8.5 Comparison of the Time Evolved Spatial Distribution of Urban PM2.5 Concentrations

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1. INTRODUCTION

Degradation of air quality along the U.S./Mexico border as a result of natural events and anthropogenic activities is of great concern. In predominately agricultural regions along the border, episodic particulate matter (PM) events are often associated with high winds and burning (Choi et al. 2006). A field study designed to investigate the spatial and temporal variability of atmospheric aerosols during high PM events near Yuma, AZ was run during the week of March 18, 2007. The experiments run during the Yuma High PM Event field study were designed to quantify chemical composition and physical phenomena governing the transport of aerosols generated from burning or high wind events. The field study included two primary monitoring sites; one rural and one urban, equipped with sonic anemometers, continuous particulate concentration monitors and ambient aerosol collection equipment. In addition to the two primary monitoring sites, five urban locations, shown in Figure 1, were equipped with particulate monitors to allow for the investigation of the spatial distribution of particulate concentrations in the urban environment.

During the week long intensive field campaign three distinct high PM events were observed. Two were high-wind events that generated high levels of PM consisting primarily of crustal material and one was a low-wind event with particulate from a burn that originated southwest of the rural site near the U.S./Mexico border. In the present work, meteorological and turbulence parameters governing the distribution and concentration of PM have been compared for the burn event and the first high-wind event. In addition, the inorganic composition and carbon concentration of the atmospheric aerosols during the two events has been quantified.

2. EXPERIMENTAL METHODS

The two main monitoring sites, Rural and Urban, used in the field study were selected because each of them had useful characteristics. During this time of year, the prevailing winds in the area are from the west (and southwest), therefore the Rural site was chosen to be west of Yuma so that non-urbanized concentrations could be measured. The area surrounding the Rural site was primarily farm land with very few buildings. The measurement tower was placed in a dry, grassy field between a small house and church, near an agricultural field. The tower was more than 32 meters away from the two buildings, and the large field, with no crop and loose soil, was 35 meters west of the tower. The Urban monitoring site, 9 kilometers east of the Rural site, was located in an industrial area with several buildings and some small dirt lots. The location was selected because it is an existing Arizona Department of Environmental Quality (ADEQ) monitoring station. The ADEQ monitoring station consisted of gas and particulate monitoring equipment installed on top of a 3 meter high building. The building was used to house the electronics that accompanied the gas and particulate monitors. The buildings immediately surrounding the Urban site were 5 – 7.5 meters tall, and major transportation sources in the area were railroad tracks and U.S. Interstate 8, 0.6 and 1.2 kilometers to the east.

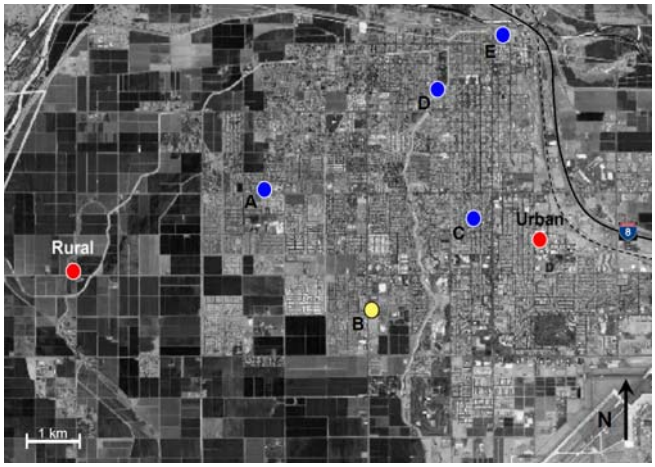

Figure 1: Satellite image showing locations of the 7 sampling sites in Yuma, AZ: 2m DustTrak (●), 7.1m DustTrak (●) and 2m DustTrak with sonic anemometer (●). Railroad tracks (- - - -) and I-8 (——) are located in eastern Yuma.

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Table 1: Locations and heights of monitoring equipment used in the Yuma High PM Event field study. Note: Information in table correlates to locations shown on map in Figure 1.

