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Comparisons of Measurements and Predictions of PM Concentrations and Emission Rates from a Wind Erosion Event

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Abstract

Wind erosion can affect agricultural productivity, soil stability, and air quality. Air quality concerns deal mainly with human health and welfare issues, but are also related to long range transport and deposition of crustal materials. Regulatory standards for ambient levels of particulate matter (PM) with equivalent aerodynamic diameters ≤ 10 µm (PM_{10}) and ≤ 2.5 µm ($PM_{2.5}$) have been established in many countries in an effort to protect the health and welfare of their citizens. Wind erosion events may lead to high PM levels that exceed air quality standards and are health hazards. Quantifying suspended wind-blown dust emissions and resulting PM concentrations from wind erosion events are, therefore, of significant interest.

A high wind event causing visible soil suspension occurred on May 20, 2008 in California's San Joaquin Valley. On this day, PM concentrations around a 10 hectare field with fine sandy loam soil were being measured as part of an agricultural tillage PM emissions study. Meteorological parameters were monitored by a weather station at 5 m and two 15.3 m towers vertically profiling wind speed, wind direction, temperature, and humidity. Point sensor PM instruments deployed were a vertical and horizontal array of optical particle counters (OPCs) and portable filter-based PM samplers. A remote sensing scanning Lidar (light detection and ranging) system with three wavelengths (1064 nm, 532 nm, and 355 nm) called Aglite was also deployed. The OPCs were used to calibrate the Lidar return signal to particle count and volume concentration. Mass concentration calibrations for both the OPCs and Lidar were calculated from OPC and filter-based PM data collected that day. The filter-based sampling was stopped upon completion of the tillage activity while the OPCs and Lidar continued to collect data during part of the wind erosion event. Since this was not designed as a wind erosion study, measurements of neither creep nor saltation were made. Emission rates (ERs) were calculated by a technique using a vertical flux equation with OPC-measured PM data, an inverse modeling technique using AERMOD with OPC-measured PM data, and through the application of a mass balancing technique to upwind and downwind vertical Lidar scans.

PM values measured downwind of the field were consistently much higher than those measured upwind, showing significant suspension and vertical dispersion of soil particles from the field up to 9 m. Particle size distributions and PM levels were also consistently higher at 2 m than 9 m in both upwind and downwind locations, suggesting most particles in the wind-blown dust plumes stayed near the surface. All OPCs, especially those downwind, had high counts for particles > 1 µm relative to counts of particles < 1 µm in comparison with typical ambient atmosphere particle size distributions. The Lidar detected wind-blown dust plumes of varying size, location, and duration on the downwind field edge from 10 m to 50 m in elevation. ERs based on the vertical flux equation were 3.9 µg/s-m^2 for $PM_{2.5}$, 174.2 µg/s-m^2 for PM_{10}, and 872.0 µg/s-m^2 for TSP while ERs from inverse modeling were 6.1 µg/s-m^2 for $PM_{2.5}$, 268.7 µg/s-m^2 for PM_{10}, and 1,488.9 µg/s-m^2 for TSP. These PM_{10} ERs are similar to other values in literature. The Lidar-based ERs were three orders of magnitude lower than those from the other two methods. A minimum measurement height of ~10 m due to safety concerns prevented the Lidar from adequately detecting plumes that are close to the ground, such as the wind erosion plumes seen on this day.

KEYWORDS: Wind erosion, PM, Emissions, Vertical flux equation, Air dispersion modeling, Remote sensing, LIDAR, Optical particle counter, Point sensor.

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INTRODUCTION

Wind erosion of soil is a potentially significant problem in the world. Concerns over soil erosion exist from resource conservation and human (and animal) health and welfare perspectives. Movement of topsoil represents a transfer and potential loss of an invaluable agricultural resource. Poor air quality conditions due to high particulate matter (PM) concentrations, such as those that exist during a wind erosion event, are health hazards (Ostro et al., 1999). Types of soil movement found during a wind erosion event can be divided into the following categories: creep, saltation, and suspension. The larger particles and greater mass is generally found in the creep and saltation categories, while the suspended soil particles tend to be smaller and transported greater distances (Stetler and Saxton, 1996; Sharratt, 2011). Suspended particles contribute to PM concentrations and potentially degrade local and regional air quality, as observed in the Columbia Plateau by Kjelgaard et al. (2004) and Sharratt et al. (2007).

