

# The Steubenville Comprehensive Air Monitoring Program (SCAMP): Analysis of Short-Term and Episodic Variations in PM<sub>2.5</sub> Concentrations Using Hourly Air Monitoring Data

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## ABSTRACT

One-hour average ambient concentrations of particulate matter (PM) with an aerodynamic diameter  $<2.5 \mu\text{m}$  (PM<sub>2.5</sub>) were determined in Steubenville, OH, between June 2000 and May 2002 with a tapered element oscillating microbalance (TEOM). Hourly average gaseous copollutant [carbon monoxide (CO), sulfur dioxide (SO<sub>2</sub>), nitrogen oxide (NO<sub>x</sub>), and ozone (O<sub>3</sub>)] concentrations and meteorological conditions also were measured. Although 75% of the 14,682 hourly PM<sub>2.5</sub> concentrations measured during this period were  $\leq 17 \mu\text{g}/\text{m}^3$ , concentrations  $>65 \mu\text{g}/\text{m}^3$  were observed 76 times. On average, PM<sub>2.5</sub> concentrations at Steubenville exhibited a diurnal pattern of higher early morning concentrations and lower afternoon concentrations, similar to the diurnal profiles of CO and NO<sub>x</sub>. This pattern was highly variable; however, PM<sub>2.5</sub> concentrations  $>65 \mu\text{g}/\text{m}^3$  were never observed during the mid-afternoon between 1:00 p.m. and 5:00 p.m. EST. Twenty-two episodes centered on one or more of these elevated concentrations were identified. Five episodes occurred during the months June through August; the maximum PM<sub>2.5</sub> concentration during these

episodes was  $76.6 \mu\text{g}/\text{m}^3$ . Episodes occurring during climatologically cooler months often featured higher peak concentrations (five had maximum concentrations between 95.0 and  $139.6 \mu\text{g}/\text{m}^3$ ), and many exhibited strong covariation between PM<sub>2.5</sub> and CO, NO<sub>x</sub>, or SO<sub>2</sub>. Case studies suggested that nocturnal surface-based temperature inversions were influential in driving high nighttime concentrations of these species during several cool season episodes, which typically had dramatically lower afternoon concentrations. These findings provide insights that may be useful in the development of PM<sub>2.5</sub> reduction strategies for Steubenville, and suggest that studies assessing possible health effects of PM<sub>2.5</sub> should carefully consider exposure issues related to the intraday timing of PM<sub>2.5</sub> episodes, as well as the potential for toxicological interactions among PM<sub>2.5</sub> and primary gaseous pollutants.

## INTRODUCTION

Many studies assessing the health effects<sup>1,2</sup> of fine particulate matter (aerodynamic diameter  $<2.5 \mu\text{m}$  [PM<sub>2.5</sub>]) or factors that affect ambient PM<sub>2.5</sub> concentrations<sup>3,4</sup> have used data that represent concentrations averaged over periods of 24 hr or longer. However, PM<sub>2.5</sub> concentrations at a given location often vary appreciably within a 24-hr time frame. Fitz-Simmons et al.<sup>5</sup> examined hourly PM<sub>2.5</sub> concentration data collected in 1999 using 31 monitors located throughout the United States and discovered an overall average diurnal profile consisting of morning and evening maxima, although the pattern varied by location and from day-to-day at a given location. Chuersuwan et al.<sup>6</sup> found that high 1-hr average PM<sub>2.5</sub> concentrations could occur on days with low 24-hr average concentrations during cool portions of the year in Newark, NJ. In Atlanta, GA, Weber et al.<sup>7</sup> similarly observed that transient episodes of elevated PM<sub>2.5</sub> concentrations evident among hourly data were largely masked when the data

## IMPLICATIONS

Previous studies assessing concentrations of PM<sub>2.5</sub> and their possible health effects in Steubenville, OH, have used 24-hr average data. However, PM<sub>2.5</sub> concentrations can vary considerably on a shorter time scale. To gain insight into these variations, this paper examines nearly 2 years of continuous (hourly) air monitoring data collected at Steubenville. Results highlight characteristics of PM<sub>2.5</sub> episodes that are not captured by 24-hr average data and provide information that may be useful for developing a PM<sub>2.5</sub> reduction strategy for Steubenville. Furthermore, the analysis reveals potentially important features of transient PM<sub>2.5</sub> episodes that should be considered when appraising possible health effects of PM<sub>2.5</sub>.

were averaged over 24 hr. These findings collectively suggest that a thorough assessment of PM<sub>2.5</sub> and its possible effects at a given location must include an evaluation of data having an hourly (or finer) resolution.

Two recent articles<sup>8,9</sup> presented analyses of daily PM<sub>2.5</sub>, co-pollutant, and meteorological data collected between May 2000 and May 2002 in Steubenville, OH, as part of the Steubenville Comprehensive Air Monitoring Program (SCAMP). The average PM<sub>2.5</sub> concentration at Steubenville during the study period (18.4 μg/m<sup>3</sup>) exceeded the annual PM<sub>2.5</sub> National Ambient Air Quality Standard (NAAQS) of 15 μg/m<sup>3</sup>, suggesting that PM<sub>2.5</sub> reduction for Steubenville will likely be required. Statistically significant associations between PM<sub>2.5</sub> and a number of gaseous co-pollutant and meteorological variables were discovered, many of which depended on the season and were particularly strong during certain episodes of elevated PM<sub>2.5</sub> concentration. The analyses suggested that the influence of meteorology must be carefully considered when developing a PM<sub>2.5</sub> reduction strategy for Steubenville, and they highlighted the potential for confounding by gaseous co-pollutants in epidemiological studies conducted there. However, the understanding gained from the analyses was ultimately restricted by the limited time resolution of the data. Fortunately, PM<sub>2.5</sub> concentration also was measured continuously at Steubenville during SCAMP, resulting in over 14,500 valid hourly data points. In this paper, these data are analyzed with hourly co-pollutant and meteorological data to further the understanding of PM<sub>2.5</sub> in the Steubenville region.

An analysis of hourly PM<sub>2.5</sub> concentrations in Steubenville has important implications for several areas of interest related to PM. To develop a successful PM<sub>2.5</sub> reduction strategy for Steubenville, a thorough understanding of the factors that influence PM<sub>2.5</sub> concentrations in the city will be required. Several studies conducted at other locations have employed hourly data to gain insight into such factors. For instance, Hansen et al.<sup>10</sup> used hourly PM<sub>2.5</sub> and gaseous co-pollutant data to identify sources likely contributing to various PM<sub>2.5</sub> pollution episodes in the southeastern United States. Triantafyllou et al.<sup>11</sup> used diurnal profiles to draw inferences about the influence of meteorological conditions and emission sources on hourly PM<sub>10</sub> concentrations in northern Greece, and Strohm et al.<sup>12</sup> used hourly data to pinpoint the behavior of PM<sub>2.5</sub> concentrations in several midwestern U.S. cities in response to changes in weather conditions during a PM<sub>2.5</sub> episode. Other studies<sup>13-17</sup> have used time-resolved measurements of particular aerosol components to study the chemistry and origins of PM. Although continuous PM<sub>2.5</sub> composition data are not available for the Steubenville monitoring site, the available data permit an investigation of the influence of meteorology on

PM<sub>2.5</sub> concentrations in Steubenville, as well as the associations between PM<sub>2.5</sub> and various pollutant gases.

Moreover, although this paper does not attempt to assess possible associations between PM<sub>2.5</sub> and human health, the analysis presented here provides information that may be useful in designing and interpreting the results of PM<sub>2.5</sub> health effects studies. Epidemiological studies<sup>1,18,19</sup> that correlated Steubenville's ambient PM concentrations with adverse health effects were performed with daily average data. A few more recent studies conducted elsewhere, however, have suggested that shorter-term acute exposures to PM may be more closely associated with adverse health effects than exposures reflected by daily average data. Delfino et al.<sup>20</sup> found that asthma symptoms were more strongly associated with 1-hr and 8-hr maximum PM<sub>10</sub> concentrations than with 24-hr mean PM<sub>10</sub> concentrations. In addition, Peters et al.<sup>21</sup> reported a statistically significant increase in the risk of myocardial infarction within 2 hr of exposure to short-term elevated PM<sub>2.5</sub> concentrations. By examining hourly PM<sub>2.5</sub> data, this paper allows for a time-resolved characterization of the frequency and intensity of episodes of elevated PM<sub>2.5</sub> concentration in Steubenville, as well as an assessment of the association between these episodes and 24-hr average PM<sub>2.5</sub> concentrations. Knowledge about the timing of these episodes also may be important for assessing human exposure to PM<sub>2.5</sub> that is "generated outdoors"<sup>22</sup> in the Steubenville region, because human activity patterns related to exposure (e.g., time spent outdoors and changes in home ventilation conditions) likely vary based on factors such as time of day and meteorological conditions. Finally, the examination of hourly PM<sub>2.5</sub> and gaseous co-pollutant data collected at Steubenville enables a better understanding of the associations that were observed among these variables when daily data were studied. Strong correlations among concentrations of PM<sub>2.5</sub> and gaseous co-pollutants may cause collinearity problems in epidemiological studies. Moreover, information about simultaneous occurrences of elevated concentrations of PM<sub>2.5</sub> and co-pollutants may be toxicologically important. Synergistic toxicological interactions among gaseous and particulate pollutants have been observed;<sup>23,24</sup> these interactions are affected by environmental factors including concentration, sequence, and duration of exposure.<sup>25</sup> Hourly PM<sub>2.5</sub> and co-pollutant data presented in this article could be extrapolated to determine the potential for such synergistic interactions to occur during pollution episodes in Steubenville.

