference from wind-blown raindrops • Operated at 16.7 L/min with a cut point of 10 ± 1.4 µm (BGI 16 inlet) • Samples onto 47 mm ringed Teflon-membrane filter (Pall Life Sciences, Port Washington, NY, USA) • Uses a built-in computer to set up sample start and stop times and data acquisition system http://www.bgiusa.com/	• Weight: ~30 kg • Dimensions[a]: 41 × 48 × 46 • Operates on 110V AC line power or built-in rechargeable 12V batteries • Used as a portable audit sampling system for $PM_{2.5}$ NAAQS
BGI OMNI Ambient Air Sampler (minivol; Waltham, MA, USA) (Two units) (BGI, 2011) 	• Uses BGI 5 minivol stainless steel impactor preceded by BGI 16 louvered PM_{10} inlet • Operated at 5 L/min with a cut point of 10 ± 1.4 µm • Uses a built-in computer to set up sample start and stop times and data acquisition system • Uses a low-volume dual-diaphragm pump http://www.bgiusa.com/	• Weight: 4.08 kg • Dimensions[a] 17.8 × 14.6 × 21.6 • Operates on 110V AC or built-in rechargeable 12V batteries • Can be mounted on power poles, fence posts, rooftops, and tripods
Met One E-BAM with built-in mechanical weather station (Grants Pass, OR, USA) (One unit) (MetOne, 2011a) 	• BAMs draw air through a louvered PM_{10} FRM inlet at 16.7 L/min then through a glass-fiber filter tape • A radioactive source (low-level C^{14}) generates a stream of electrons (beta rays) through the sample spot as the particle deposit accumulates • As the filter spots load up, the penetrated electron count decreases proportionally to the sample loading • Filter tape advances as it reaches selected mass loadings (E-BAM uses a scintillation probe detector) • Uses a dual-diaphragm pump • Optional wind sensors can be installed at 1 m above ground level (agl) http://www.Met One.com/	• Weight: 13 kg • Dimensions[a]: 41 × 36 × 20 • Powered by a 12V DC, 4 amp power supply or battery • Serial output

Table 1. *(continued).*

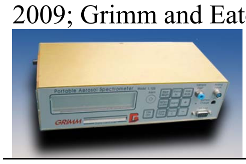
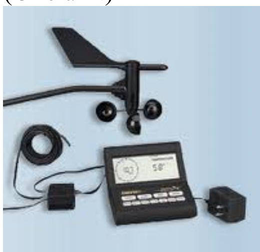
System/Manufacturer (Number of units used) (Reference)	Description (website)	Specifications
Met One E-Sampler (Grants Pass, OR, USA) (Two units) (Varma *et al.*, 2003; MetOne, 2011b) 	• The E-Sampler consists of a nephelometer with an unexposed 47 mm diameter filter drawing air at 2 L/min through an impaction inlet using an internal rotating vane • A forward light-scattering device with sensitivity of 1 µg/m^3 • Sampled air is drawn into a detection zone where it is illuminated by a collimated laser diode source, and the scattered light is detected at a specific angle relative to the light source is related to PM concentrations • Uses an automatic flow control by diaphragm pump with LCD • The filter can be weighed; based on the sample volume, gravimetric mass concentrations are calculated and used as the K-factor to normalize the light scattering signal over the filter sampling period • The manufacturer's default K-factor is 10 for mass concentrations ranging 0–65 mg/m^3 http://www.Met One.com/	• Weight: 14 kg • Dimensions[a]: 26.7 × 23.5 × 14.5 • Powered by 110V AC or 12V rechargeable battery. Runs for 30 hours on battery without heater or 10 hours with heater • Serial output
TSI Model 8520 DustTrak (Shoreview, MN, USA) (Four units) (Kuhns *et al.*, 2001; Kuhns *et al.*, 2005; Etyemezian *et al.*, 2006; Gillies *et al.*, 2007) 	• A light-scattering nephelometer using a long-wavelength laser (λ = 780 nm) calibrated with Arizona road dust • Air is sampled through a PM_{10} inlet at 1.7 L/min, providing output in mg/m^3 • Model 8520 output can be normalized to simultaneous PM_{10} concentrations collected on filters http://www.tsi.com/en-1033/index.aspx	• Weight: 1.5 kg • Dimensions[a]: 22.1 × 15 × 8.7 • Powered by four alkaline C cell batteries or a 6V DC 0.3 amp external power supply • Serial output
TSI Model 8533 DustTrak DRX aerosol monitor (Shoreview, MN, USA) (One unit) (TSI, 2009; Wang *et al.*, 2009) 	• Combines a light-scattering nephelometer (λ = 655 nm) for $PM_{2.5}$ and an OPC for sizing particles 0.5–15 µm, operated at 3 L/min, yielding mass readings in mg/m^3 for PM_1, $PM_{2.5}$, PM_4, PM_{10}, and TSP (> ~15 µm) • Calibrated with Arizona road dust by factory default • More accurate than Model 8520 because it counts individual coarse particles with low scattering efficiencies • Measures higher concentrations than OPC because it uses the nephelometer for $PM_{2.5}$ which reduces coincidence losses for high concentrations of small particles http://www.tsi.com/en-1033/index.aspx	• Weight: 2.0 kg • Dimensions[a]: 13.5 × 21.6 × 22.4 • Powered by 24V rechargeable Lithium-Ion battery or 115–240V AC external power supply • USB and Ethernet output
Grimm 1.108 Optical Particle Counter (Ainring, Germany) (Two units) (Peters *et al.*, 2006; Heim *et al.*, 2008; Hoffmann *et al.*, 2008; Grimm, 2009; Grimm and Eatough, 2009) 	• Individual particles pass through the sensing cells, operated at 1.2 L/min, are illuminated by a λ = 795 nm diode laser with size bins from 0.3–20 µm • Mass concentrations are estimated by assuming spherical particles and uniform particle densities for each size bin, and summing the size bins up to obtain $PM_{2.5}$ or PM_{10} http://www.grimm-aerosol.com/	• Weight: 2.4 kg • Dimensions[a]: 24 × 12 × 6 • Powered by 12V rechargeable battery (9 hr) or 110/220V AC with external power supply

Table 1. *(continued).*

System/Manufacturer (Number of units used) (Reference)	Description (website)	Specifications
Davis Instruments Wind Wizard III (Hayward, CA, USA) (One unit) 	• A weather station that monitors and logs inside and outside temperature, wind direction, wind speed and wind chill. • Includes an anemometer, inside and outside temperature sensors, junction box, and console • Options include a rain collector, and WeatherLink which provides data logging and a serial interface to a computer http://www.davisnet.com/	• Weight: 1.53 kg • Dimensions[a]: Console 13.3 × 13.7 × 7.6 • Battery (9-12V) or 110V AC • Optional rechargeable batteries on solar cells
Davis Instruments Vantage Pro II (Hayward, CA, USA) (One unit) 	• A weather station that monitors and logs temperature, wind speed, wind direction, relative humidity, barometric pressure, and dewpoint • Contains an integrated sensor suite (including a rain collector, anemometer, temperature, humidity, and pressure sensors), and a console • Transmits weather data wirelessly up to 300 m http://www.davisnet.com/	• Weight: Sensors 2.6 kg; console 0.85 kg • Dimensions[a]:console 27 × 15.6 × 4.1 • Sensors are solar powered. Console may be powered by AC adapter or three C batteries

[a] All dimensions given are length × width × height in cm.

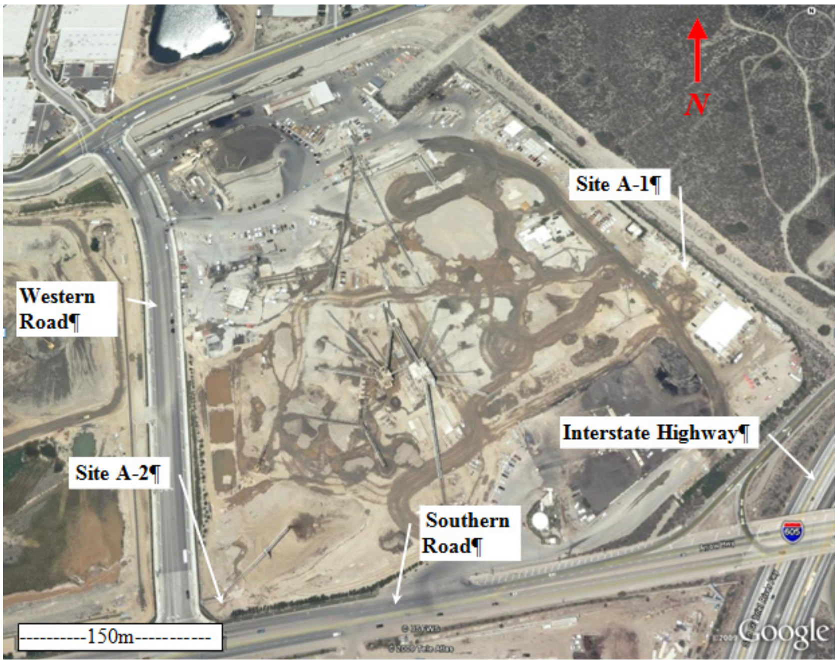


Fig. 1. Locations of sampling sites at Facility A. Site A-1 was nominally downwind and Site A-2 was nominally upwind of the sand and gravel operations (elevation 138 m above sea level [asl]). Some roadway and storage pile configurations differed from those depicted in this satellite picture that was taken at an earlier date. Sampling at Facility A was conducted during September 11–27, 2008.

secured by a tripod base at ~5 m agl to measure wind speed and wind direction, respectively. An example of site configuration for Facility A is shown in Fig. 3.