Map	Latitude	Longitude	Height (m)	Type
Rural	32.6844	114.7112	3.04	Anemometer
Rural	32.6844	114.7112	2	PM_{10}
Rural	32.6844	114.7112	2	$PM_{2.5}$
A	32.6990	114.6715	2	$PM_{2.5}$
B	32.6778	114.6493	7.1	$PM_{2.5}$
B	32.6778	114.6493	7.5	PM_{10} (BAM)
C	32.6939	114.6282	2	$PM_{2.5}$
D	32.7172	114.6355	2	$PM_{2.5}$
E	32.7269	114.6222	2	$PM_{2.5}$
Urban	32.6904	114.6146	2	$PM_{2.5}$
Urban	32.6904	114.6146	5	$PM_{2.5}$
Urban	32.6904	114.6146	5.82	Anemometer
Urban	32.6904	114.6146	5	$PM_{2.5}$ (BAM)
Urban	32.6904	114.6146	4.62	XRF
Urban	32.6904	114.6146	4.56	EC, OC, TC

2.1 METEOROLOGICAL MEASUREMENTS

Each of the two micrometeorology stations was equipped with one Campbell Scientific Inc. (Logan, UT) CSAT-3 three-dimensional sonic anemometer. The anemometers were set up to measure three components of wind speed and sonic temperature at a frequency of 10Hz. Three-dimensional wind speed is necessary to calculate turbulence parameters that influence the transport of particulates in the atmosphere. Details of locations and heights of the sonic anemometers are listed in Table 1.

2.2 PARTICULATE MEASUREMENTS

Continuous particulate mass concentrations were acquired using TSI Incorporated (Shoreview, MN) Model 8520 DustTrak aerosol monitors. With the exception of one Rural DustTrak, all DustTrak monitors were set up with inlet nozzles to collect concentration data for particulate with an aerodynamic diameter of 2.5 micrometers and less ($PM_{2.5}$). One DustTrak at the Rural site was set up with an inlet for particulate with an aerodynamic diameter of 10 micrometers and less (PM_{10}). The DustTrak monitors were set up to sample every 3 seconds at the Rural and Urban sites, and every minute at the other locations. The heights and locations of the DustTrak monitoring devices are listed in Table 1.

In addition, mass samples of ambient $PM_{2.5}$ were collected for chemical analysis using two collection devices located 4.5 meters above the ground at the Urban monitoring site: an Airmetrics (Eugene, OR) MiniVol portable air sampler and a dichotomous type collection device (University of Utah) with a BGI Incorporated (Waltham, MA) $PM_{2.5}$ sharp cut inlet cyclone.

The MiniVol sampling device sampled ambient air at 5 liters per minute and collected on 47mm SKC Inc. (Eighty Four, PA) Mixed Cellulose Ester (MCE) filters with a pore size of 0.8μm. These filters were analyzed for inorganic elements with x-ray fluorescence (XRF) by Chester LabNet (Tigard, OR) using an Environmental Protection Agency (EPA) approved method (EPA 1999).

The dichotomous sampler collected particulate, at 16.7 liters per minute, on Whatman (Florham Park, NJ) EPM 2000 quartz filter sheets that were cut with a 22mm punch. The 22mm quartz filters were acid washed in a nitric acid bath and baked at 600^{o}C for 12 hours prior to sample collection. Integral carbon analysis was done by DataChem Laboratories,