## METHODS

### Ambient Air Monitoring

All data reported in this paper were collected at the SCAMP central outdoor ambient air monitoring site,<sup>8</sup>

located on the campus of Franciscan University of Steubenville in Steubenville, OH. A number of industrial facilities, including coke plants, metal smelting and processing plants, coal-fired electric power plants, and manufacturing facilities, are concentrated along the Ohio River, which flows approximately due north to due south in the vicinity of Steubenville. The SCAMP monitoring site was situated atop a bluff that overlooks the river and the major vehicular thoroughfare through Steubenville, and it was within a few kilometers of several major industrial plants. A long-term parking lot near the monitoring site was usually full but experienced only infrequent traffic.

Ambient  $PM_{2.5}$  mass concentrations were measured continuously from June 14, 2000, through May 14, 2002, with a Rupprecht & Patashnick Series 1400a tapered element oscillating microbalance (TEOM)<sup>26</sup> equipped with a sharp cut inlet for  $PM_{2.5}$ . The instrument was configured in the standard way to collect  $PM_{2.5}$  from a 3 L/min sample stream on a Teflon-coated glass-fiber filter. The TEOM filter and sample stream were maintained at 50 °C to remove moisture from the sampled air and prevent condensation on the filter. However, operation at this temperature may also cause the loss of some semi-volatile PM (e.g., ammonium nitrate, semi-volatile organic compounds, and particle-bound water), resulting in an underestimation of total  $PM_{2.5}$  mass.<sup>27,28</sup> The magnitude of this artifact depends on the composition of the sampled  $PM_{2.5}$ , and therefore varies with location and time.<sup>27</sup> TEOMs can be equipped with a Nafion diffusion dryer for moisture removal and operated at 30 °C to reduce the loss of semi-volatile material; however, this was not common practice at the time of SCAMP. All TEOM data collected during SCAMP were validated against operational performance criteria established by the instrument manufacturer.<sup>29</sup>

Ambient concentrations of gaseous priority pollutants ( $SO_2$ ,  $NO_x$ , CO, and  $O_3$ ) were measured continuously from May 16, 2000, through May 14, 2002, with an Advanced Pollution Instruments (API) model 900 turnkey ambient air sampling system, which has been described previously.<sup>9</sup> The  $NO_x$  analyzer determined concentrations of  $NO_x$  and NO;  $NO_2$  concentrations were computed by difference. All gas measurements were made in accordance with quality assurance guidelines outlined by the U.S. Environmental Protection Agency (EPA).<sup>30,31</sup> The performance of each analyzer was monitored by taking daily (shortly after midnight) calibration readings for zero and span concentrations of appropriate certified gas standards. Zero and span control charts were used to determine the validity of measured data and to determine when physical adjustments to the instruments were required.

Meteorological conditions, including wind speed (WS), temperature (Temp), relative humidity (RH), solar radiation (Rad), and barometric pressure (BP), were monitored continuously from May 16, 2000, through May 14, 2002, with standard instrumentation (Met One) atop a 10-m tower.

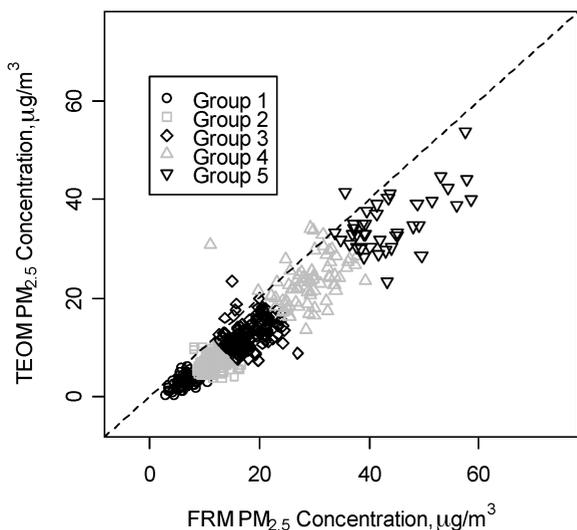
All continuous data were recorded and averaged over 1-hr time periods by an automated data logger. For each gaseous co-pollutant, to account for changes in instrument performance over time, these hourly average concentrations were subsequently corrected by linear interpolation between adjacent daily calibration readings.<sup>30</sup>

Twenty-four-hour average data also were collected at the Steubenville site, as described previously.<sup>8</sup> Mass concentrations of  $PM_{2.5}$  were measured each day using the Federal Reference Method (FRM) for  $PM_{2.5}$ . In addition, for every fourth day of the program, mass concentrations of fine particulate ionic species ( $SO_4^{2-}$ ,  $NO_3^-$ ,  $NH_4^+$ , and  $Cl^-$ ) were determined by ion chromatography, and mass concentrations of elemental carbon and organic carbon were determined by a thermal optical transmittance procedure. These data were available for comparison with the continuous data that are the focus of this article.

#### **Accuracy and Precision of TEOM and FRM $PM_{2.5}$ Measurements**

Because of the aforementioned compositionally dependent artifact of the TEOM method for determining  $PM_{2.5}$  mass concentrations, an assessment of the performance of the TEOM monitor relative to the performance of the collocated FRM monitor at the Steubenville site was performed. For the purpose of this comparison, hourly TEOM data were averaged over 24-hr periods corresponding to the FRM sampling schedule; at least 19 valid hourly data were required for a valid 24-hr average. Five hundred fifteen pairs of collocated 24-hr average measurements were available for the analysis. Measurement errors were more nearly normal when these data were transformed with a fourth root Box-Cox transformation; hence, estimates of bias and imprecision were computed in the transformed metric and then converted back to the original scale.

Although often improperly employed for this purpose, regression analysis cannot be used to assess the bias and precision of two collocated instruments because, among other problems, the results are inconsistent (i.e., the regression results change depending on which device is used as the dependent variable). Rather, because the range of  $PM_{2.5}$  concentrations measured at the Steubenville site was large ( $\sim 60 \mu\text{g}/\text{m}^3$ ) whereas the sampler imprecision was comparatively small, the data set was divided into five subgroups with more homogeneous  $PM_{2.5}$  concentrations. Figure 1 shows these



**Figure 1.** Scatter plot of paired 24-hr average PM<sub>2.5</sub> concentrations measured with the collocated TEOM and FRM samplers at the Steubenville monitoring site between June 2000 and May 2002. The five subgroups used to compute separate estimates of bias and imprecision are denoted.

groups in the untransformed metric. This strategy, which was feasible because of the large number of available collocated observations, avoids the assumption that the bias is constant over the entire range of observed concentrations. For each group, the imprecisions of the FRM and TEOM samplers were estimated (imprecision was computed as the square root of the difference between the variance in the method being considered and the covariance between the two methods), and the bias of the TEOM relative to the FRM was computed (relative bias was assumed to be constant in each group).

Results are shown in Table 1. The table indicates that 24-hr average PM<sub>2.5</sub> concentrations measured by the TEOM during SCAMP tended to be lower than concentrations measured by the FRM sampler, and that the magnitude of this bias increased with concentration, ranging from about  $-3.7 \mu\text{g}/\text{m}^3$  to  $-8.4 \mu\text{g}/\text{m}^3$  as the FRM-determined concentration increased from  $6.6 \mu\text{g}/\text{m}^3$  to  $43.2 \mu\text{g}/\text{m}^3$ . Hence, the two samplers have a nonconstant relative bias. Bias as a percentage of the FRM-determined PM<sub>2.5</sub> concentration decreased as observed concentrations increased. These findings are consistent with the hypothesis that as the total mass of PM<sub>2.5</sub> increases, so too does the mass of semi-volatile PM<sub>2.5</sub>, resulting in a greater amount of mass that can be lost from the TEOM filter. However, the proportion of mass lost on high PM<sub>2.5</sub> days is smaller than the proportion lost on low PM<sub>2.5</sub> days, perhaps because the PM<sub>2.5</sub> mass on high concentration days tends to include a smaller fraction of semi-volatile material, or

**Table 1.** Bias and imprecision of the TEOM and FRM samplers used during SCAMP as a function of measured PM<sub>2.5</sub> concentration.