In-field measurements of wind erosion emission rates (ER) and contributions to PM_{10} (particles ≤ 10 μm in equivalent aerodynamic diameter) have been made using several methods in a variety of soils and conditions by Gillette et al. (1972), Saxton et al. (2000), Kjelgaard et al. (2004), and Sharratt et al. (2007), among others. Zobeck et al. (2003) provides a description of the instrumentation and methods generally accepted and used in measuring wind erosion soil loss.

A high wind event created visible suspended soil plumes near the end of and following a tillage activity being monitored for PM emissions. Both point and remote optical sensors were utilized to measure PM concentrations upwind and downwind of the freshly tilled field for up to 2 hours. This paper presents PM concentration and ER analyses for this dataset. Note that only PM concentrations from 2 to 9 m above ground level were measured; creep and saltation fraction measurements were not collected because these observations were not from a designed wind erosion study.

METHODOLOGY

A study of PM emissions from a spring sequence of agricultural tillage was conducted in May and June 2008 in California's San Joaquin Valley. The production field was rotated from a winter silage wheat crop to silage corn and was monitored on a full-field scale (~10 hectares). The investigated tillage sequence was chisel, disc 1, disc 2, lister, and build up ditches from May 17-20 and break down ditches, cultivate, roll, plant, fertilize injection, and cultivate from June 5-25. The high wind event measured during the first portion of this study occurred on May 20 during the end of the lister tillage pass to create furrows and ridges, throughout the build-up-ditches pass, and immediately following this last activity. Therefore, the soil surface was fully disturbed throughout the high wind event.

Soil type 130 (Kimberlina fine sandy loam, saline-alkali) was reported across the entire field by the Web Soil Survey (USDA, 2009). Mean soil composition was 62% sand, 29% silt, and 9% clay using the Hygrometer Method (Carter, 1993). The average soil moisture level, ± 1 σ, was determined gravimetrically (Doran and Jones, 1996) to be 3.3% ± 1.6% (n = 10) for May 20, taken prior to the lister activity. Post-campaign stable aggregate analyses were conducted following the Dry-Sieve Method (Carter, 1993). These data show that stable aggregate mass decreased after the first tillage activity to between 50% and 60%, with the largest decrease in the first sieve (pore size = 4 mm). Samples for these analyses were not collected immediately after the lister activity to describe soil conditions at the time of the wind erosion event. However, data from prior to the lister activity may be used as a conservative estimate of soil conditions during the afternoon high winds.

Measurements

PM measurements were made during the wind erosion event using a horizontal and vertical array of optical particle counters (OPCs) and the Aglite Lidar system described by Marchant et al. (2009). The

OPCs were Met One Instruments, Inc. Model 9012 Aerosol Profilers with eight bins (0.3-0.5 µm, 0.5-0.6 µm, 0.6-1.0 µm, 1.0-2.0 µm, 2.0-2.5 µm, 2.5-5.0 µm, 5.0-10.0 µm, and >10 µm) operating on 20 sec sample periods. Average volume concentrations ($\mu m^3/m^3$) per 20 sec period were calculated using reported particle concentration ($\#/m^3$) and assuming a spherical particle shape. Time-averaged, filter-based mass concentration data for $PM_{2.5}$, PM_{10}, and total suspended particulate (TSP) were collected during the tillage activity sample periods using Airmetrics MiniVols. Filter handling, preparation, storage, and weighing were all accomplished using the guidelines in 40 CFR Appendix J. OPC and MiniVol clusters were located upwind and downwind of the field at heights of 2 m and 9 m.

A scalar relationship, the Mass Conversion Factor (MCF), was calculated between the MiniVol mass concentration (PM_k) for mass fraction k and the corresponding collocated OPC volume concentrations (V_k) averaged over the MiniVol sample time and across all locations. Although the MCF has units of density, it is not exactly equivalent to particle density; instead, it incorporates many complex factors, including particle shape, index of refraction, porosity, and density, among others, into a single value for conversion of optical measurements (OPC, Lidar) to mass concentrations. Multiplication of the time series OPC V_k data by the MCF_k allows the examination of temporal changes in mass concentration on a much finer scale than the filter-based systems (Zavyalov et al., 2009). The MCF_{10} (1.55 g/cm^3) and MCF_{TSP} (1.37 g/cm^3) calculated for the lister pass were utilized in this analysis, while problems with the $MCF_{2.5}$ lead to the use of the mean mass density of soil, 2.65 g/cm^3, as given by USDA (2007).