Standard Operating Procedures (SOPs) were created for each air quality and meteorological measurement system, including: 1) instrument operating principles; 2) equipment and accessory lists; 3) calibration and performance test methods and frequencies; 4) daily checklists and data sheets; 5) data acquisition and downloading instructions; 6) quality assurance (QA) and quality control (QC) instructions;

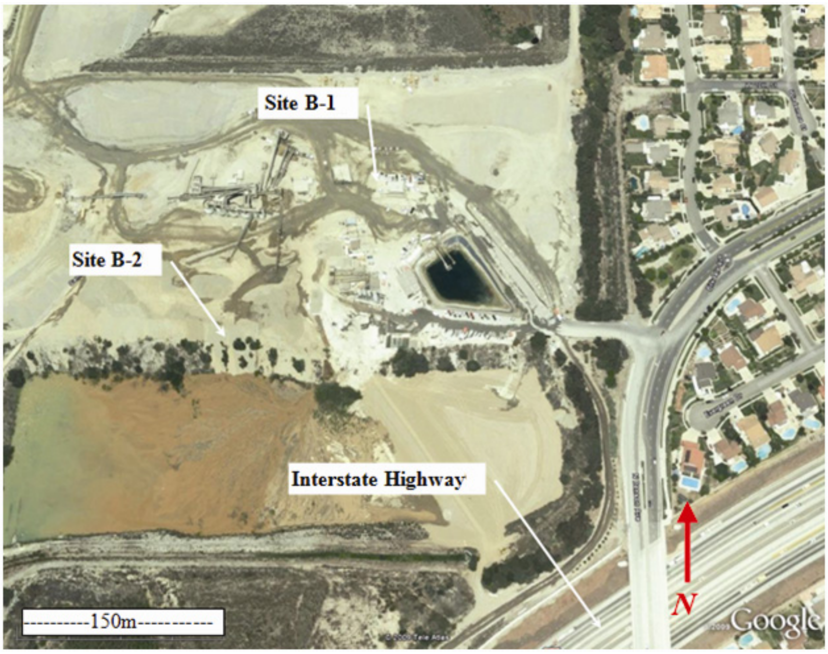


Fig. 2. Locations of sampling sites at Facility B. Site B-1 was nominally downwind and Site B-2 was nominally upwind of the sand and gravel operations (elevation 520 m above sea level [asl] for Site B-1 and 510 m asl for site B-2). Some roadway and storage pile configurations differed from those depicted in this satellite picture that was taken at an earlier date. Sampling at Facility B was conducted during October 2–20, 2008.

and 7) references to operating manuals and scientific publications. QA/QC procedures were followed to ensure the accuracy, precision, and validity of the measurements. Filters were weighed in the DRI Environmental Analysis Facility (Reno, NV) and shipped in cooled containers by overnight mail to and from the field sites before and after each study.

Five-hour duration PM_{10} hivol SSI, low-volume (lovol) PQ200, and minivol OMNI filter samples were acquired each day between 1100 and 1600 Pacific Daylight Time (PDT). The other monitors operated continuously, both during and between the filter sampling periods. Sampling periods were September 11–27, 2008 for Facility A and October 2–20, 2008 for Facility B. Site B-2 did not have line power, so a 3500 watt generator was installed ~10 m downwind of the monitors. Only the hivol SSI required 110 V AC line power, so the generator was filled with gasoline (~15 liter capacity for 12–15 hrs operation as indicated by an AC clock) and started each morning at ~0930 PDT to set the hivol SSI timer and check the flows. The hivol SSI timer was apparently tied to the 60 cycle line current, which was not precisely maintained by the generator. As a result, sample start and stop times at Site B-2 could deviate from the set points by up to 20 minutes. The generator also powered a 12 V charger connected to two deep cycle 12 V batteries in parallel. The minivol OMNI, E-BAM, E-Sampler, and optical particle counter (OPC) were connected to these batteries so they could operate continuously after the generator shut down. The four DustTraks were powered by internal batteries.

Size-selective inlets operated at 1.2–1130 L/min flow rates were cleaned before and after monitoring at each facility. They accumulated moderate amounts of dust on the impaction plates after ~2 weeks of sampling. The meteorological instruments also acquired substantial dust loadings due to deposition at all sites, and these were disassembled and cleaned before and after each of the sampling periods. Flow rates were calibrated and verified against transfer standards, and deviations from the standard were less than ± 2%.

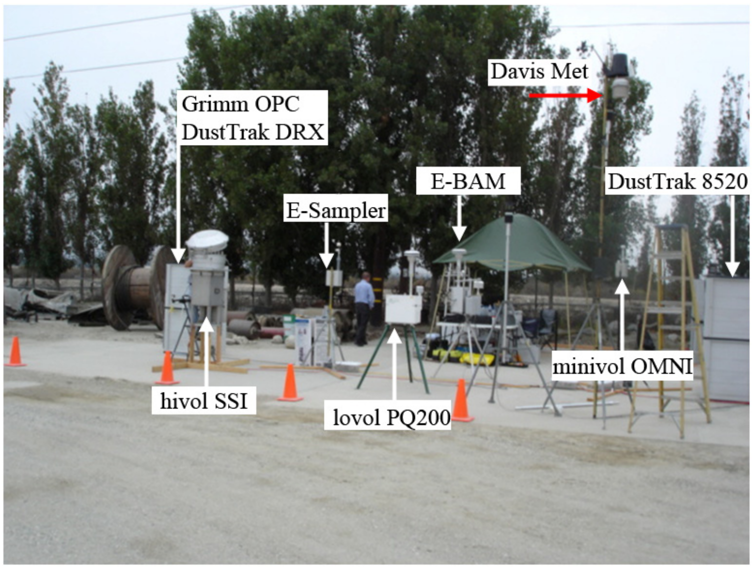
A special study was conducted on September 25 and 26, 2008 to evaluate fugitive dust impacts without normal pollution controls. The roadway was left unswept, watering systems were turned off, material was lifted from and dumped into storage piles, and trucks were run along the unpaved turnout just south of monitors at Site A-1. PM spatial inhomogeneities and rapid changes (~ every 10 sec) are evident in photographs of visible plumes from these studies in the supplemental data (Fig. S-5).

RESULTS

Same-Sampler Comparisons

Previous PM_{10} comparison studies (Rodes *et al.*, 1985a, b; McFarland and Ortiz, 1985; Sweitzer, 1985; Wedding *et al.*, 1985a, b; Purdue *et al.*, 1986; Mathai *et al.*, 1990; Gertler *et al.*, 1993; Chow, 1995; Tsai, 1995; Tsai and Cheng, 1996; Allen *et al.*, 1997; Hopke *et al.*, 1997; Magliano *et al.*, 1999; Heal *et al.*, 2000; Ono *et al.*, 2000; Williams *et al.*, 2000; Lane *et al.*, 2001; Noack *et al.*, 2001; Motallebi *et al.*, 2003; Price *et al.*, 2003; Salminen and Karlsson, 2003; Charron *et al.*, 2004; Hitzenberger *et al.*, 2004; Muller *et al.*, 2004; Chow *et al.*, 2006; Kingham *et al.*, 2006; Buser *et al.*, 2008; Cheng, 2008; Grimm and

(a)



(b)

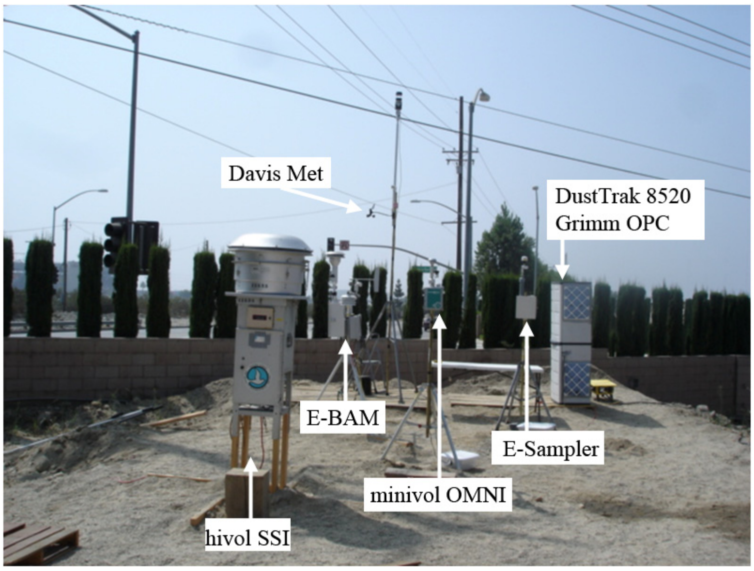


Fig. 3. Example of: a) downwind (Site A-1), and b) upwind (Site A-2) equipment layout.