Group	N	Mean Concentration ( $\mu\text{g}/\text{m}^3$ )		Relative Bias of TEOM <sup>a</sup>		Imprecision ( $\mu\text{g}/\text{m}^3$ )	
		TEOM	FRM	$\mu\text{g}/\text{m}^3$	% <sup>b</sup>	TEOM	FRM
1	90	2.9	6.6	-3.7	-55.6	1.7	0.0
2	160	6.7	11.4	-4.7	-41.2	1.9	1.3
3	150	12.2	17.8	-5.6	-31.7	2.8	1.8
4	75	22.8	28.6	-5.8	-20.4	4.2	3.8
5	40	34.9	43.2	-8.4	-19.4	4.0	4.2

*Notes:* Bias and imprecision were computed on the basis of 24-hr average concentrations; Groups of collocated measurements are defined in Figure 1; All computations were made in the transformed metric, and then converted back to the original scale; <sup>a</sup>Bias of the TEOM relative to the FRM, defined to be negative if the TEOM-measured concentration is lower than the FRM-measured concentration; <sup>b</sup>Percent bias =  $100 \times (\text{relative bias in } \mu\text{g}/\text{m}^3 / \text{mean FRM concentration})$ .

because thermodynamic conditions on high concentration days are less favorable for volatilization. It should also be noted that although the bias of the TEOM was determined relative to the FRM, the FRM is also subject to artifacts for semi-volatile species<sup>32</sup> (although presumably to a lesser extent than the TEOM) and does not necessarily measure true ambient PM<sub>2.5</sub> concentrations.

Table 1 also shows that the imprecisions (in  $\mu\text{g}/\text{m}^3$ ) of the TEOM and FRM generally tended to increase with increasing PM<sub>2.5</sub> concentration. The estimated imprecision of the TEOM ranged from  $1.7 \mu\text{g}/\text{m}^3$  for Group 1 to  $4.2 \mu\text{g}/\text{m}^3$  for Group 4, and the estimated imprecision of the FRM ranged from  $0.0 \mu\text{g}/\text{m}^3$  for Group 1 to  $4.2 \mu\text{g}/\text{m}^3$  for Group 5. For a given group, the imprecisions of the two methods were generally fairly similar, differing by no more than  $1.7 \mu\text{g}/\text{m}^3$ . The greatest disparity occurred for the lowest observed PM<sub>2.5</sub> concentrations (Group 1), for which the FRM exhibited better precision than the TEOM.

A more thorough evaluation of the performance of the TEOM at Steubenville might closely examine the influence of variables such as season, temperature, RH, and PM<sub>2.5</sub> composition. Such variables may be useful for inclusion in models aimed at adjusting TEOM data for comparison with air quality standards based on the FRM.<sup>33</sup> This article, however, is not focused on determining compliance with PM<sub>2.5</sub> standards, but rather it examines PM<sub>2.5</sub> episodes marked by changes in concentration that are much greater in magnitude than the bias observed between the TEOM and the FRM. Nonetheless, this bias should be considered when interpreting the results presented here; hourly average PM<sub>2.5</sub> concentrations reported in this article are likely lower than true ambient concentrations.

**Table 2.** Descriptive statistics for all valid 1-hr average PM<sub>2.5</sub>, gaseous co-pollutant, and weather data measured at the Steubenville monitoring site between May 2000 and May 2002.

Variable	N	Mean	SD	Min	Percentile				Max
					25	50	75	90	
PM <sub>2.5</sub> (μg/m <sup>3</sup> )	14,682	12.7	12.5	-9.0	4.3	8.6	17.0	29.5	139.6
SO <sub>2</sub> (ppb)	14,969	10.6	14.0	0.4	2.9	6.0	12.4	24.0	233.9
NO (ppb)	13,857	6.8	14.9	-1.4	0.3	1.2	4.9	20.8	215.3
NO <sub>2</sub> (ppb)	12,562	12.7	8.9	-0.5	5.6	10.1	18.0	26.0	52.9
NO <sub>x</sub> (ppb)	12,952	18.8	19.8	-0.8	6.4	11.5	23.5	43.5	196.9
CO (ppm)	14,881	0.30	0.58	-0.19	0.05	0.13	0.29	0.70	8.09
O <sub>3</sub> (ppb)	13,482	27.9	19.2	-0.4	12.1	25.7	39.5	54.9	104.3
WS (m/sec)	16,860	2.52	1.40	0.24	1.43	2.23	3.29	4.46	11.78
Temp (°C)	16,853	11.0	10.0	-16.5	2.9	12.1	19.3	23.5	32.8
RH (%)	16,840	72.09	17.80	13.63	59.37	73.72	86.92	94.94	99.64
Rad (W/m <sup>2</sup> )	14,653	152	236	0	1	8	226	544	1120
BP <sup>a</sup> (mmHg)	16,849	733.4	4.6	715.5	730.8	733.8	736.4	738.9	746.8

<sup>a</sup>Not corrected to sea level; measurements were taken ~315 m above sea level.

## RESULTS AND DISCUSSION

### Statistical Summary of Hourly Air Monitoring Data

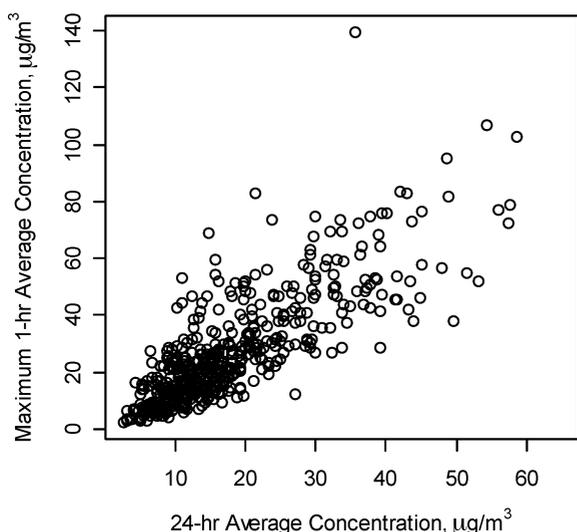
Table 2 presents descriptive statistics for all 1-hr average PM<sub>2.5</sub> concentrations, gaseous co-pollutant concentrations, and weather conditions measured at the Steubenville monitoring site between May 2000 and May 2002. Some 1-hr average PM<sub>2.5</sub> concentrations measured with the TEOM were negative, probably because the mass of PM<sub>2.5</sub> lost from the filter because of volatilization exceeded the mass of fresh PM<sub>2.5</sub> collected on the filter during those periods. In addition, negative values were obtained for several hourly average gaseous co-pollutant concentration measurements that otherwise met all validation criteria, indicating that ambient concentrations were smaller than instrument noise during those 1-hr periods. Although negative concentrations clearly do not represent physical reality, these negative values were used in the analyses presented in this article, because adjusting them would introduce bias.

As implied in Table 2, the distribution of hourly average PM<sub>2.5</sub> concentrations measured at Steubenville during SCAMP was positively skewed. Hourly PM<sub>2.5</sub> concentrations at the monitoring site were typically low-to-moderate; half of all hourly PM<sub>2.5</sub> concentrations were  $\leq 8.6 \mu\text{g}/\text{m}^3$ , and 75% were  $\leq 17 \mu\text{g}/\text{m}^3$ . However, large positive deviations from these typical concentrations were observed during a number of instances. The maximum 1-hr average PM<sub>2.5</sub> concentration measured during SCAMP was  $139.6 \mu\text{g}/\text{m}^3$ , and 1-hr average concentrations  $>65 \mu\text{g}/\text{m}^3$  were measured 76 times during the program. Hour-to-hour changes in PM<sub>2.5</sub> concentrations during SCAMP were also typically small in magnitude,

ranging from a twenty-fifth percentile of  $0.6 \mu\text{g}/\text{m}^3$  to a seventy-fifth percentile of  $3.3 \mu\text{g}/\text{m}^3$ . Rapid short-term changes in concentration similar to those observed by Weber et al.<sup>7</sup> in Atlanta occurred in several instances, however. Positive or negative 1-hr changes of  $\geq 20 \mu\text{g}/\text{m}^3$  occurred 154 times during SCAMP, and positive or negative 1-hr changes of  $>60 \mu\text{g}/\text{m}^3$  occurred 4 times. Because of their particular relevance to understanding possible causes and effects of ambient PM<sub>2.5</sub> concentrations, episodes marked by these abnormally elevated PM<sub>2.5</sub> concentrations and rapid changes in concentration are the major focus of this article.