The Aglite Lidar is a photon-counting micropulse Nd:YAG system with three laser wavelengths of 1.064, 0.532, and 0.355 µm pulsed at 10,000 Hz and an effective range of 500 m to 2,000+ m in 6 m range bins. A turret system allows for a 280 degree azimuth scanning range and an elevation scanning range between -10 to 45 degrees. During this field measurement, the detected return signals were integrated into 0.5 sec time-averaged measurements. OPC data were used to calibrate the Lidar signal to aerosol number and size distribution. Lidar data were processed and inverted to particle volume concentration according to the procedures outlined in Marchant et al. (2009) and Zavyalov et al. (2009) and using the Kalman filter method in Marchant et al. (2011). The MCF_k values were used for mass concentration conversion. Sample collection by the Lidar was accomplished in two modes: 1) stare mode, and 2) scanning mode. During stare mode, the beam was held in constant position for at least 60 seconds immediately adjacent to an elevated OPC for calibration purposes. During scanning mode, the beam was moved in an either horizontal or vertical motion, sweeping through a two-dimensional plane of the atmosphere. Vertical scans were performed both upwind and downwind of the field, scanning between 2 and 15 degrees elevation in order to detect the incoming and outgoing aerosol. A scan angle of 2 degrees elevation meant that the lidar laser beam was higher than 10 m at the field, a height selected in order to minimize eye safety risks to personnel working in the field and to maintain the beam above structures on an adjacent dairy. Horizontal scans over the field area were performed between alternating pairs of upwind and downwind vertical scans, also at the same elevation angle of 2 degrees, in order to map the horizontal spatial distribution of PM the over the field.

Meteorological measurements were collected on two identical 15.3 m towers, one crosswind from the field and the other downwind. Each tower measured: wind speed at 2.5, 3.9, 6.2, 9.7, and 15.3 m using RM Young Gill 3-cup anemometers; wind direction at 15.3 m a Met One Instruments, Inc Wind Vane; and temperature and relative humidity at 1.5, 2.5, 3.9, 6.2, and 9.7 m using Vaisala HMP45C sensors. Pressure, temperature, relative humidity, incoming solar radiation, wind speed, wind direction, and precipitation were recorded by a Davis Instruments, Inc. Vantage Pro2 Plus weather station at 5 m.

Emissions Estimation

PM ERs from the wind erosion event were calculated using three methods: 1) inverse modeling with OPC PM data, 2) the vertical flux method described by Sharratt et al. (2007) with OPC PM data, and

3) a mass balancing technique applied to the lidar data. In inverse modeling, the impact of a source is known while the strength of the source is not; a model is used to predict concentrations and the input ER is adjusted until the concentrations predicted by the model best match the measured concentrations. The impact on PM concentration from the wind erosion event was calculated by differencing the period-averaged upwind and individual downwind OPC PM measurements. The model employed was AERMOD, executable file version 07026, with the AERMOD View user interface from Lakes Environmental. Wind speed data from 9.7 m and temperature data from 2.5 m on the meteorological tower downwind of the field were used by AERMET to create the meteorological file used in AERMOD. The following values were selected for noontime albedo, surface roughness (z_0), and Bowen ratio, respectively: 0.18 based on the value given for light colored, dry soil by Hansen (1993); 0.05 m, assuming that the freshly furrowed field was closest to the default AERMET value for agricultural fields in autumn; and 1.0, the spring-time AERMET default under dry conditions for cultivated land. The initial ER was arbitrarily chosen as 1.0 g/s-m^2 and adjusted to best match the observed $PM_{2.5}$, PM_{10}, and TSP impacts using a least sum of squares (LSS) approach and an iterative solver in MS Excel. The modeled times were 13:00-15:00, the two full hours of OPC data; AERMOD uses hourly average meteorological data and calculates hourly average concentrations.

The vertical flux method described by Sharratt et al. (2007) is based on the following equation using period-average PM concentrations (C, μg/m^3) at heights z_1 and z_2 and friction velocity (u_*, m/s)

$$F_v = \frac{ku_*(C_1 - C_2)}{\ln(z_2 / z_1)} \quad (1)$$

where vertical flux (F_v) has units of g/s-m^2 and k is the von Karman constant (0.4). The 13:00-15:00 time frame was chosen to correspond with the inverse modeling time and source-impact measurements used for inverse modeling from 2 m and 9 m were used for C_1 and C_2. The u_* at each anemometer height was estimated from the period-averaged wind speeds and the logarithmic wind profile equation

$$u_z = \frac{u_*}{k}\ln(z / z_0) \quad (2)$$

A mean u_* value across the anemometer heights of 0.552 m/s was found for z_0 = 0.05 m, the value used for AERMOD calculations.