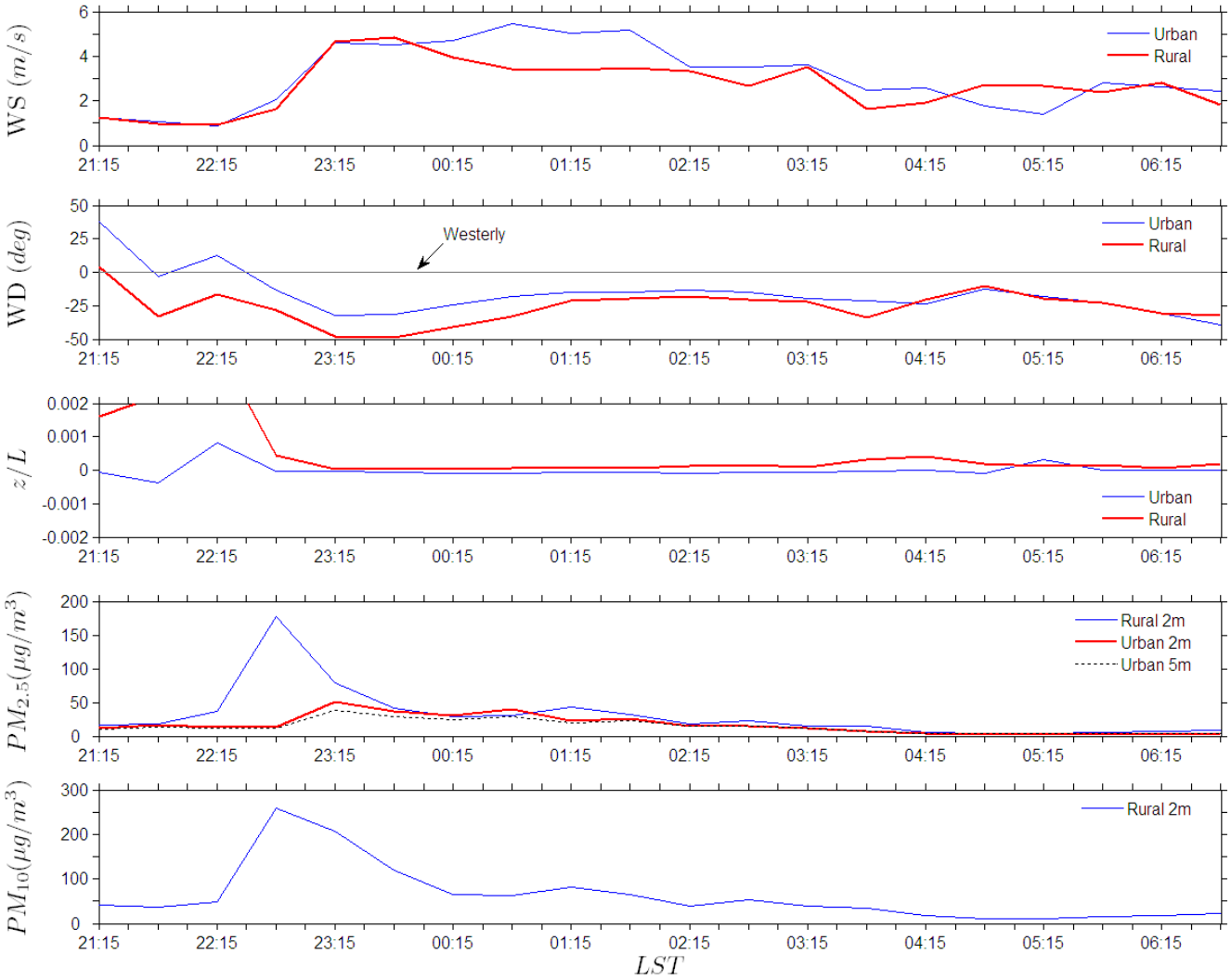

Figure 2: *High-wind Event* PM and meteorological data for March 20-21, 2007 at the Urban (——) and Rural (═══) monitoring sites: (a) mean horizontal wind speed, (b) horizontal wind direction (0 degrees from the west) and (c) Monin-Obukhov stability parameter. PM concentration from DustTrak monitors at both sites, Rural 2 meters (——), Urban 2 meters (═══) and Urban 5 meters (——): (d) PM2.5 and (e) PM10. Note: The stability parameter from plot (c) is nearly zero, indicating a neutral boundary layer.

Inc. (Salt Lake City, UT) using a National Institute for Occupational Safety and Health (NIOSH) approved method (NIOSH 2003) for thermal-optical analysis to determine the carbonaceous fraction of the particulate matter.

Currently, the ADEQ is using Beta-Attenuation Mass (BAM) monitors to collect PM_{10} concentrations at two locations in Yuma and one location in San Luis Rio Colorado, Sonora, Mexico. For the duration of this field experiment, the BAM monitor at the ADEQ Supersite (Urban site) was equipped with a $PM_{2.5}$ inlet cyclone. Hourly averaged, quality controlled BAM data for the Yuma High PM Event field study was obtained from the ADEQ.

3. RESULTS

Sonic data were collected at 10Hz, post-processing steps were necessary to calculate the mean and turbulent quantities. All averaging, and mean quantities, were calculated using a 30 minute block average. To determine fluctuating components the sonic data were linearly detrended with a 2 minute window. Time series PM concentration data, from DustTrak monitors, were block averaged with a 30 minute window.