The distributions of hourly average gaseous co-pollutant concentrations measured at Steubenville were also positively skewed. Despite the prevalence of point source emissions of gaseous pollutants in the Steubenville region, 1-hr average gaseous pollutant concentrations measured during SCAMP were well below regulatory levels set by the EPA. No hourly CO concentration exceeded the 1-hr CO NAAQS of 35 ppm, and no hourly O<sub>3</sub> concentration exceeded the 1-hr O<sub>3</sub> NAAQS of 120 ppb. All 1-hr average SO<sub>2</sub> concentrations were well below the 3-hr SO<sub>2</sub> NAAQS of 500 ppb, and all NO<sub>2</sub> concentrations were below the annual NO<sub>2</sub> NAAQS of 53 ppb. Nonetheless, substantial positive deviations from average concentrations were observed for each gaseous co-pollutant. Associations between these deviations and occurrences of abnormally elevated PM<sub>2.5</sub> concentrations will be evaluated in this article.

Figure 2 presents a scatterplot of 24-hr average PM<sub>2.5</sub> concentrations measured with the FRM and maximum 1-hr average PM<sub>2.5</sub> concentrations measured during the

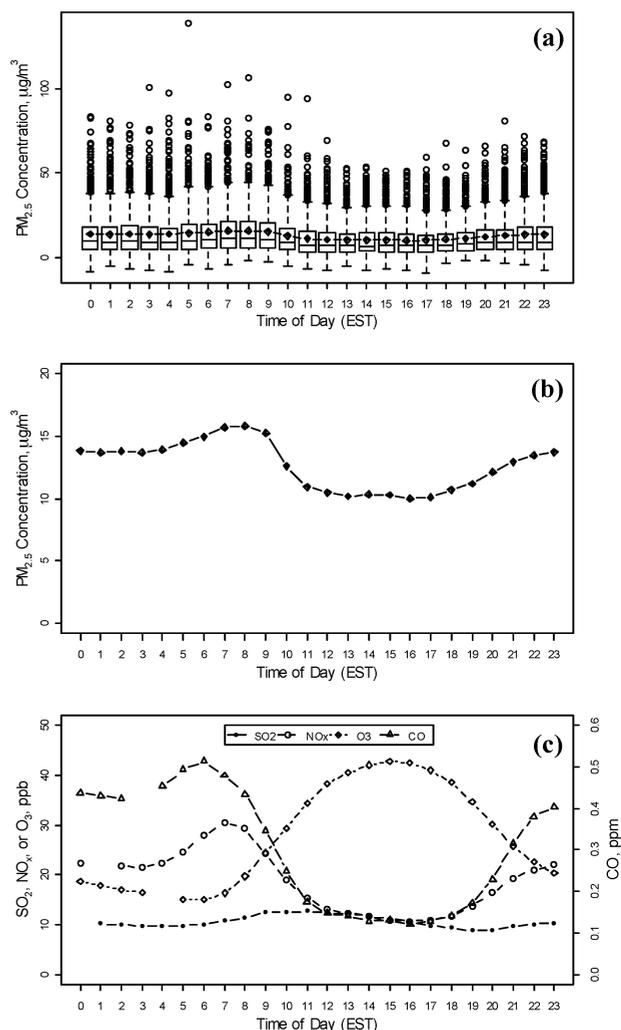


**Figure 2.** Pairwise comparison of daily average and 1-hr max PM<sub>2.5</sub> concentrations measured at Steubenville between June 2000 and May 2002. Daily averages were measured with the FRM sampler; 1-hr maxima were measured with the TEOM sampler.

same 24-hr periods. Twenty-four-hour average concentrations generally indicated the potential for exposure to high 1-hr average PM<sub>2.5</sub> concentrations, although there were several exceptions. For 5 days, the 1-hr maximum PM<sub>2.5</sub> concentration was >65 µg/m<sup>3</sup>, whereas the 24-hr average concentration was ≤30 µg/m<sup>3</sup>. Moreover, the highest hourly PM<sub>2.5</sub> concentration observed during SCAMP (139.6 µg/m<sup>3</sup>) occurred on a day when the average concentration was only 35.7 µg/m<sup>3</sup>. These results are consistent with previous findings<sup>6,7</sup> that short-term exposures to high PM<sub>2.5</sub> concentrations can be masked by the use of 24-hr average data, although extreme occurrences of this disparity occurred infrequently at Steubenville during SCAMP.

### Diurnal Patterns in PM<sub>2.5</sub> and Co-Pollutant Concentrations

To preliminarily assess the intraday variability of PM<sub>2.5</sub> concentrations in Steubenville, average diurnal patterns in PM<sub>2.5</sub> concentrations measured during SCAMP were studied. Figure 3a shows the distributions of all hourly PM<sub>2.5</sub> concentrations grouped by time of day (Eastern Standard Time). An average diurnal profile is slightly discernible, although it is small compared with the considerable variability (range) in concentrations observed at each hour. Hence, although PM<sub>2.5</sub> concentrations in Steubenville exhibit an overall average diurnal pattern when many measurements are averaged together, Figure 3a suggests that substantial deviations from this pattern can occur. This is consistent with the findings of Fitz-Simmons et al. in other U.S. locations.<sup>5</sup>



**Figure 3.** Diurnal patterns in the hourly concentrations of PM<sub>2.5</sub> and gaseous co-pollutants measured at the Steubenville monitoring site between May 2000 and May 2002: (a) Box plot showing distribution of PM<sub>2.5</sub> concentrations by time of day (EST). The horizontal lines denote median concentrations; the boxes extend to the 25th and 75th quartiles; the whiskers extend to the most extreme data points within 1.5 times this interquartile range. Circular points represent outliers; connected diamonds represent mean concentrations. (b) Mean PM<sub>2.5</sub> concentrations by time of day. (c) Mean concentrations of gaseous co-pollutants by time of day.

A noteworthy feature of Figure 3a is that 1-hr average PM<sub>2.5</sub> concentrations >65 µg/m<sup>3</sup> were never observed at Steubenville during the mid-afternoon between 1:00 p.m. and 5:00 p.m. EST. Rather, the 76 1-hr concentrations >65 µg/m<sup>3</sup> occurred during the morning and, to a lesser extent, the evening hours. The five highest hourly PM<sub>2.5</sub> concentrations observed during SCAMP occurred between 3:00 a.m. and 8:00 a.m. EST. These findings suggest that the potential for transient exposure to high outdoor ambient PM<sub>2.5</sub> concentrations in Steubenville is greatest during the early and mid-morning, and is lowest during the mid-afternoon. However, the relationship between outdoor ambient PM<sub>2.5</sub> concentrations and actual personal

exposure to PM<sub>2.5</sub> depends on a number of factors, including human activity patterns and home ventilation conditions. An assessment of the implications of the intraday timing of outdoor PM<sub>2.5</sub> episodes for personal exposure to PM<sub>2.5</sub> is beyond the scope of this paper, but it should be pursued.

Figure 3b, which shows mean PM<sub>2.5</sub> concentrations by time of day plotted on a narrower  $y$ -axis scale, more clearly depicts the overall average PM<sub>2.5</sub> diurnal profile observed at Steubenville. On average, PM<sub>2.5</sub> concentrations were relatively constant at 13.5–14  $\mu\text{g}/\text{m}^3$  during the nighttime before increasing to a peak of 15.8  $\mu\text{g}/\text{m}^3$  at 8:00 a.m. EST, and then decreasing to an afternoon level of 10–10.5  $\mu\text{g}/\text{m}^3$  by 12:00 p.m. EST. Concentrations gradually increased back to the nighttime level between 4:00 p.m. and 10:00 p.m. EST. The shape of the average diurnal profile was approximately the same when data were studied by season, although a small secondary mid-afternoon peak was observed during summertime.