Emission estimates from Lidar data were obtained by applying a mass balancing technique (outgoing minus incoming) to the calculated PM concentrations with the incorporation of wind speed. Periods during which the wind direction was outside of 60 degrees from perpendicular to the vertical scanning plane were excluded. This removed very few scans from the dataset during this analysis since the wind direction was very stable out of the northwest (mean = 316.0 degrees, min. = 296, max. = 329.2 degrees) while the Lidar beam was directed towards 32 degrees (upwind) and 74 degrees (downwind). The difference between the measured PM levels in the upwind and downwind scans is a function of the net gain or loss of aerosol mass from the field, and therefore, the amount of aerosol emitted.

RESULTS AND DISCUSSION

Sporadic and isolated wind-blown dust plumes originating from and lofting away from the freshly tilled field surface were visually observed and noted by site personnel as early as 9:30 (am PST?). Observation frequency increased after 11:00, and again after 12:30. As tillage activities were conducted from 8:00-12:50, all data from this period were excluded in this analysis. One-minute averaged wind speed data at 2.5 and 9.7 m heights are shown for 8:00-24:00 in Figure 1. Maximum wind speeds were measured around 16:45 and 19:00. Unfortunately, PM data do not exist throughout the day; the value of monitoring a wind erosion event was not realized at the time and all PM sampling ended by 15:45. Lidar data exist until 13:50, OPC data until 15:30, and no filter samples were collected after 13:00. The fetch over the field was 280 m based on a mean wind direction of 314 deg., including a 10 m distance

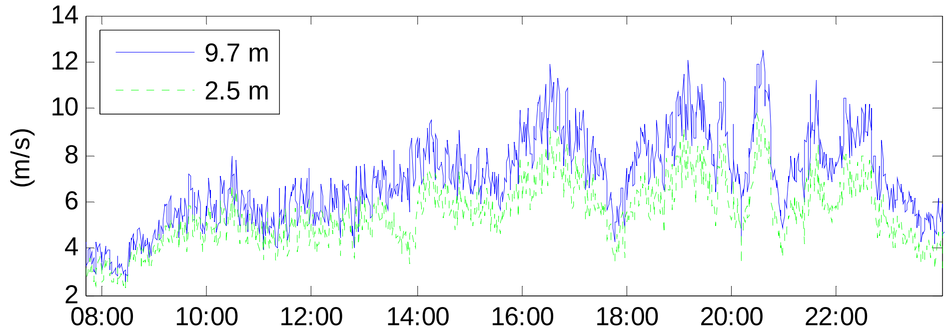

Figure 1. One minute averaged wind speeds measured at 2.5 and 9.7 m above ground level throughout May 20, 2008.

from the field edge to sampler locations across an unpaved road. It is possible that fugitive dust from the unpaved road contributed to the measured PM concentrations, but for this analysis all emissions were attributed to the field surface.

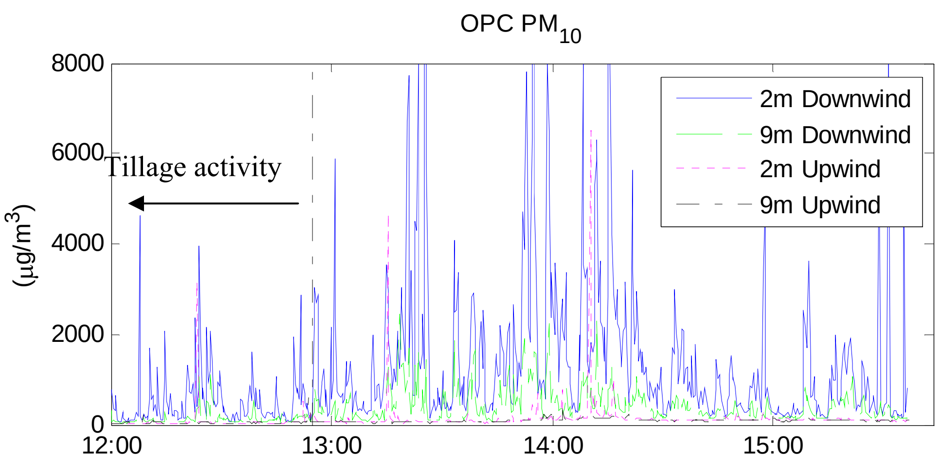

Figure 2. PM_{10} concentrations calculated from OPC data for the afternoon of May 20 at three vertical levels downwind and one upwind. Note that tillage operations were only conducted prior to 12:50.