3.1 HIGH-WIND EVENT

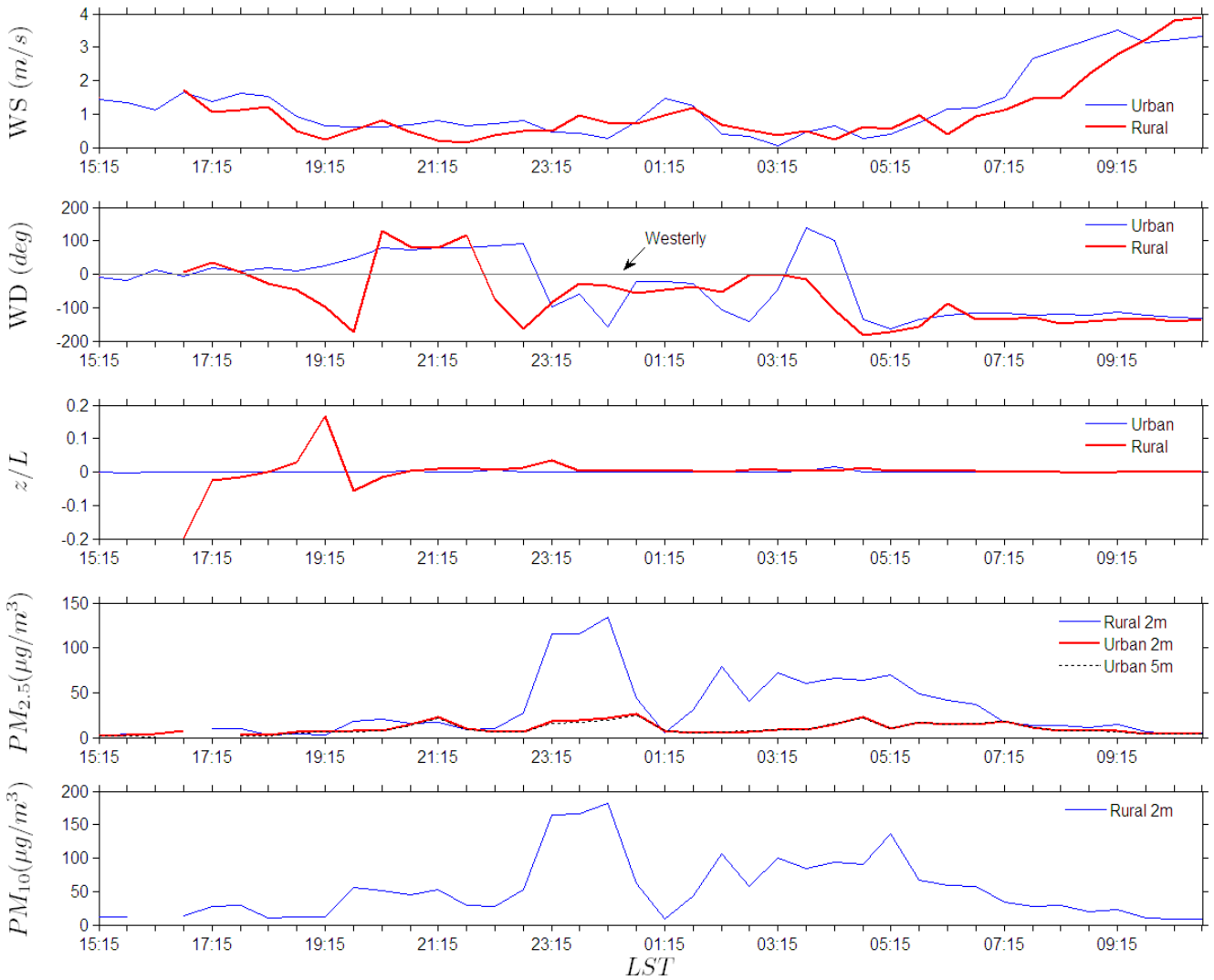

Figure 3: *Burn Event* PM and meteorological data for March 21 – 22, 2007 at the Urban (——) and Rural (═══) monitoring sites: (a) mean horizontal wind speed, (b) horizontal wind direction (0 degrees from the west) and (c) Monin-Obukhov stability parameter. PM concentration from DustTrak monitors at both sites, Rural 2 meters (——), Urban 2 meters (═══) and Urban 5 meters (——): (d) PM2.5 and (e) PM10. Note: Average values of the stability parameter shown in plot (c) are 0.002 for the Urban site and 0.005 for Rural, indicating a slightly stable boundary layer.