Average diurnal patterns in the concentrations of gaseous co-pollutants measured at the Steubenville monitoring site are shown in Figure 3c. One early morning point is missing for each gas, corresponding to the calibration time of that gas's analyzer. The average diurnal profiles of CO and NO<sub>x</sub> were similar to the average profile of PM<sub>2.5</sub>; these gases exhibited pronounced morning maxima at 6:00 a.m. and 7:00 a.m. EST, respectively, and afternoon minima at 4:00 p.m. EST. O<sub>3</sub> concentrations exhibited an average diurnal profile opposite those for PM<sub>2.5</sub>, CO, and NO<sub>x</sub>. As expected, ozone concentrations were typically highest during the late afternoon, when photochemical activity is at a maximum, and were lowest around 6:00 a.m. EST. SO<sub>2</sub> displayed a somewhat different and less-pronounced average diurnal pattern, with a maximum occurring at 9:00 a.m. EST and local minima occurring at 4:00 a.m. and 7:00 p.m. EST.

One possible explanation for the observed average diurnal pattern in PM<sub>2.5</sub> concentrations at Steubenville is the influence of anthropogenic emission sources with a similar pattern. Chuersuan et al.<sup>6</sup> attributed an average morning (6:00 a.m. to 9:30 a.m. EST) peak in PM<sub>2.5</sub> concentrations in New Jersey to the influence of local motor vehicle traffic. Motor vehicle traffic may also contribute to the morning peak observed in Steubenville's PM<sub>2.5</sub> diurnal profile. This argument is supported by the concurrent peak in CO, which is often used as a tracer for motor vehicle emissions.<sup>17</sup> However, elevated average nighttime concentrations and the lack of a pronounced peak corresponding to the afternoon rush hour indicate the influence of other factors as well. Meteorological conditions, such as temperature, RH, wind speed, and mixing height, also typically exhibit strong diurnal cycles, and may help to explain the diurnal pattern observed in PM<sub>2.5</sub>

concentrations at Steubenville. Case studies presented later in this article provide further insight into this diurnal pattern and the factors that contribute to its variability.

### Episodes of Elevated PM<sub>2.5</sub> Concentrations

Connell et al.<sup>9</sup> previously examined episodes of elevated PM<sub>2.5</sub> concentrations at Steubenville using daily data collected during SCAMP. However, to better understand the nature of transient PM<sub>2.5</sub> episodes in Steubenville, an investigation using hourly data is required. For the purposes of this analysis, an episode is defined as a period of PM<sub>2.5</sub> concentrations centered on at least one hourly concentration  $>65 \mu\text{g}/\text{m}^3$ , and extending in either direction to the end of the first 24-hr interval for which all hourly concentrations are either less than the 90th percentile concentration (29.5  $\mu\text{g}/\text{m}^3$ ) or missing.

Twenty-two episodic periods satisfying these criteria were observed during SCAMP. These episodes are summarized in Table 3. As defined above, the duration of episodes ranged from 56 to 206 hr; however, because each episode period began and ended with a 24-hr window of low or missing PM<sub>2.5</sub> concentrations, a more accurate range for the "hearts" of the episodes is 8–158 hr. PM<sub>2.5</sub> concentrations often varied appreciably even during the heart of an episode, however, as will be shown in the case studies. Nine of the 22 episodes had PM<sub>2.5</sub> data recoveries  $<100\%$ .

On the basis of 24-hr average data collected at the Steubenville monitoring site, a previous study<sup>8</sup> reported that PM<sub>2.5</sub> concentrations at Steubenville exhibited a seasonal pattern of higher summertime and lower wintertime concentrations, with the highest mean monthly concentration observed in August and the lowest observed in December. Table 3 suggests, however, that short-term episodes of high hourly PM<sub>2.5</sub> concentrations were more likely to occur during autumn than during summer. Nine of the 22 episodes (40.9%) and 35 of the 76 1-hr PM<sub>2.5</sub> concentrations  $>65 \mu\text{g}/\text{m}^3$  (46.1%) occurred during the months of September through November, which included 25.1% of all hourly PM<sub>2.5</sub> concentrations observed during SCAMP. By comparison, only 5 of the 22 episodes (22.7%) and 13 of the 76 highest 1-hr PM<sub>2.5</sub> concentrations (17.1%) occurred during the months of June through August, which included 22.8% of all hourly PM<sub>2.5</sub> observations. In addition, the severity of PM<sub>2.5</sub> concentrations reached during the summertime episodes was mild in comparison to other seasons. Maximum PM<sub>2.5</sub> concentrations for the five summertime episodes ranged from 67.9 to 76.6  $\mu\text{g}/\text{m}^3$ ; four episodes during October or November included 1-hr average PM<sub>2.5</sub> concentrations  $\geq 95 \mu\text{g}/\text{m}^3$ , and an April episode included a 1-hr concentration of 139.6  $\mu\text{g}/\text{m}^3$ . Collectively, these findings suggest that although PM<sub>2.5</sub> concentrations are

**Table 3.** Episodes of elevated hourly PM<sub>2.5</sub> concentrations at Steubenville during SCAMP, as defined in the text.

Month	Duration (hr)	PM <sub>2.5</sub> Data Recovery (%)	Mean PM <sub>2.5</sub> Concentration (μg/m <sup>3</sup> )	Max PM <sub>2.5</sub> Concentration (μg/m <sup>3</sup> )	r <sub>s</sub> for Pairwise Comparison of Gas and PM <sub>2.5</sub> Concentrations <sup>a</sup>					
					SO <sub>2</sub>	CO	NO	NO <sub>2</sub>	O <sub>3</sub>	
1	Aug 2000	108	100	23.4	76.6	0.41	0.18	-0.07	-0.12	NA
2	Aug 2000	76	97	23.6	73.7	0.42	0.76	0.34	0.46	NA
3	Sep-Oct 2000	99	100	23.7	83.1	0.72	0.71	0.43	0.47	-0.27
4	Oct 2000	152	97	26.3	76.9	0.74	0.86	0.65	NA	-0.60
5	Oct 2000	206	83	29.6	102.5	NA	0.39	NA	NA	-0.48
6	Nov 2000	84	100	21.8	95.0	0.63	0.83	0.70	NA	-0.55
7	Jan 2001	131	100	25.1	78.9	NA	0.91	0.90	NA	-0.38
8	Apr 2001	59	100	24.1	139.6	0.79	0.87	NA	NA	-0.28
9	Apr-May 2001	163	88	25.2	67.7	0.54	0.71	0.47	0.51	-0.34
10	Jun 2001	151	87	32.0	72.7	0.46	NA	NA	NA	NA
11	Jul 2001	138	100	29.6	67.9	NA	NA	NA	NA	NA
12	Jul-Aug 2001	148	84	36.3	72.6	0.45	0.11	-0.13	0.22	0.12
13	Oct 2001	117	82	22.2	97.5	-0.25	0.51	0.34	0.31	-0.42
14	Oct 2001	149	89	21.8	76.0	0.49	0.67	0.64	0.50	-0.65
15	Oct-Nov 2001	78	69	23.5	71.8	0.85	0.84	0.58	0.69	-0.24
16	Nov 2001	62	100	16.6	68.5	0.89	0.84	0.81	0.84	NA
17	Nov 2001	116	100	26.8	106.9	NA	0.60	0.27	0.34	-0.25
18	Dec 2001	120	100	18.5	83.4	0.79	0.83	0.77	0.66	-0.73
19	Jan 2002	101	100	18.8	81.5	0.54	0.62	0.59	0.70	-0.71
20	Mar 2002	102	100	21.6	82.7	0.72	0.82	0.86	0.86	-0.62
21	Mar 2002	73	100	22.5	76.0	0.52	0.85	0.67	0.74	-0.69
22	Apr 2002	56	100	16.9	67.2	0.40	0.54	0.24	0.46	-0.23

Notes: <sup>a</sup>r<sub>s</sub> = Spearman rank-order correlation coefficient; r<sub>s</sub> is reported only if >70% of hourly gas concentrations were available for comparison with hourly PM<sub>2.5</sub> concentrations; NA = not applicable.

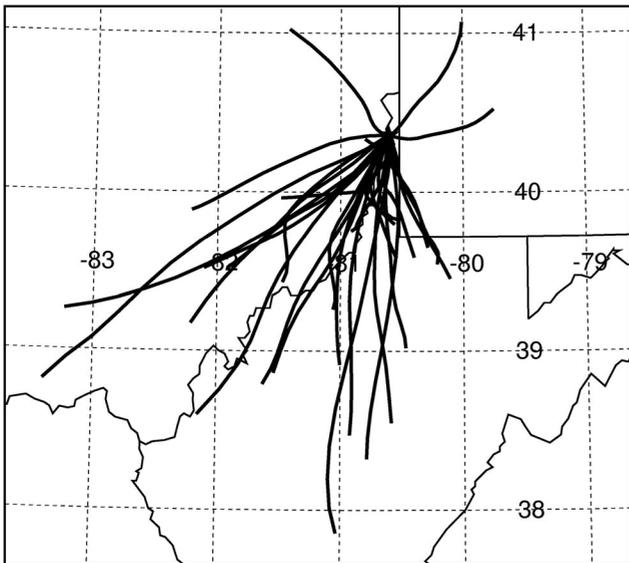
most chronically elevated during summertime in Steubenville, the potential for transient exposure to the highest 1-hr average PM<sub>2.5</sub> concentrations is greater during other times of the year.