Eatough, 2009; Guo *et al.*, 2009; Park *et al.*, 2009) show mixed results with high comparability in laboratory tests and in ambient environments with non-volatile aerosols and minimal levels of coarse particles (i.e., $PM_{10–2.5}$). Moderate to low comparability was found in source-oriented environments with large spatial gradients, large coarse particle ($PM_{10–2.5}$) fractions, and/or high levels of semi-volatile aerosol components. Since many ambient size distributions containing fugitive dust peak at ~10 µm (Lundgren *et al.*, 1984; Burton and Lundgren, 1987), even small differences in the PM_{10} sampling effectiveness can have a large effect on the collected mass (Watson *et al.*, 1983; Wedding and Carney, 1983; Lundgren and Burton, 1995).

Samplers were operated side-by-side from September 8–10, 2008 at Site A-1 and from October 23–30, 2008 at Site B-1 with the intent to characterize the sampling array rather than to determine collocated precision (Mathai *et al.*, 1990) as done in the formal intercomparison studies cited above. Owing to limited equipment availability and reliability, a sufficient number of paired samples was only available for the hivol SSIs, minivol OMNIs, E-Samplers, and DustTraks. Within the limited space available, the sampling array was confined within a 20 m × 20 m sampling platform. The two hivol SSI were in the south, the minivol OMNI in the middle, the E-samplers to the east, and the DustTrak samplers to the north.

Fig. 4 compares PM_{10} concentrations from similar instruments. On average, the two filter samplers (i.e., hivol SSI operated at 1130 L/min and minivol OMNI operated at 5 L/min) returned similar results, with slopes close to unity (0.96–1). There is more scatter in the minivol OMNI than hivol SSI data, as reflected in the lower correlation coefficient (R = 0.82 in Fig. 4(b)). Based on propagating the precisions of replicate filter weights and flow rate of the five-hour measurements (Watson *et al.*, 2001a), precisions were ± 3 µg/m^3 and ± 8 µg/m^3 for hivol SSI and minivol OMNI PM_{10}, respectively. Most of the values were within three precision intervals, but lower minivol OMNI precisions for these short-duration samples resulted in a lower correlation. The two largest deviations were found at high concentrations; PM_{10} concentrations differed by 14 µg/m^3 and 25 µg/m^3 on October 23 and October 27, 2008, respectively. The downwind B-1 Site was adjacent to the weigh station, therefore local traffic with loaded trucks and variations of wind may have resulted in narrow dust plumes that contributed to the inhomogeneity across the sampling array.

E-Samplers were more comparable when the nephelometer output was normalized to the multi-day filter mass (Fig. 4(d)), as indicated by the near-unity slopes (0.94) and improved correlation (R = 0.94). The factory nephelometer calibrations, using a K-factor of 10 (Fig. 4(c)) yield a lower slope (0.71) and lower PM_{10} concentrations, but they are reasonably correlated (R = 0.91). K-factors found during the experiment ranged from 15 to 36 by comparing nephelometer output with weekly filter samples. E-Sampler PM_{10} concentrations were < 50% of those measured by the hivol SSI and minivol OMNI filter samplers, consistent with the lower sensitivities of nephelometers to larger particles in the $PM_{10-2.5}$ fraction (Watson, 2002; Wang *et al.*, 2009).

TSI Model 8520 DustTrak nephelometers were compared under two different situations in Figs. 4(e) and 4(f). In each case the two DustTraks were located in weather-protected cabinets at opposite ends of the sampler

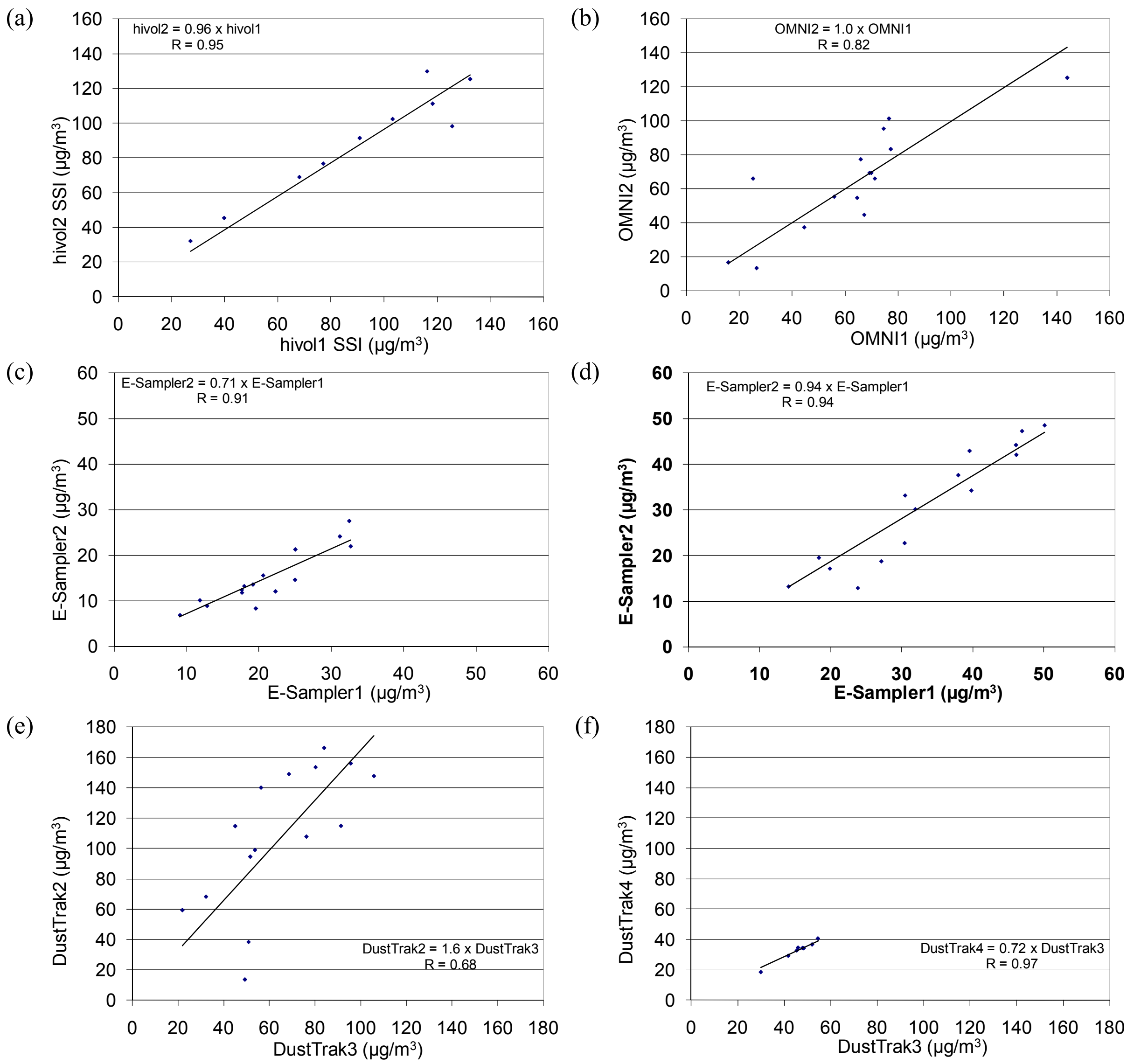


Fig. 4. Comparison of PM_{10} mass for: a) hivol SSIs, b) minivol OMNIs, c) E-Samplers with factory calibration using a K-factor of 10, d) E-Samplers normalized to multi-day filter mass measurements (e.g., based on weekly filter measurement of five-hour sampling per day), e) DustTrak Units 2 and 3 (on the west and east ends of Site A-1, respectively), and f) DustTrak Units 3 and 4 (on the east and west ends of Site B-1, respectively). Side-by-side sampling took place during September 8–10, 2008 at Site A-1 and October 23–30, 2008 at Site B-1. Trendlines are derived from unweighted ordinary linear regression with zero intercept.