Data for the first *High-wind Event* are shown in Figure 2, starting on March 20, 2007 at 21:00 and ending on March 21, 2007 at 07:00. The initial wind speed was calm in the evening and abruptly increased at 22:30 from 1 to 5 meters per second. There were westerly and southwesterly winds throughout the night, with minimal change in wind direction, 45 degrees. The sharp increase in wind speed was accompanied by drop in the Monin-Obukhov stability parameter to nearly zero, indicating a neutral boundary layer.

The PM concentration, both $PM_{2.5}$ and PM_{10}, at the Rural site peaked with the initial suspension of loose crustal material. Since the Obregon Dunes were more than 10 kilometers northwest of the Rural site and the winds were southwesterly, we hypothesize that much of the large PM was from a local source (disturbed agricultural land). After the initial peak at the Rural site, the larger particulate settled out and the remaining PM was well mixed, contributing to a leveling off of the PM at an elevated concentration until morning.

The PM concentration at the Urban site increased 45 minutes after the initial peak at the Rural site. At the Urban site, there were a few local sources of loose crustal material, but much of the area was paved or irrigated turf grass. The westerly winds and lack of local sources

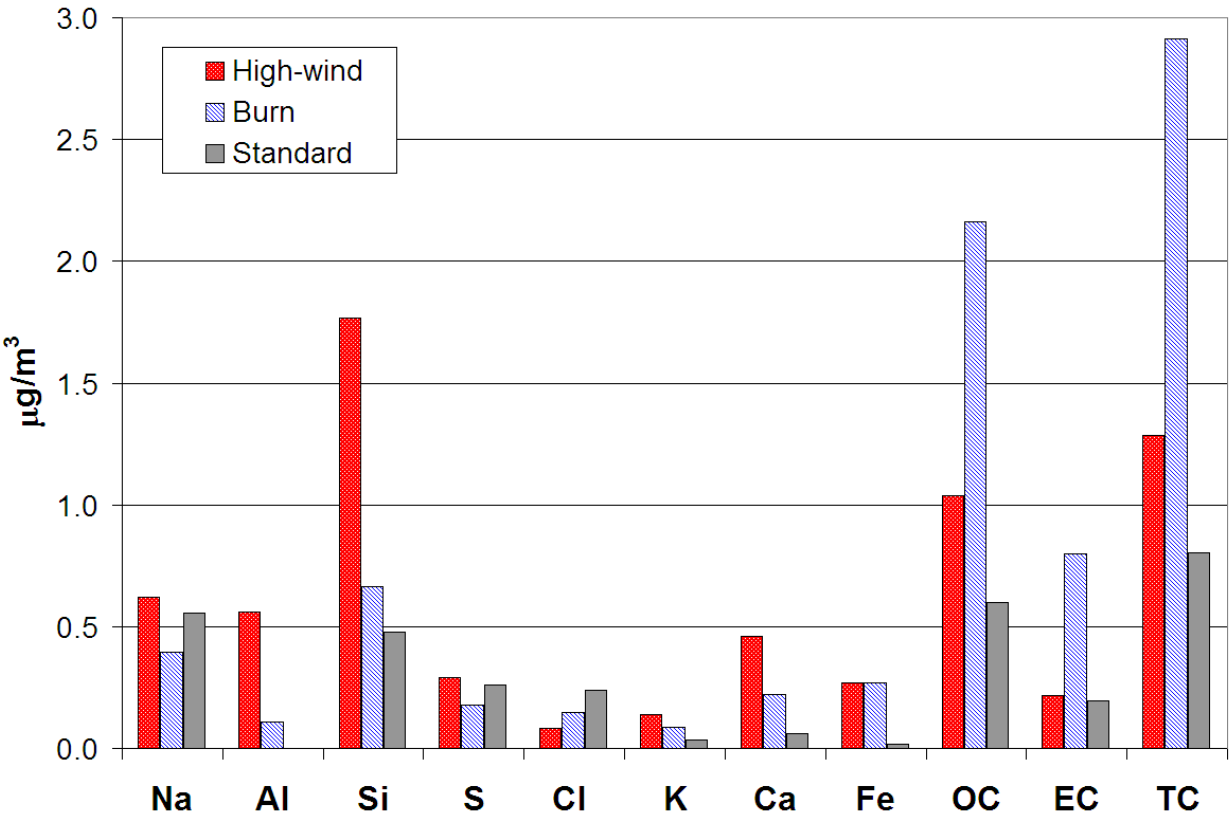

Figure 4: Results of chemical analysis during the *High-wind Event* (■), *Burn Event* (■) and a *Standard Day* (■) for samples taken at the Urban monitoring site. Inorganic elements were evaluated using X-ray fluorescence and the carbon concentrations were determined with thermal-optical analysis.

indicate that the PM was advected from the west through Yuma until it reached the Urban monitoring station.

3.2 BURN EVENT