Table 3 also shows the Spearman rank-order correlation coefficient (r<sub>s</sub>) for pairwise comparisons of hourly PM<sub>2.5</sub> concentrations with hourly concentrations of each gaseous co-pollutant for each episode period. The non-parametric Spearman correlation was used because data were highly non-normal in many cases; r<sub>s</sub> is only shown if at least 70% of hourly gas concentrations were available for comparison with hourly PM<sub>2.5</sub> concentrations. Values of r<sub>s</sub> presented here are used merely in the descriptive sense to indicate covariation or a lack thereof; to more thoroughly assess associations among variables, autocorrelation among the time series would need to be accounted for. Connell et al.<sup>9</sup> previously noted strong associations among daily concentrations of PM<sub>2.5</sub>, CO, NO<sub>x</sub>, and SO<sub>2</sub> during several PM<sub>2.5</sub> episodes at Steubenville, which occurred primarily during climatologically cool portions of the year. Table 3 shows similar findings for hourly data. Many but not all episodes were characterized

by strong positive correlations between PM<sub>2.5</sub> concentrations and concentrations of CO, NO, NO<sub>2</sub>, or SO<sub>2</sub>. For 10 of the 22 episodes, values of r<sub>s</sub> describing these correlations were >0.7 for at least 2 of the aforementioned co-pollutants. (As a point of reference, r<sub>s</sub> values computed with all hourly data collected during SCAMP were 0.50 for SO<sub>2</sub>, 0.46 for CO, 0.33 for NO, 0.50 for NO<sub>2</sub>, and -0.16 for O<sub>3</sub>). None of these episodes occurred during summer, although data were missing for two summertime episodes. The findings of Connell et al.<sup>9</sup> using daily average data offered limited insight into the nature of the associations among PM<sub>2.5</sub> and co-pollutants, because the data did not capture the considerable intraday variability often exhibited by these variables. However, the presence of considerable positive correlations among hourly PM<sub>2.5</sub> concentrations and hourly concentrations of CO, SO<sub>2</sub>, and NO<sub>x</sub> during some PM<sub>2.5</sub> episodes at Steubenville strongly suggests the importance of a common factor influencing ambient concentrations of these species. Moreover, the correlations indicate the potential for simultaneous exposure to elevated concentrations of PM<sub>2.5</sub> and one or more of these co-pollutants.

Hourly ozone concentrations were negatively correlated with hourly PM<sub>2.5</sub> concentrations during all but one of the episodes shown in Table 3. The lone episode exhibiting a small positive association was the only summertime episode for which sufficient O<sub>3</sub> data were available. Because ozone consistently exhibits a pronounced diurnal pattern, the negative correlations of varying magnitudes observed during the other three seasons likely reflect PM<sub>2.5</sub> concentrations following an opposite diurnal pattern of higher early morning concentrations and lower afternoon concentrations.

To assess transport conditions associated with elevated hourly PM<sub>2.5</sub> concentrations at Steubenville, 12-hr backward trajectories from Steubenville were estimated using the HYSPLIT model<sup>34</sup> with Eta Data Assimilation System (EDAS) data for all hours having a PM<sub>2.5</sub> concentration >65 µg/m<sup>3</sup>. Because these elevated concentrations generally occurred during the night or early morning, when vertical mixing heights tend to be low, a starting elevation of 50 m above model ground level was specified. Estimated trajectories are plotted in Figure 4. Only one trajectory is shown for cases in which multiple concentrations >65 µg/m<sup>3</sup> occurred within 9 hr of each other; as a result, 30 trajectories are plotted, although 76 hr had concentrations >65 µg/m<sup>3</sup>. The trajectories are mostly concentrated in a swath extending clockwise from approximately the south-by-southeast to the southwest. This suggests the possibility that pollutants transported

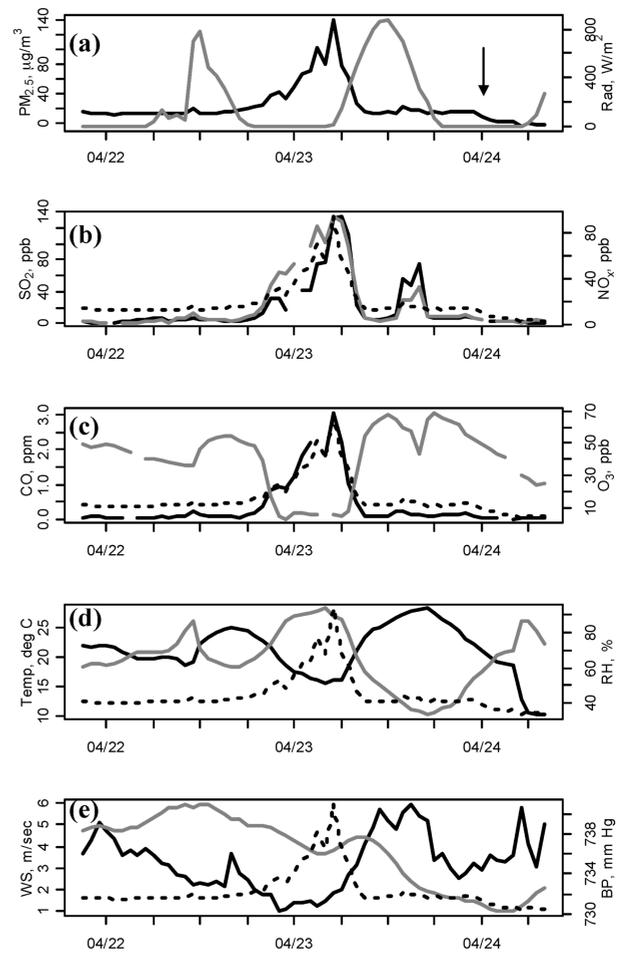


**Figure 4.** Estimated 12-hr backward trajectories from Steubenville for hours having PM<sub>2.5</sub> concentrations >65 µg/m<sup>3</sup>. Trajectories were calculated by the HYSPLIT model with EDAS data for a starting height of 50 m above model ground level. Only one trajectory is shown for cases in which multiple concentrations >65 µg/m<sup>3</sup> occurred within 9 hr of each other. Thirty trajectories are plotted. Latitude (N) and longitude (W) in degrees are shown on the dotted lines.

from point sources located along the Ohio River to the south of Steubenville contributed to high 1-hr average PM<sub>2.5</sub> concentrations observed at the Steubenville monitoring site. However, factors other than transport must also be considered when assessing the causes of these high hourly concentrations.

### Case Studies of PM<sub>2.5</sub> Episodes

To better understand the implications of the data in Table 3, several episodes are now examined as case studies. The highest 1-hr average PM<sub>2.5</sub> concentration (139.6 µg/m<sup>3</sup>) observed during SCAMP occurred at 5:00 a.m. EST on April 23, 2001. The episode containing this observation (episode 8) had the second shortest duration of the episodes outlined in Table 3. Time series plots presented in Figure 5 show hourly average PM<sub>2.5</sub> concentrations, co-



**Figure 5.** Time series of 1-hr average air monitoring data measured at the Steubenville station between 9:00 p.m. EST on April 21, 2001, and 8:00 a.m. EST on April 24, 2001 (episode 8). For each plot, the variable on the left-hand axis is shown in black; the variable on the right-hand axis is shown in gray. The PM<sub>2.5</sub> time series shown in plot (a) is superimposed on plots (b) through (e) as a dashed line to facilitate comparison. Tick marks denote every sixth hour; labels are located at 12:00 a.m. EST. A frontal system passed through the region within 6 hr of the arrow shown in plot (a).

pollutant concentrations, and meteorological conditions measured during the episode. When interpreting the time series plots, which include multiple  $y$ -axis scales, it is important to carefully consider the range of each scale, because compressed or expanded scales can exaggerate or hide the apparent magnitude of fluctuations in the data being plotted.