PM_{10} concentrations calculated from OPC measurements made at upwind and downwind heights of 2 m and 9 m are shown in Figure 2. Note that, in order to preserve the viewability of the graph, the y-axis does not show the 2 m height downwind maximum concentrations of nearly 14,000 μg/m^3 (these are conservative numbers as the manufacturer-stated maximum number of particles the OPC can count individually was exceeded). The graph shows the differences between the upwind and downwind measurements and between measurements at different elevations. Though occasional elevated upwind PM_{10} concentrations suggest contributions from upwind areas, most of the downwind PM_{10} is assumed to originate from wind erosion in the field of interest. The largest measured PM_{10} levels occurred at the 2 m height downwind during the period of highest measured wind speeds, which occurred after 14:00 when the tillage activities were completed. Figure 3 shows the average measured size distributions from 13:00 to 15:00 for the same samplers as in Figure 2. Concentrations of particles < 1.0 μm were generally the same regardless of location and elevation. Greater numbers of larger particles, however, were found closest to the ground and downwind, similar to findings by Sharratt (2011).

The Lidar detected concentrated plumes throughout the one hour of data collection, such as the one shown in Figure 4. The example in Figure 4 shows a horizontal scan across the field followed by a

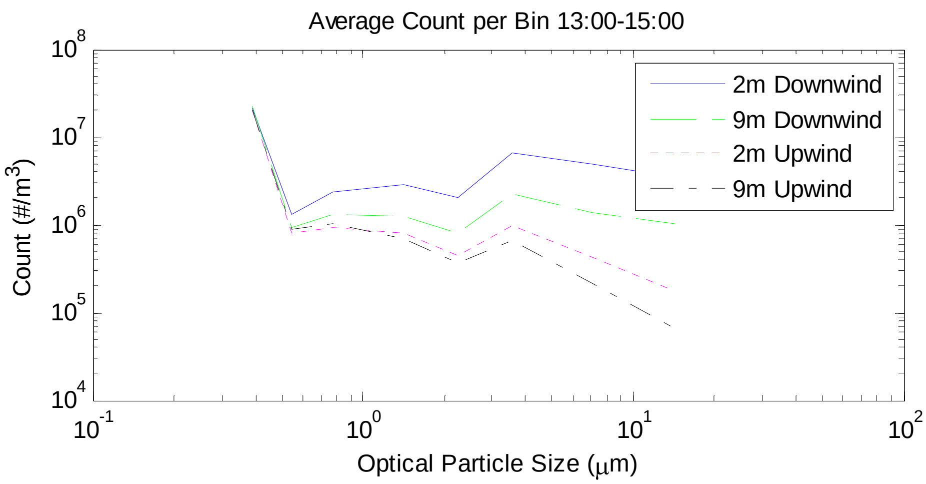

Figure 3. Mean particle size distributions recorded at multiple upwind and downwind elevations.