Meteorological and PM data for the *Burn Event* is shown in Figure 3, starting on March 21, 2007 at 15:00 and ending on March 22, 2007 at 11:00. The wind speed during the burn was low, less than 1 meter per second, until it increased in the morning. The wind direction meandered substantially throughout the event, especially at the Rural site, where the winds shifted from westerly to southerly. The boundary layer was slightly stable and the Monon-Obukhov stability parameter, averaged from midnight to 05:00 on the 22nd, was 0.002 and 0.005 at the Urban and Rural sites respectively.

The PM concentrations at the Rural site increased before the PM at the Urban site, indicating that the particulate had to be advected through Yuma. The PM peak at the Rural site occurred when the wind came from the south, and the concentration decreased when the westerly wind returned. The low wind speed allowed the PM to accumulate throughout the night, until the wind speed increased in the morning.

3.3 CHEMICAL ANALYSIS

Results from the chemical analysis performed on filter samples are shown in Figure 4. The XRF data for the inorganic elements, Sodium (Na), Aluminum (Al), Silicon (Si), Sulfur (S), Chlorine (Cl), Potassium (K), Calcium (Ca) and Iron (Fe) are shown on the left side of the graph. The remaining items, on the right side of the graph, are data from the integrated carbon analysis; organic carbon (OC), elemental carbon (EC) and total carbon (TC). Three events are shown in the figure, the *High-wind* (*HW*) and *Burn Events* (*BE*) that coincide with the previous results and a *Standard Day* (*SD*) to compare with the two high PM events. Samples for the *SD* come from two different time periods; carbon samples were taken during the day on March 23, 2007 and XRF samples were taken late on