array. Even though the three units had been factory re-calibrated prior to the study, and individual flow rates were adjusted with a calibrated external rotameter along with zero-span checks prior to each study, DustTrak Units 3 and 4 (Fig. 4(f)) showed a ~30% difference, similar to that for the E-Samplers (Fig. 4(c)). The results are highly correlated at Site B-1 (R = 0.97, Fig. 4(f)), even on October 23 and 27, 2008 when the hivol SSIs and minivol OMNIs showed the largest discrepancies. At Site A-1, however, the correlation between DustTrak Units 2 and 3 was low and the data are scattered (Fig. 4(e)). DustTrak Unit 2 had a much larger calibration difference with respect to DustTrak Units 3 and 4.

Inter-Sampler Comparisons

Time series of five-hour PM_{10} equivalents for each site are shown in Figs. 5 and 6. PM_{10} concentration levels and day-to-day variations are consistent with the site descriptions. Except for the September 25–26, 2008 fugitive dust generation events at Site A-1, upwind Site A-2 shows higher PM_{10} levels than any of the other sites. As shown in Fig. 5(b), over 50% of the hivol SSI FRM PM_{10} concentrations exceeded the 150 µg/m^3 NAAQS limit (note that the NAAQS is based on a 24-hour sample and these samples were five hours). The lowest PM_{10} concentrations were found on Sundays (i.e., September 14 and 21, 2008), when Facility A was inoperative and there was negligible traffic on the boundary roadways. Lower PM_{10} levels were also observed for Saturdays (i.e., September 13 and 20, 2008), when aggregate materials were picked up by customers, but minerals were not processed, with moderate traffic on the roadways.

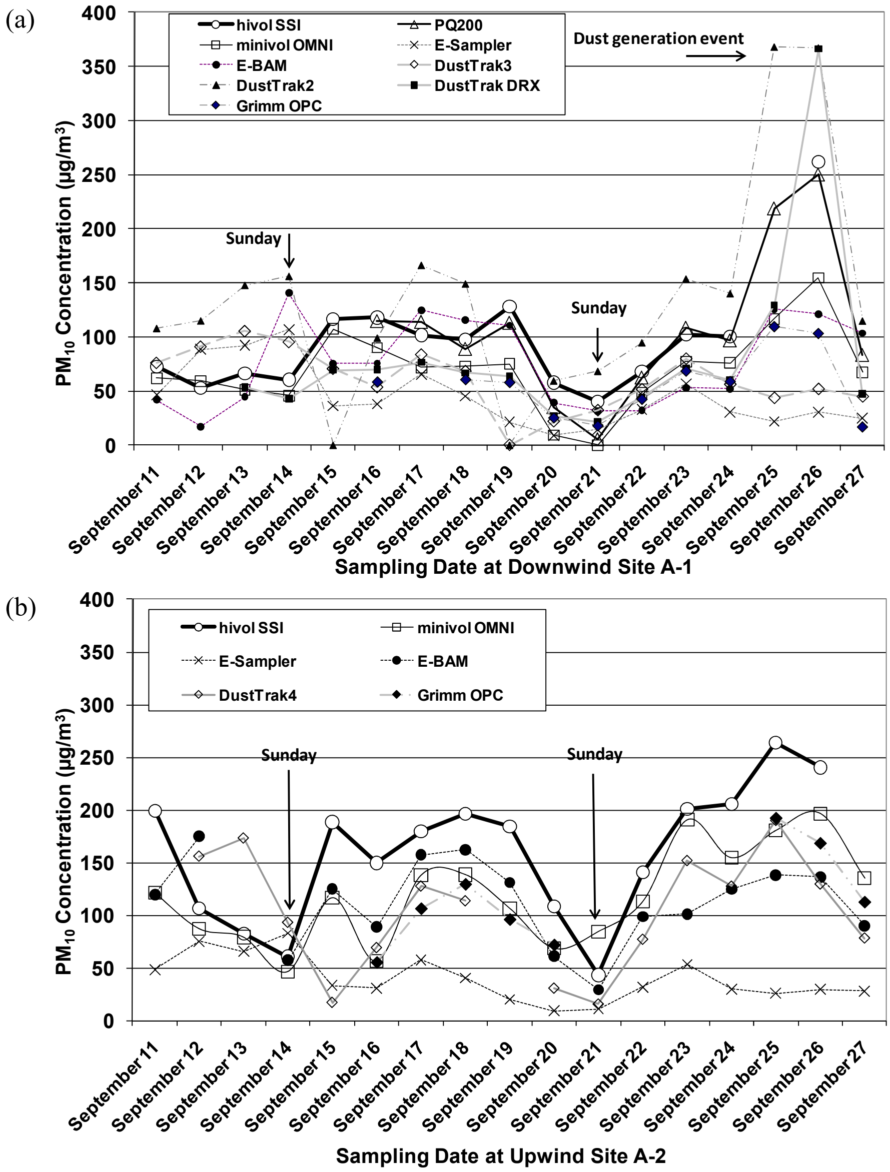


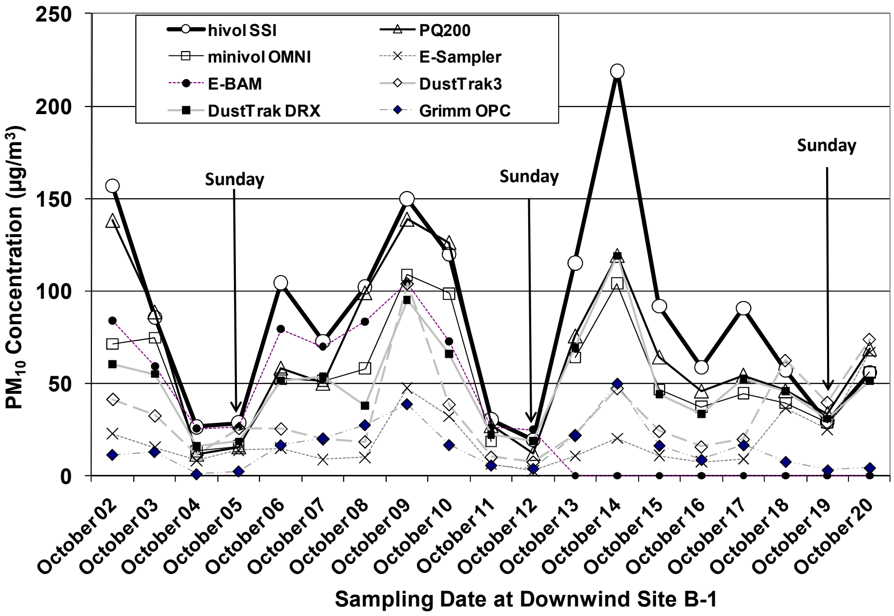
Fig. 5. Five-hour average PM_{10} concentrations for: a) downwind Site A-1, and b) upwind Site A-2 for the period from September 11–27, 2008. Fugitive dust events were simulated at Site A-1 during September 25–26, 2008 (Sundays were September 14 and 21, 2008).

Lower weekend concentrations are also evident at Site B-1 (Fig. 6), when Facility B was not in operation. Upwind Site B-2 (Fig. 6(b)) shows the lowest PM_{10} concentrations and the least day-to-day variability, consistent with its isolation from most routine activities. A few excursions are evident at this site.

PM_{10} for the E-Samplers, E-BAMs, Model 8520 DustTrak, and DustTrak DRX using factory calibrations are plotted in Figs. 5 and 6. The Grimm OPCs provided number counts in the different size bins, so PM_{10} mass was estimated by: 1) calculating particle volumes assuming spherical particles with diameters equal to the size bin specification; 2) assigning particle densities of 1.5 g/cm^3 for diameters < 3 µm and 2.5 g/cm^3 for diameters > 3 µm; and 3) summing the resulting mass estimates for all size bins up to 10 µm.