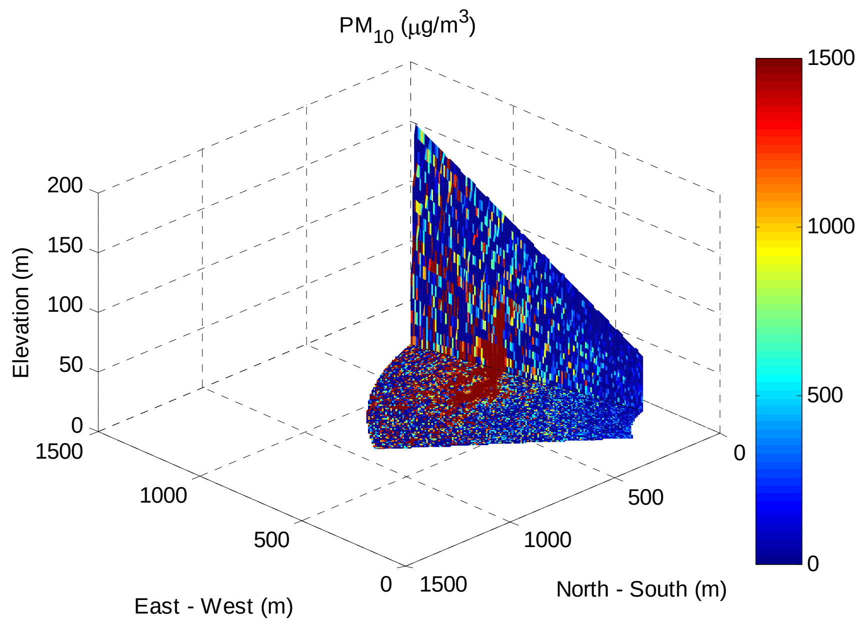

Figure 4. PM_{10} concentrations calculated from Lidar data for one horizontal and vertical scan sequence at 13:17.

vertical scan. The horizontal and vertical extent of the dust plume is clearly visible in these two planes – the plume is >150 m wide and reaches 50 m in elevation at the downwind field edge. Also, the PM_{10} concentrations >1,500 μg/m^3 in the plume are similar to levels detected by OPCs at 9 m at this time (Figure 2) and in the range of maximum 10-minute averages reported by Sharratt et al. (2007).

ERs for wind-blown soil in the $PM_{2.5}$, PM_{10}, and TSP size fractions were calculated on a mass per unit time per unit area of field through inverse modeling and vertical flux calculations using OPC measurements and by applying the mass balancing technique to the Lidar data. The results of these calculations are presented in Table 1. The ERs estimated using the vertical flux equation were about 60% of those calculated using inverse modeling. The average ERs from Lidar data were three orders of magnitude lower than the inverse modeling and vertical flux ERs, which is likely due to the inability of the Lidar to sample below 10 m because of safety concerns. The majority of suspended mass in a wind erosion event has been found close to the ground (Sharratt et al., 2007). Therefore, it is suggested that the suspended material ERs estimated using inverse modeling and the vertical flux equation are more representative of actual conditions. Gillette et al. (1997) reported a PM_{10} loss of 235 µg/s-m^{2}at Owens Lake, CA and PM_{10} loss estimated by Sharratt et al. (2007) ranged from 10 to 255 µg/s-m^2 on the Columbia Plateau. The inverse modeling PM_{10} ER is slightly larger than that from Gillette et al. and the maximum of Sharratt et al., while the vertical flux equation PM_{10} ER is within the reported range.

Table 1. Suspended soil ER calculation results of the detected wind erosion event on May 20, 2008. Inverse modeling and vertical flux ERs are single values, the lidar mass balance ERs are averages ± 95% confidence interval.

Method	Time	***n*** **(OPC - # samplers, Lidar - # scans)**	**ERs (µg/s-m^2)**		
			$PM_{2.5}$	**PM_{10}**	**TSP**
Inverse modeling (OPC)	13:00-15:00	3	6.1	268.7	1,488.9
Vertical flux (OPC)	13:00-15:00	2	3.9	174.2	872.0
Mass balance (Lidar)	12:50-13:50	39	$5.03\text{x}10^{-3} \pm 6.23 \text{x}10^{-3}$	0.137 ± 0.169	0.645 ± 0.801

CONCLUSION

PM concentrations around a field with a fine sandy loam soil under dry and recently-tilled conditions were monitored using OPCs and a Lidar system during part of a high wind event (6-10 m/s). The data were analyzed to examine $PM_{2.5}$, PM_{10}, and TSP concentration trends and ERs during the measured period. PM levels calculated from OPC data decreased significantly from 2 m to 9 m. The Lidar detected wind-blown dust plumes of varying size, location, and duration on the downwind field edge up to heights of 50 m. ERs based on inverse modeling using OPC data were 6.1 µg/s-m^2 for $PM_{2.5}$, 268.7 µg/s-m^2 for PM_{10}, and 1,488.9 µg/s-m^2 for TSP and those calculated using the vertical flux equation were 3.9 µg/s-m^2 for $PM_{2.5}$, 174.2 µg/s-m^2 for PM_{10}, and 872.0 µg/s-m^2 for TSP. These PM_{10} ERs are similar to other values in literature (Gillette et al., 1997; Sharratt et al., 2007). The ERs calculated from Lidar data were three orders of magnitude lower than ERs from the other two methods, likely due to the limitation of 10 m minimum measurement heights due to safety requirements. While Lidar is very useful for imaging plumes over large areas and at elevated heights, safety requirements may limit its usefulness under conditions where the majority of the plume remains close to the ground.

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