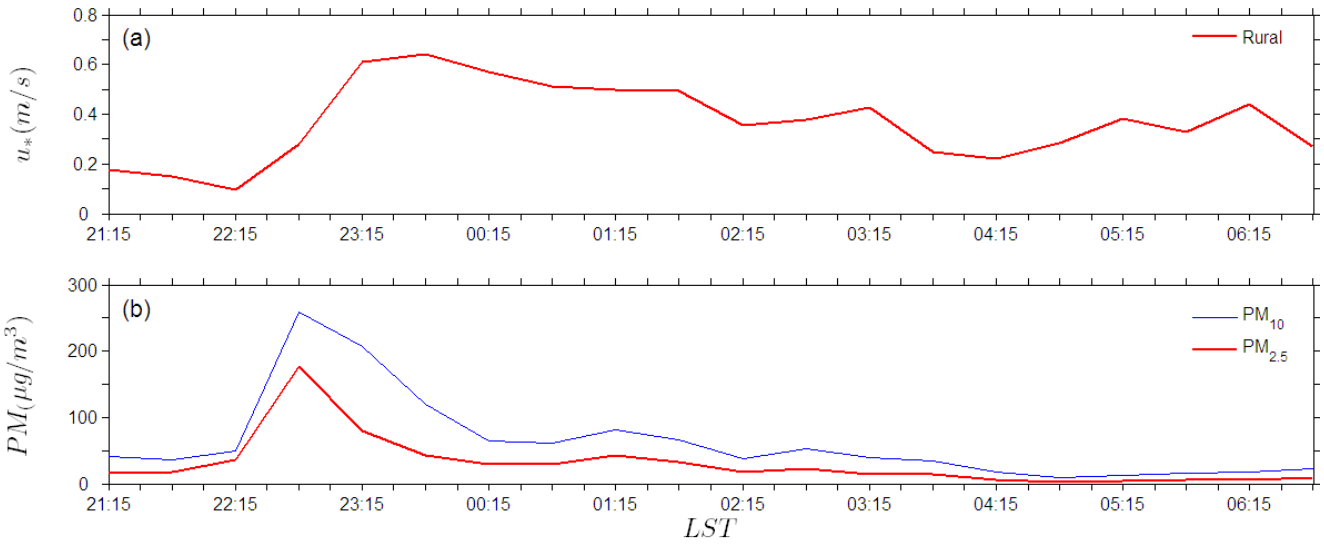

Figure 5: *High-wind Event* friction velocity and PM data for March 20-21, 2007 (a) friction velocity at Rural site ( ) to investigate threshold friction velocities for soils in the area and (b) particulate concentration at the rural site, PM10 ( ) and PM2.5 ( ).

March 23 through early morning on March 24, 2007, both were after it rained the morning of the 23rd.

During the *HW* event the concentration of the inorganic elements are elevated, especially the Si, compared to the *BE* and *SD*. This is to be expected because the sand and soil particles being suspended in the air are composed primarily of inorganic material. The TC content during the *BE* is significantly larger than the wind event or standard day. Elemental carbon is indicative of an incomplete combustion process (Seinfeld & Pandis 1998), and during the *BE* the EC content is 3.5 times greater than during the *HW* and *SD*.

4. DISCUSSION

The physical mechanisms that lead to increased levels of PM in the atmosphere for the *HW* and *BE* are significantly different. The origin and type of the particle for the two cases differ as well. Spatial PM concentrations, chemical analysis and wind data can be used to investigate these differences.

4.1 HIGH-WIND EVENT

The maximum hourly PM_{10} concentration from the BAM monitor located in San Luis Rio Colorado, Sonora, Mexico during the *HW* was 382μg/m^3, compared to 340 μg/m^3 for the same time period in Yuma, AZ. Since the soil properties, and land use (i.e. agricultural), are similar it is logical to expect that the elevated PM concentration from naturally occurring wind events would be similar on either side of the border. As expected, the maximum hourly concentration of $PM_{2.5}$ in Yuma during the *HW* was 42 μg/m^3, much lower than the Yuma PM_{10} concentration. This observation is commensurate with a large fraction of the mass of PM residing in larger particle sizes during erosion of crustal material during wind events.

It is interesting to point out that during the *HW* the initial peak of particulate at the Rural site occurs before the largest wind speed (Figure 2). This initial spike in PM concentration occurs at the Rural site, and not the Urban site, because loose soil and agricultural fields surround the Rural monitoring station. The disturbed soil has a threshold friction velocity that correlates to the ability of the wind to disturb the soil and cause erosion.

The agricultural fields west of the Rural monitoring site are composed primary of clay type soils; Gadsden clay, Glenbar silty clay loam, Holtville clay and Kofa clay (USDA-NRCS 2007). The Colorado River was 3km west of the Rural monitoring site, and the soil near the river is classified as Rositas sand (USDA-NRCS 2007). Through Natural Resources Conservation Services (NRCS) the United States Department of Agriculture (USDA) developed Wind Erodibility Groups (WEG) for soil characterization. Soils are classified into nine categories, groups 1 through 8 and 4L, the lower the number the greater chance the soil is susceptible to wind erosion. The clay type soils

at the Rural site are classified as WEG 4, the silty clay loam WEG 4L and the Rositas sand WEG 1 (USDA-NRCS 2007).

Using the WEG information a threshold friction velocity (u_{*t}) for the soil type can be inferred and compared to the friction velocity (u_*) measured at the Rural site during the *HW* event. Threshold friction velocity values for loose soil in WEG 4, 4L and 1 are 0.4-0.9 m/s, 0.7 m/s and 0.2-0.3 m/s respectively (Gillette 1988).