The highest PM_{10} concentrations, with the hivol SSI exceeding 250 µg/m^3, occurred at Site A-1 on September 26, 2008 during non-controlled fugitive dust studies. Model 8520 DustTrak Unit 2 was removed from the sampling array on September 25–26, 2008, and the DustTrak DRX was removed on September 26, 2008, for location within the observable plumes from the different fugitive dust generating activities. The distance from the sample array was < 20 m, yet the PM_{10} levels from these units were more than double those of most of the other samplers, consistent with the generated plumes having localized impacts. Minor wind shifts placed some samplers completely outside of the visible plume (see supplemental data for a photographic example).

(a)



(b)

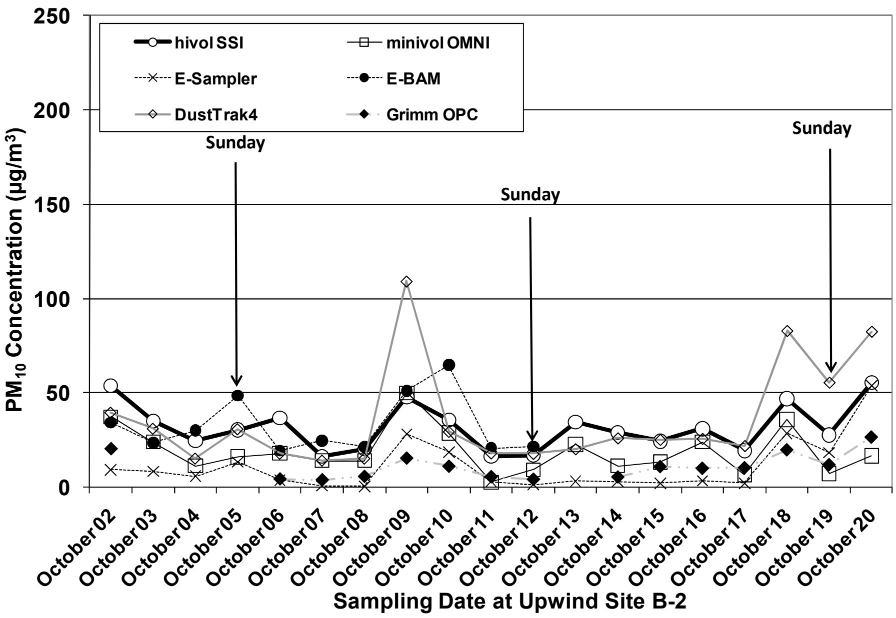


Fig. 6. Five-hour average PM_{10} concentrations for: a) downwind Site B-1, and b) upwind Site B-2 for the period from October 2–20, 2008 (Sundays were October 5, 12, and 19, 2008).

PM_{10} concentrations from different samplers rose and fell with each other (Figs. 5(a) and 6(a)), but there were exceptions outside of the September 25–26, 2008 dust studies. The hivol SSI and lovol PQ200 tracked each other most closely, which is reasonable since both are U.S. EPA-designated PM_{10} FRMs. However, their PM_{10} concentrations differed from each other, as seen in Fig. 7. On average, the PQ200 yielded ~82% of the SSI PM_{10} concentrations as indicated by the slope of the regression equation. The measurement scatter is beyond the ± 3 µg/m^3 precisions of both concentration measurements.

Fig. 5(a) shows that DustTrak Unit 2 obtained the highest PM_{10} concentrations, consistent with the bias indicated in Fig. 4(e) with respect to DustTrak Unit 3 and the variant calibration for Unit 2. The other instruments typically showed lower PM_{10} levels than the hivol SSI and lovol PQ200 FRMs, with some exceptions. The E-Samplers yielded the lowest PM_{10} levels at all four sites (Figs. 5 and 6) and did not track day-to-day variations as well as the other measurement systems.

Even though Figs. 5 and 6 demonstrate that the absolute values are different, inter-sampler correlation coefficients in Table 2 demonstrate good relationships among the hivol SSI, lovol PQ200, minivol OMNI, and DustTrak DRX PM_{10} measurements at downwind sites. The higher correlation (0.83 < R < 0.91) of the DustTrak DRX with respect to the SSI, PQ200, and OMNI indicates the value of adding the OPC function for coarse particles in addition

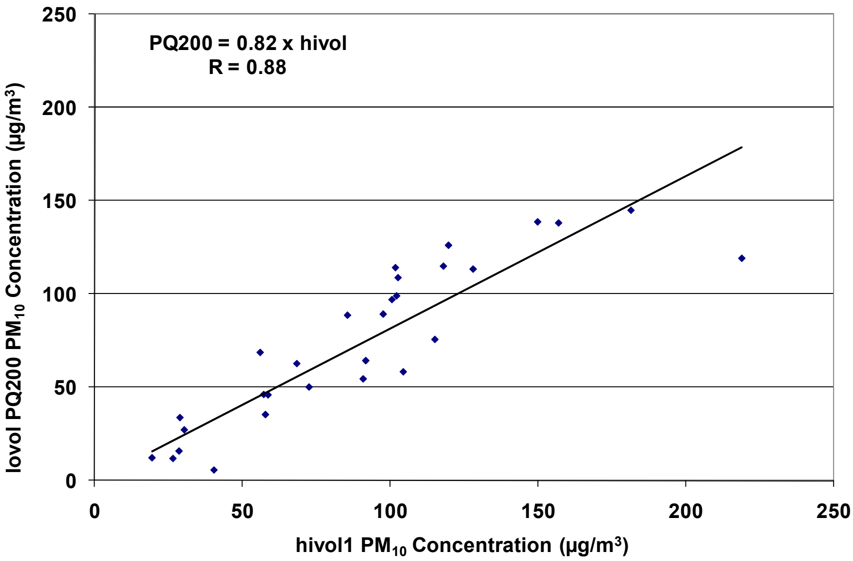


Fig. 7. Comparison between five-hour average PM_{10} from the two FRMs: hivol SSI and lovol PQ200 samplers at Sites A-1 and B-1. Samples during dust generation events at Site A-1 on September 25–26, 2008 are excluded.

Table 2. PM_{10} correlation coefficients (R) for downwind and upwind sites. Downwind data include 9 samples from Site A-1 and 18 samples from Site B-1, excluding dust generation events on September 25–26, 2008. Upwind data include 13 samples from Site A-2 and 11 samples from Site B-2. (Grimm OPC data was insufficient for inclusion.)

Downwind Sites	hivol SSI	lovol PQ200	Minivol OMNI	E-Sampler	E-BAM	Model 8520 DustTrak3	DustTrak DRX
hivol SSI	1.00						
lovol PQ200	0.86	1.00					
minivol OMNI	0.85	0.94	1.00				
E-Sampler	0.20	0.49	0.49	1.00			
E-BAM	0.36	0.58	0.47	0.35	1.00		
Model 8520 DustTrak3	0.29	0.49	0.51	0.89	0.28	1.00	
DustTrak DRX	0.90	0.83	0.91	0.47	0.33	0.55	1.00

Upwind Sites	Hivol SSI	minivol OMNI	E-Sampler	E-BAM	Model 8520 DustTrak4
hivol SSI	1.00				
minivol OMNI	0.95	1.00			
E-Sampler	0.50	0.52	1.00		
E-BAM	0.86	0.82	0.71	1.00	
Model 8520 DustTrak4	0.77	0.79	0.71	0.80	1.00

to the fine particle scattering by nephelometer in the DustTrak DRX, even though the factory calibration does not represent the aerosol sampled in this study. The Model 8520 DustTrak Unit 3 yielded low correlations with three filter samplers (i.e., SSI, PQ200, and OMNI) in the range of 0.29–0.51. Correlations at the upwind sites are higher, with the minivol OMNI and lovol E-BAM PM_{10} highly correlated ($0.86 < R < 0.95$) with the hivol SSI PM_{10}. DustTrak Unit 3 and the E-Sampler correlated well ($R = 0.89$) at the downwind sites ($n = 27$), but this correlation was not found for the upwind sites ($n = 24$) for DustTrak Unit 4 ($R = 0.71$). Given that both instruments are based on particle light scattering with nephelometers, a better correlation should be expected. Further study is needed to explain this inconsistency.

Particle Size Distributions

Fig. 8 shows the daily particle size distributions from the TSI DustTrak DRX (comparable plots for the Grimm OPCs are in supplemental data). Since the DustTrak DRX PM_{10} is reasonably correlated with the hivol SSI PM_{10} ($R = 0.9$ in Table 2), even though the absolute concentrations differ, the relative fractions in each size range provide insight into the causes of differences between sampling systems. Size differentiation in Fig. 8 indicates that a large fraction of the suspended PM at the sand/gravel facilities is present in the coarse size fraction, especially for PM above 10 µm in size.