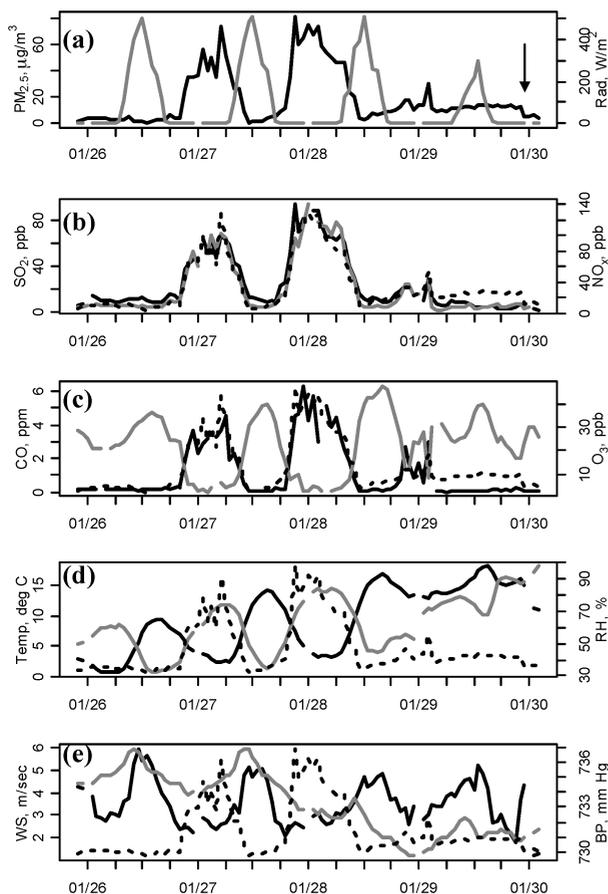
As shown in Figure 5a, the “heart” of the episode occurred entirely during one nighttime period.  $PM_{2.5}$  concentrations began to increase gradually as solar radiation decreased during the late afternoon on April 22, and then increased more rapidly beginning around midnight. Concentrations  $>65 \mu\text{g}/\text{m}^3$  were observed for 6 consecutive hours (1:00–6:00 a.m. EST on April 23), and 1-hr average concentrations  $>100 \mu\text{g}/\text{m}^3$  were observed at both 3:00 a.m. and 5:00 a.m. EST. The peak at 5:00 a.m. occurred just as solar radiation began to increase on April 23;  $PM_{2.5}$  concentrations then rapidly decreased to  $14.9 \mu\text{g}/\text{m}^3$  by 9:00 a.m. EST. Figures 5b and 5c reveal that concentrations of  $\text{SO}_2$ ,  $\text{NO}_x$ , and CO were also elevated well above their normal levels during the episode and generally

tracked  $PM_{2.5}$  concentrations closely. Maximum concentrations of all of these species occurred within 1 hr of 5:00 a.m. EST; during this hour, average concentrations of  $\text{SO}_2$ ,  $\text{NO}_x$ , and CO were 132 ppb, 95.5 ppb, and 3.08 ppm, respectively. Conversely, ozone concentrations displayed a pronounced trough during the heart of the episode, remaining below 10 ppb from 10:00 p.m. EST on April 22 through 7:00 a.m. EST on April 23.

An episode (episode 19) marked by similar characteristics is presented in Figure 6. A previous analysis<sup>9</sup> of this episode with daily data concluded that concentrations of  $PM_{2.5}$ , CO,  $\text{SO}_2$ , and  $\text{NO}_x$  built up from January 25 through January 27, 2002, during a period of locally high barometric pressure, and then decreased with the approach and passage of a frontal system. However, Figure 6 reveals that the episode was not marked by a gradual buildup and decay in concentrations, but rather consisted of two distinct nighttime subepisodes characterized by more acutely elevated concentrations of  $PM_{2.5}$  and these gases. Each subepisode began with an increase in  $PM_{2.5}$  concentration of  $20 \mu\text{g}/\text{m}^3$  or more during the late evening (8:00 p.m. or 9:00 p.m. EST) and concluded with a rapid decrease in  $PM_{2.5}$  concentration coinciding with the morning increase in solar radiation. Like the episode shown in Figure 5, concentrations of CO,  $\text{SO}_2$ , and  $\text{NO}_x$  behaved similarly to  $PM_{2.5}$  concentrations during the episode period, whereas  $\text{O}_3$  concentrations exhibited an opposite pattern.

The episodes depicted in Figures 5 and 6 both occurred just before the passage of a frontal system through the region. Frontal systems passed through Steubenville between 7:00 p.m. EST on April 23, 2001, and 7:00 a.m. EST on April 24, 2001, and between 7:00 p.m. EST on January 29, 2002, and 7:00 a.m. EST on January 30, 2002.<sup>35</sup> The slight decreases in  $PM_{2.5}$  concentration denoted by arrows in Figures 5a and 6a likely reflect the arrival of cleaner air masses with the passage of these frontal systems. However, it does not appear that the fronts directly caused the rapid changes in  $PM_{2.5}$  concentrations observed during the episodes. Moreover, because major emissions of CO and  $\text{SO}_2$  are not generally expected to originate from a common source, the episodes cannot be attributed to any single source based on the available data.

Rather, the pollutant and meteorological data shown in Figures 5 and 6 suggest the possible influence of nocturnal radiational surface inversions. The ability of temperature inversions to affect pollutant concentrations is well documented.<sup>36–38</sup> Nocturnal inversions generally result from radiational cooling of the earth’s surface, which in turn causes a shallow layer of air in contact with the surface to become cooler than the air above. The inversion layer, which is marked by a negative lapse rate (i.e.,



**Figure 6.** Time series of 1-hr average air monitoring data measured at the Steubenville station between 10:00 p.m. EST on January 25, 2002, and 2:00 a.m. EST on January 30, 2002 (episode 19). Plots are constructed as in Figure 5. A frontal system passed through the region within 6 hr of the arrow shown in plot (a).

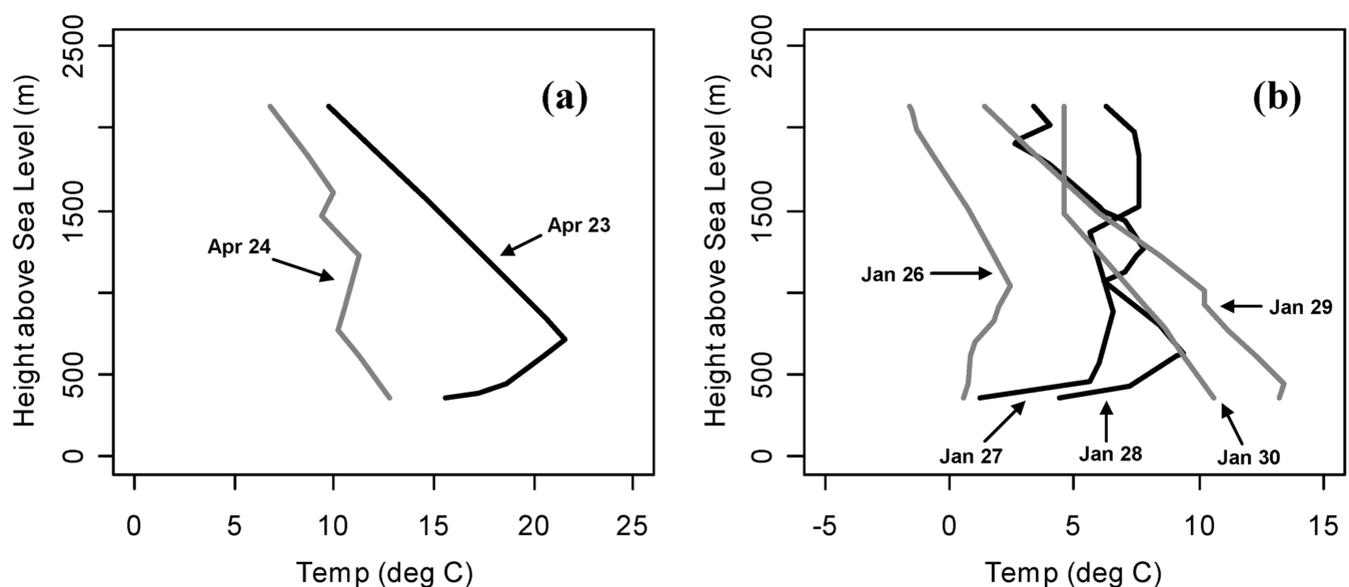
increase in temperature with height), is statically stable and often contains laminar flow.<sup>37</sup> Hence, vertical mixing is inhibited and freshly emitted pollutants are concentrated within a small volume of air near the surface, resulting in elevated nighttime concentrations of many locally emitted pollutants. Ground-level ozone concentrations decrease substantially during a nocturnal inversion, however, as photochemical formation of O<sub>3</sub> ceases, whereas depletion of O<sub>3</sub> by deposition and reaction with concentrated levels of other freshly emitted pollutants (e.g., NO) occurs rapidly. A pronounced diurnal surface temperature profile (accompanied by an opposite diurnal RH profile) is expected, reflecting substantial nighttime radiational cooling. Low nighttime surface wind speeds contribute to the formation of radiational inversions by limiting mechanical mixing of cool and warm air; they also result from the vertical stability associated with these inversions. A morning increase in solar radiation causes heating of the earth's surface, breaking the inversion and resulting in rapid decreases in the concentrations of trapped pollutants, as well as an increase in the concentration of O<sub>3</sub>.