The friction velocity, and PM concentration, measured at the Rural site during the *HW* are shown in Figure 5. The spike in PM concentration occurs at a u_* value of ~0.3 m/s, which is within the range of expected u_{*t} values at that location. After the loose soil was suspended in the air the PM became well mixed and the concentration stabilized at an elevated level until the wind speed decreased in the early morning.

4.2 BURN EVENT

During the *BE*, the maximum PM_{10} in San Luis Rio Colorado, 790$\mu g/m^3$, was much greater than the PM_{10} concentration in Yuma, 79$\mu g/m^3$. The high PM_{10} concentration data in Mexico are indicative of the burn originating on the Mexican side of the border. The $PM_{2.5}$ concentration in Yuma was 32$\mu g/m^3$ a reasonable fraction of the PM for this type of episode (Seinfeld & Pandis 1998).

The wind direction during the *BE* (Figure 3) indicates that the increase in PM at the Rural site occurs when the wind in coming from the south. However, at the Urban site, the wind was westerly, hence the increase in PM at the Urban site occurs after the peak at the Rural site. This in conjunction with the increased surface roughness associated with the urban area likely resulted in the dilution of PM concentration that occurred as the plume was advected from the west through Yuma to the Urban site. Once the wind direction shifted, and the wind was from the west at the Rural site, the PM concentrations decreased. However, since the wind speed was low the PM remains until the wind speed increased in the morning.

The chemical analysis results (Figure 4) show increased levels of elemental carbon during the *BE*. This is usually the result of an anthropogenic combustion process, i.e. trash burning, industrial fuel combustion or diesel exhaust (Seinfeld & Pandis 1998). Since it is harder to enforce air quality regulations for informal industries in Mexico there are often increased levels of PM due to fuel combustion, another indicator that the burn may have originated in Mexico (Blackman *et al* 2006).

5. SUMMARY

The observations presented in this work indicate significant spatial heterogeneity associated with PM concentrations during high PM events along the U.S./Mexico border. Here substantial differences, during burn and high-wind PM events, were observed between urban and rural sites located in close proximity. The Rural site was located near agricultural fields with loose, disturbed soil that were correlated with high local particulate concentrations during a high-wind event. The PM concentrations at the Yuma Urban site were considerably diluted, in both cases, compared to the Rural site. In addition, the Yuma Urban observations during the burn event were an order of magnitude lower than those observed in the urban area of San Louis Rio Colorado. Regardless of the type of event, burn or wind, the Rural site tended to have higher levels of particulate concentration.

Although the increased PM concentration caused by the naturally occurring wind event was similar on either side of the border, the PM concentration during the burn was greater on the Mexico side. The concentration was higher in Mexico because the man-made burn likely originated there. Since Yuma is located northeast of San Luis Rio Colorado and the prevailing winds in the area are from the southwest, it is expected that PM originating on the Mexico side of the border will commonly be advected through Yuma.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Blackman, A., Shih, J-S, Evans, D., Batz, M., Newbold, S. & Cook, J. (2006) The benefits and costs of informal sector pollution control: Mexican brick kilns. *Environ. Dev. Econ*. **11**, 603-627.

Choi, Y.-J., Hyde, P. & Fernando, H.J.S. (2006) Modeling of episodic particulate matter events using a 3-Dair quality model with fine grid: Applications to a pair of cities in the U.S./Mexico border. *Atmos. Environ*. **40**, 5181-5201.

EPA (1999) Determination of metals in ambient particulate matter using x-ray fluorescence (XRF) spectroscopy. *Compendium Method IO-3.3*, EPA/625/R-96/010a.

Gillette, D.A. (1988) Threshold friction velocities for dust production for agricultural soils. *J. Geophys. Res.,* **93**, 12645-12662.

NIOSH (2003) Manual of Analytical Methods (NMAM). O'Connor, P.F. & Schlect, P.C. Monitoring of diesel particulate exhaust in the workplace. *Chapter Q* Third Supplement to NMAM, 4th Ed, Publication No. 2003-154.

Seinfeld, J. H. & Pandis, S. N. (1998) *Atmospheric chemistry and physics*. John Wiley & Sons.

USDA-NRCS (2007) National Cooperative Soil Survey, accessed through Web Soil Survey, http://websoilsurvey.nrcs.usda.gov/app/, August 28, 2007.