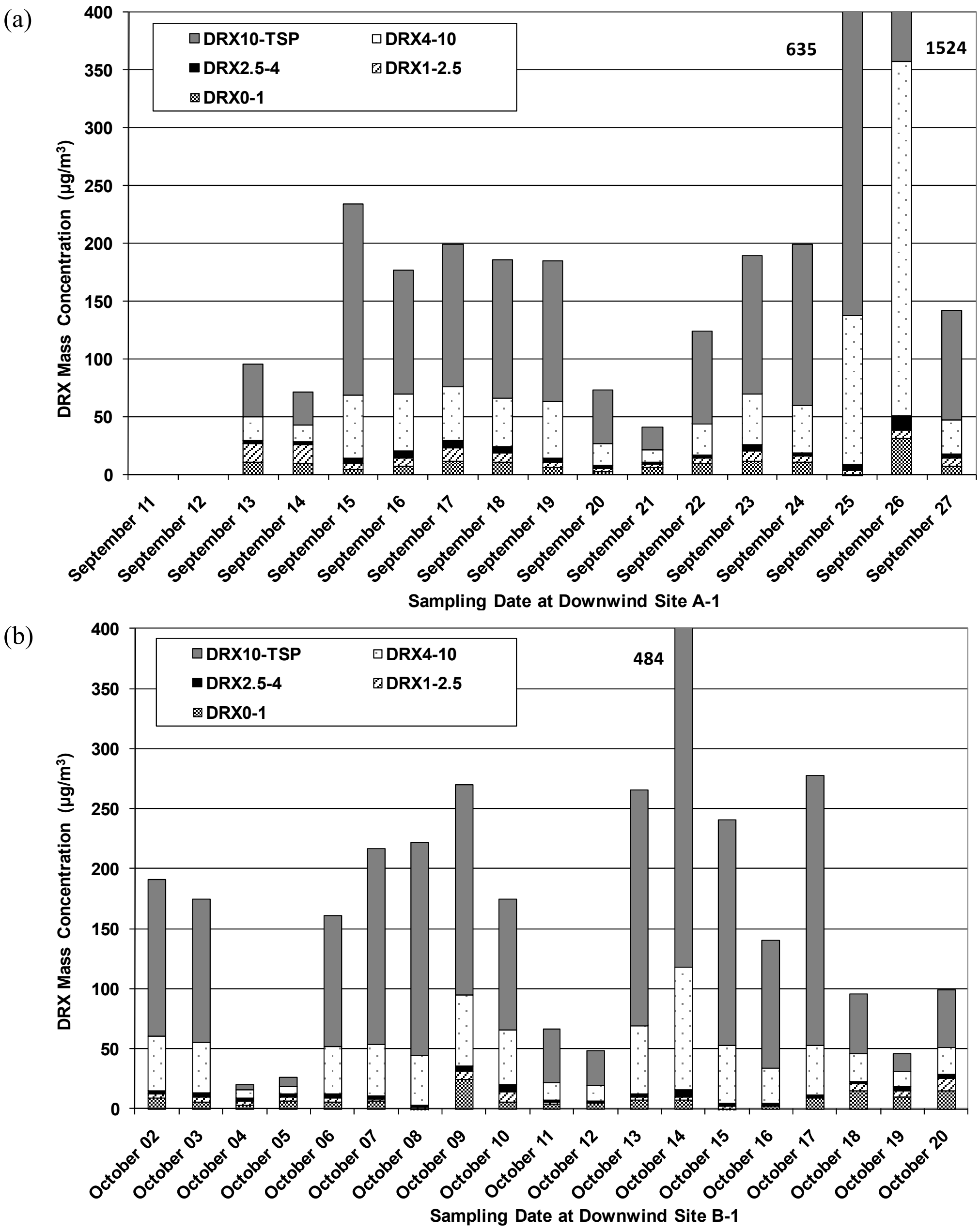


Fig. 8. DustTrak DRX mass size distributions at: a) Site A-1 during September 11–27, 2008, and b) Site B-1 during October 2–20, 2008. Particle size bins are in five size ranges: 0–1 µm, 1–2.5 µm, 2.5–4 µm, 4–10 µm, and 10 µm–TSP.

$PM_{1.0}$ was a small portion of the total mass, averaging 8 and 7 µg/m^3 for the DustTrak DRX at Sites A-1 and B-1, respectively. The highest $PM_{1.0}$ concentration was 31 µg/m^3 when the DustTrak DRX was within the uncontrolled fugitive dust plume on September 26, 2008. The plumes were visible to the naked eye (see supplemental photographic data), indicating that dust particles scattered a large amount of light. The highest $PM_{1.0}$ concentration of 25 µg/m^3 at Site B-1 occurred on October 9, 2008. Fig. 9(b) shows this is a different type of event with relatively constant $PM_{2.5}$ and PM_4 throughout the five-hour period, with a slight tail-off near the end. Wildfires were probably the cause of the higher concentrations of fine particle fractions seen in Fig. 8(b) on October 18–20, 2008 at Facility B.

The one-minute resolution in the DustTrak DRX offers insights into the causes of these high concentrations. As illustrated in Fig. 9(a), $PM_{1.0}$ is clearly related to the fugitive dust plumes, indicated by the corresponding rapid increases in concentrations for all of the DustTrak DRX size fractions between 1400 and 1530 PDT. The sharpness of the spikes reflects the narrowness and short durations of the plumes, yet the concentrations over these short time periods are so large that they dominate the five-hour average concentrations in each size fraction, as seen in Fig. 8(a). The impact of these sharp peaks can be evaluated to distinguish micro- (< 500 m) and neighborhood-scale (500–4000 m) influences based on the method of Watson and Chow (2001a). This study emphasized the constrained nature of nearby plumes, as the Grimm OPC at Site A-1 that was within 20 m of the TSI DustTrak DRX did not register the event.

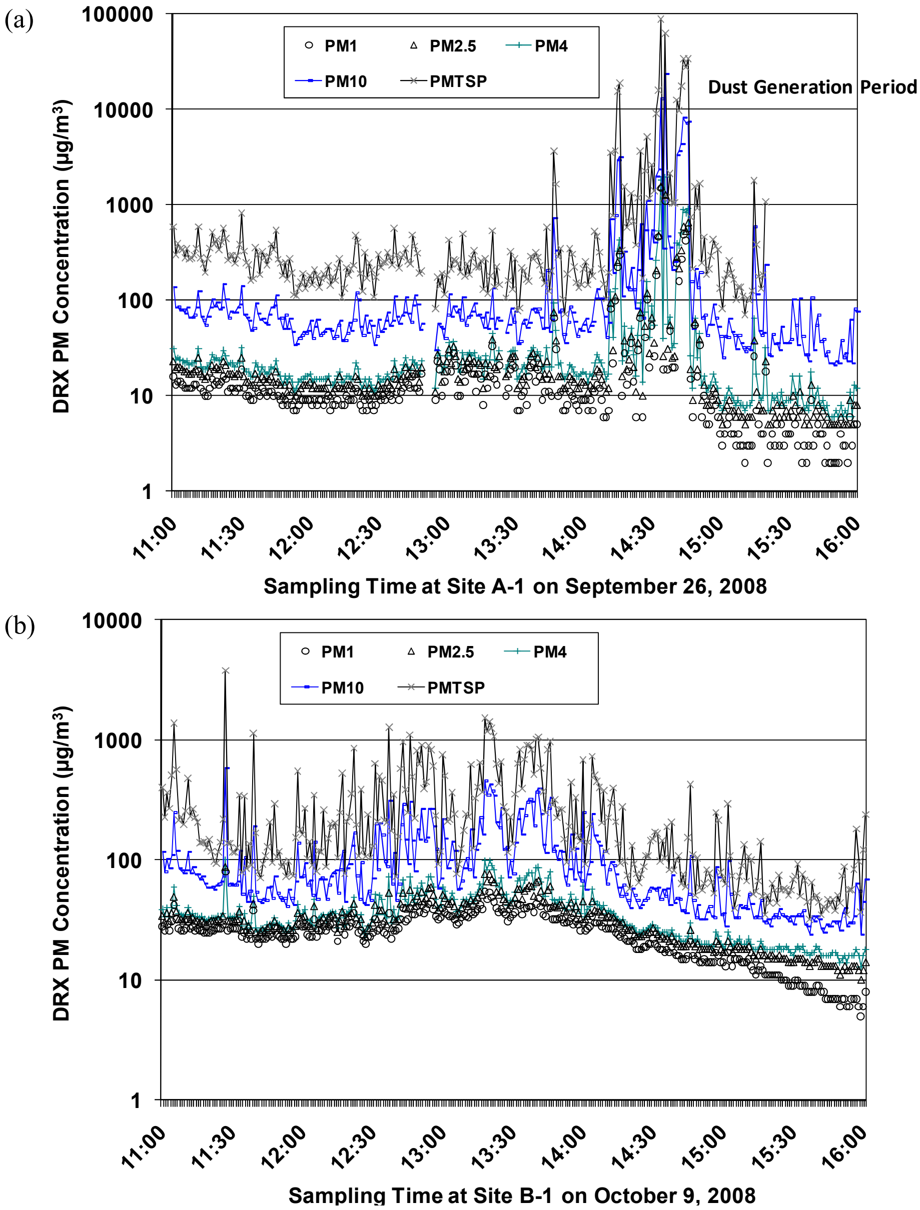


Fig. 9. One-minute DustTrak DRX size variations for days with the highest five-hour $PM_{1.0}$ concentrations for: a) Site A-1 on September 26, 2008, and b) Site B-1 on October 9, 2008.

Engine exhaust contributions would manifest themselves as $PM_{1.0}$ that is not necessarily accompanied by concurrent increases in the other size fractions. These would appear as spikes in the time series with wind directions from nearby roads (Watson and Chow, 2001a). However, more detailed chemical speciation (Chow *et al.*, 2007a, 2008; Chow and Watson, 2011) would be needed to confirm this. Engine exhaust is composed primarily of organic and elemental carbon that distinguishes it from mineral matter that contains elemental oxides (Chow *et al.*, 1994; Vega *et al.*, 2001; Watson *et al.*, 2001b; Watson and Chow, 2001b; Chow *et al.*, 2003; Ho *et al.*, 2003; Chow *et al.*, 2004; Labban *et al.*, 2004; Cao *et al.*, 2008; Wu *et al.*, 2011). Outside of the dust events, $PM_{1.0}$ levels were < 10 μg/m^3 and are similar at the upwind and downwind sites.

Wind Direction and Wind Speed Variability

Fig. 10 compares wind direction distributions at each Facility. Upwind Site A-2 experienced southwest winds for over 65% of the monitoring period, the most consistent of any site. While these winds were still generally from the southwest, directions were spread out more among the neighboring sectors. As seen in Fig. 1, there are many tall obstructions between Sites A-2 and A-1 that can cause flows to vary. The 5 m wind mast at Site A-1 (Fig. 3(a)) was also lower than the trees located to the north (see supplemental data); this natural windbreak could block the wind flow. Distributions of wind directions for individual days (supplemental data) reflect the frequencies for the entire period (Fig. 10(a)), except for September 12, 2008 at Site A-1 where winds were predominantly from the north.

At Facility B, wind direction distributions between the upwind and downwind sites were similar. Prevailing winds were primarily from the west, typical of the well-documented flow patterns in the South Coast Air Basin (Blumenthal *et al*., 1978; Schultz and Warner, 1982). As a result, Site B-2 is not really an "upwind" site, even though its measurements appear to be regionally representative and only occasionally affected by local source contributions. The individual days experienced wind direction distributions similar to those of Fig. 10(b), except for October 3, 2008 at downwind Site B-1 which showed a northerly flow for part of the period (supplemental data). This northerly wind flow did not register at Site B-2, however, and may be an anomaly.

Wind speed distributions at the upwind and downwind sites (supplemental data) were also more similar at Facility B than at Facility A. Upwind Site A-2 experienced ~30% calm conditions (wind speed < 1 m/s), compared to < 6% at downwind Site A-1, during the sampling period. This difference can be attributed to the siting of the upwind meteorological tower (Fig. 3(b)), which was immediately adjacent to tall conveyors that may have attenuated wind speeds. The downwind Site A-1 monitor was further away from similar obstructions but, as noted earlier, the fetch was insufficient for more than a local-scale characterization. The situation was reversed at upwind Site B-2, which was surrounded by few obstructions and offered a good fetch. Calms were recorded < 6% of the time during the study period. The downwind Site B-1, however, was closer to obstructions and was often blocked by large trucks passing through the scales; this site recorded ~17% calms during the five-hour sampling periods.

The differences in wind roses between the upwind and downwind sites show the importance of placing the wind vane in an exposed area above nearby obstructions to obtain an accurate transport direction. This is not often possible for a temporary site, as towers taller than ~5 m require a stable (usually concrete) base and guy wires. The 1 m agl wind directions from the E-BAM wind sensors

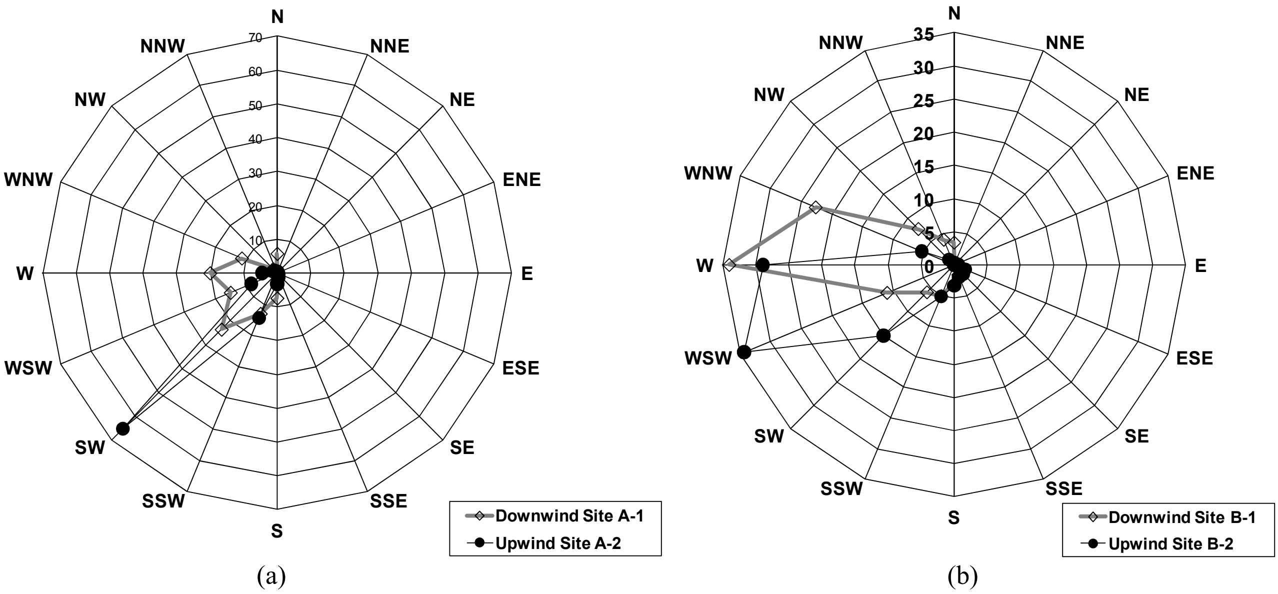


Fig. 10. Wind direction frequencies from 1100 to 1600 Pacific Daylight Time (PDT) at: a) Sites A-1 and A-2 from September 11–27, 2008, and b) Sites B-1 and B-2 from October 2–20, 2008. Scale is percent of time from the indicated direction.

were not correlated with those on the mast, being mostly affected by very local flows, including passing vehicles and other mechanical processes.

Upwind/Downwind PM_{10} Differences

Fig. 11 summarizes the differences in PM_{10} concentrations between the upwind and downwind sites at the two facilities. These differences further indicate the uncertainty of the "upwind" and "downwind" site designations.

Nearly all of the differences in PM_{10} are negative, and by large amounts for Facility A (Fig. 11(a)). The differences are not the same for hivol SSI FRM and minivol OMNI, with September 16 and 26, 2008 differences showing both positive and negative values. It is evident that upwind Site A-2 was affected by more local sources (i.e., adjacent raw material conveyors and two heavily traveled paved roads southwest of the site) than downwind Site A-1 and does not represent the neighborhood-scale PM_{10} concentrations that should be subtracted from the levels transported to the downwind facility. Given the abundance of industrial activities in the neighborhood of Facility A, especially other sand and gravel operations, and the heavy-duty diesel traffic that serves these industries, it is unlikely that a suitable neighborhood-scale upwind site would be found.

Fig. 11(b) shows more realistic upwind/downwind PM_{10} concentrations at Facility B than at Facility A, even though Site B-2 is not located strictly "upwind". Again, the hivol SSI and minivol OMNI differences do not match, with the hivol SSI usually measuring a higher increment. There are several examples of PM_{10} difference exceeding 50 µg/m^3,

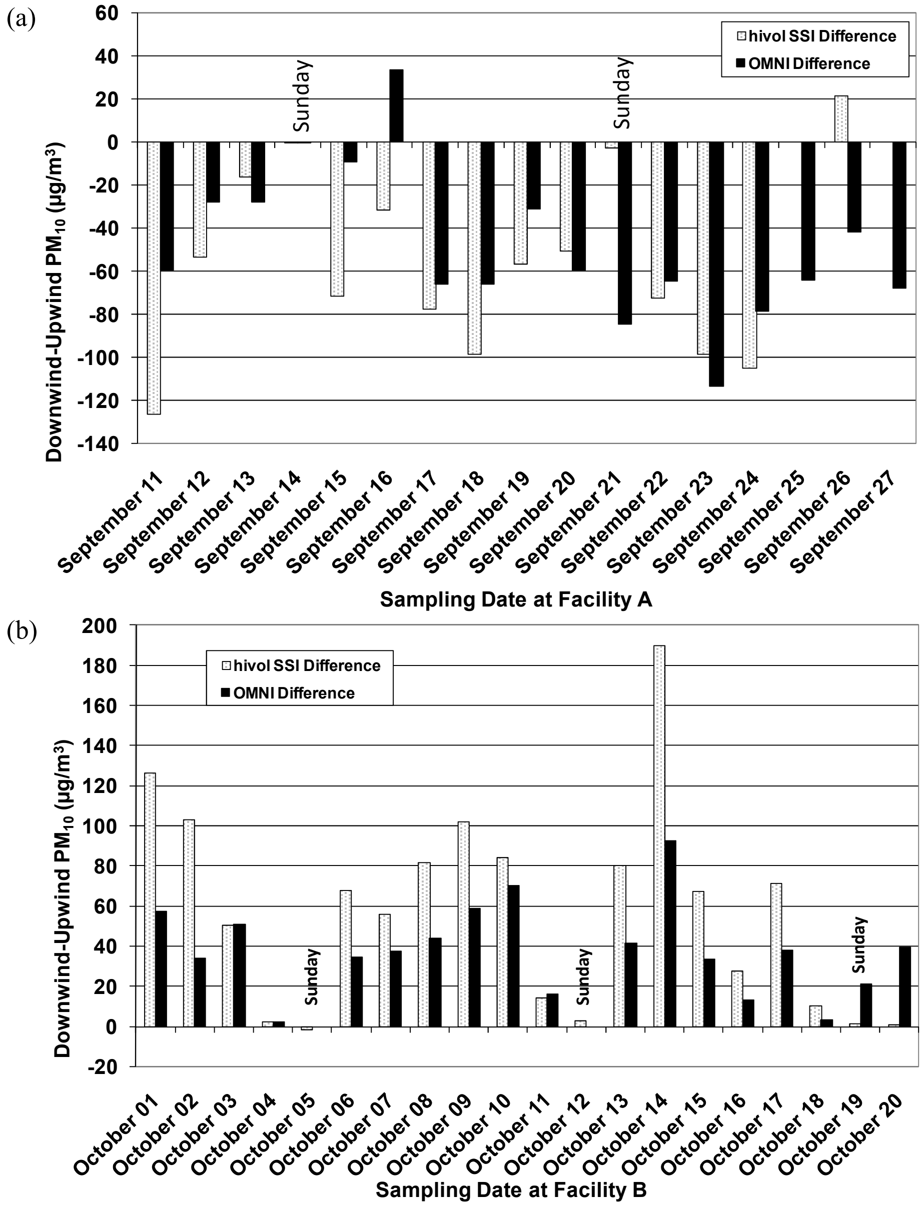


Fig. 11. Differences between downwind (Sites A-1 and B-1) and upwind (Sites A-2 and B-2) PM_{10} concentrations for hivol SSI and minivol OMNI filter samplers at: a) Facility A during September 11–27, 2008, and b) Facility B during October 2–20, 2008.

but this is expected given the proximity of the downwind Site B-1 to dust generating activities. Given the particle size distributions' weighting toward super-coarse particles, it is unlikely that such high differences would be measured near the property fence lines that are distant from most of the dust generating activities. Only one negative PM_{10} difference was measured on Sunday, October 5, 2008, and the difference was < 2 µg/m^3, within the hivol SSI measurement uncertainty of ± 3 µg/m^3. The remaining Sundays (October 12 and 19, 2008) also show negligible differences in hivol SSI PM_{10} between downwind Site B-1 and upwind Site B-2, demonstrating that both sites are capable of characterizing neighborhood-scale PM_{10} levels in the absence of mineral processing activities.

SUMMARY AND CONCLUSIONS

Eight PM_{10} measurement instruments and two meteorological systems were evaluated at two sand/gravel facilities. Precisions of the five-hour integrated filter PM_{10} measurements were ± 3 µg/m^3 for the hivol SSI and ± 8 µg/m^3 for the minivol OMNI based on error propagation of replicate analyses and flow rates. The Met One E-Samplers provided more comparable results in side-by-side sampling when the nephelometer output was normalized to multi-day mass concentrations. One of the TSI Model 8520 DustTraks (Unit 2) showed large calibration differences and was replaced in the later part of the study.

During the field study, PM_{10} concentrations from different samplers rose and fell consistently with each other. Lower concentrations were found on the weekends, when raw material was not processed and there was less traffic on the boundary roadways. While the two FRMs, hivol SSI and BGI lovol PQ200, tracked each other most closely with an 18% difference, the E-samplers yielded the lowest PM_{10} levels at all sites and didn't track day-to-day variations as well as the other measurement systems. From a practicality standpoint, the lovol PQ200 is preferable to the hivol SSI since it is much smaller and lighter, has its own support stand, and operates on a rechargeable 12 V battery. The 5 L/min minivol OMNI did not acquire sufficient mass over the five-hour sampling period to be comparable with each other or with the other samplers.

In a fugitive-dust dominated environment, the factory calibrations for the nephelometers for the Met One E-Samplers and TSI Model 8520 DustTrak did not represent the particle light scattering to PM_{10} mass relationship; light scattering is sensitive to the $PM_{2.5}$ fraction, with large uncertainties for coarser particles. Although absolute PM_{10} concentrations are different at each facility, intersampler comparisons demonstrated good relationships among the hivol SSI, lovol PQ200, minivol OMNI, and DustTrak DRX. Multiple particle size ranges (i.e., 1, 2.5, 4, 10, and ~15 µm) in DustTrak DRX indicate a large fraction of the suspended PM at the sand/gravel facilities were present in the super-coarse (> 10 µm) fraction. Elevated $PM_{2.5}$ at Facility A during non-controlled fugitive dust events showed $PM_{2.5}$ increasing over periods of a few minutes along with the larger particle sizes, indicating the immediate impact from a local dust source. These elevated concentrations emphasize the constrained nature of nearby plumes, as the Grimm OPC at Site A-1 that was within 20 m of the TSI DustTrak DRX did not register the event.

This study demonstrated the challenges in the application of upwind/downwind studies to estimate incremental PM_{10} concentrations of fugitive dust emissions from a sand/gravel operation. Since site selection was based primarily on the prevailing wind direction at each facility, and was limited by the availability of space, power, and security, a suitable neighborhood-scale upwind site was difficult to locate. Consequently, monitors were closer to dust generating activities than would be the case for tests conducted outside the fence line. Wind direction shifted over the short (five hour) sampling duration for the integrated filter samplers, thereby obscuring the upwind or downwind designation of the monitoring site.

The concepts of upwind and downwind sampling need to be refined. The differences in wind roses between the upwind and downwind sites show the importance of placing the wind vane in an exposed area above nearby obstructions to obtain an accurate transport direction. On the other hand, a wind vane closer to ground level will better represent transport of nearby emissions and wind speeds that might exceed threshold velocities (Watson *et al.*, 2000). The upwind site should represent the neighborhood-scale PM_{10} level, even if it is not strictly upwind of the dust-emitting facility. The downwind site should represent a mixed plume from the multiple emitters within the facility and not be dominated by nearby fugitive dust sources. The influence of local sources can be assessed by locating an array of OPCs, such as the TSI DustTrak DRX or Grimm OPC monitors, in a lateral direction with respect to the PM_{10} filter sampler. The one-minute resolution in the DustTrak DRX offers insights into the cause of elevated PM concentrations, and the sharpness of the spikes also reflects the narrowness and short duration of the dust plumes.

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SUPPLEMENTARY MATERIALS

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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