The periods of elevated nighttime PM<sub>2.5</sub> concentrations shown in Figures 5 and 6 exhibit these characteristics of nocturnal inversions. Vertical temperature soundings were not taken at the Steubenville monitoring site; however, soundings taken daily at 7:00 a.m. EST at the National Weather Service station in Moon Township, PA, were available.<sup>39</sup> This station is located ~38 km east-northeast of Steubenville, and it is situated 357 m above sea level. Figure 7 shows vertical temperature profiles taken at 7:00 a.m. EST on each day of the two episodes discussed above. (Data were not available for April 22,

2001.) Strong surface-based inversions are evident for each morning during which acutely elevated concentrations of PM<sub>2.5</sub>, SO<sub>2</sub>, NO<sub>x</sub>, and CO occurred (i.e., April 23, 2001, January 27, 2002, January 28, 2002). However, mornings during these episodes without high concentrations experienced either no surface inversion or a much weaker surface inversion. As previously discussed, both of these inversion-driven pollution episodes ended with the approach or passage of a frontal system, probably because winds accompanying the front caused considerable mechanical mixing or because overcast conditions or the arrival of a new air mass disrupted the diurnal radiational heating and cooling cycle.

Several other PM<sub>2.5</sub> episodes observed during SCAMP also showed evidence of the influence of nocturnal inversions. For instance, episodes 4, 18, 20, and 21, which occurred in October 2000, December 2001, March 2002, and March 2002, respectively, exhibited strong diurnal patterns of higher nighttime concentrations of PM<sub>2.5</sub>, CO, NO<sub>x</sub>, and SO<sub>2</sub>, and higher daytime concentrations of O<sub>3</sub>. Soundings from the Moon Township station showed evidence of the presence of surface inversions during these episodes, and the strong diurnal patterns in PM<sub>2.5</sub> concentrations ceased in each case with the passage of a frontal system. Collectively, these findings suggest that nocturnal radiational surface inversions are important in driving elevated nighttime concentrations of PM<sub>2.5</sub> and primarily emitted gaseous co-pollutants in Steubenville, especially during climatologically cool portions of the year.

The nature of these inversion-driven episodes must be carefully considered when assessing potential health



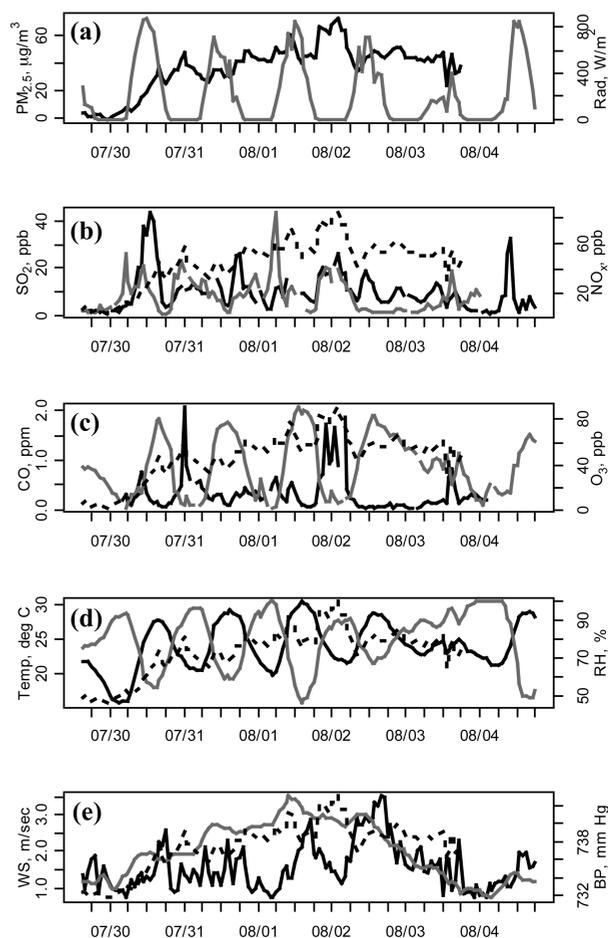
**Figure 7.** Vertical temperature soundings taken at the National Weather Service station in Moon Township, PA, at 7:00 a.m. EST on (a) April 23–24, 2001, and (b) January 26–30, 2002. Days having the strongest surface-based temperature inversions are shown in black; other days are shown in gray.

effects of PM<sub>2.5</sub>. An elevated 24-hr average PM<sub>2.5</sub> concentration may seem to suggest a high risk of exposure to ambient fine particles throughout the course of the day. However, during nocturnal inversion-driven episodes, very high concentrations of PM<sub>2.5</sub> occur predominantly during the overnight hours, when a majority of the human population is sleeping indoors. Afternoon concentrations of PM<sub>2.5</sub> during these episodes are considerably lower. For instance, the 24-hr average FRM-measured PM<sub>2.5</sub> concentration from 9:00 a.m. EST on January 27, 2002, through 9:00 a.m. EST on January 28, 2002, was 49.0 μg/m<sup>3</sup>; however, during this 24-hr period, hourly average concentrations were >50 μg/m<sup>3</sup> from 9:00 p.m. EST on January 27 through 5:00 a.m. EST on January 28, but were <10 μg/m<sup>3</sup> from 10:00 a.m. EST to 6:00 p.m. EST on January 27. The greatest risk for direct outdoor exposure to acutely elevated PM<sub>2.5</sub> concentrations in Steubenville might occur during the early part of morning rush hour as people leave their homes before the nocturnal inversion has been destroyed. During the overnight period, however, the relationship between elevated outdoor PM<sub>2.5</sub> concentrations and actual human exposure to PM<sub>2.5</sub> of outdoor origin is governed primarily by factors that influence the infiltration of PM<sub>2.5</sub> into homes, including air-exchange rate, particle filtration by the building shell, and particle deposition and reaction in the indoor environment.<sup>40</sup> Epidemiological studies assessing the health effects of PM<sub>2.5</sub> in Steubenville and other cities whose PM<sub>2.5</sub> concentrations are frequently influenced by nocturnal inversions must carefully consider these points when modeling human exposure to PM<sub>2.5</sub>.

Furthermore, the PM<sub>2.5</sub> episodes considered above highlight the potential for simultaneous exposure to elevated concentrations of PM<sub>2.5</sub> and several co-pollutant gases in Steubenville. Few controlled toxicological studies with human subjects have examined the effect of simultaneous exposure to PM<sub>2.5</sub> and co-pollutants; in perhaps the most noteworthy study, Brook et al.<sup>41</sup> exposed human subjects to ~150 μg/m<sup>3</sup> of concentrated ambient fine particles and 120 ppb of O<sub>3</sub> for 2 hr in an attempt to mimic conditions experienced during actual outdoor pollution episodes. The study found that short-term inhalation of the mixture caused acute conduit artery vasoconstriction. However, on the basis of hourly data collected during SCAMP, simultaneous exposure to high concentrations of PM<sub>2.5</sub> and O<sub>3</sub> is less likely to occur in Steubenville than simultaneous exposure to high concentrations of PM<sub>2.5</sub>, CO, SO<sub>2</sub>, and NO<sub>x</sub>. In fact, when 1-hr average O<sub>3</sub> concentrations >80 ppb were measured at Steubenville, PM<sub>2.5</sub> concentrations were always <60 μg/m<sup>3</sup>; when 1-hr average PM<sub>2.5</sub> concentrations >70 μg/m<sup>3</sup> were measured, O<sub>3</sub> concentrations were always <15 ppb.

A more realistic exposure scenario for Steubenville occurred at 8:00 a.m. EST on November 14, 2001, when concentrations of PM<sub>2.5</sub>, NO<sub>x</sub>, and CO were 106.9 μg/m<sup>3</sup>, 160.7 ppb, and 4.67 ppm, respectively, and the concentration of O<sub>3</sub> was only 4.6 ppb (SO<sub>2</sub> data were not available). These findings suggest that toxicology studies should focus more attention on potential interactions between PM<sub>2.5</sub>, CO, SO<sub>2</sub>, and NO<sub>x</sub>.

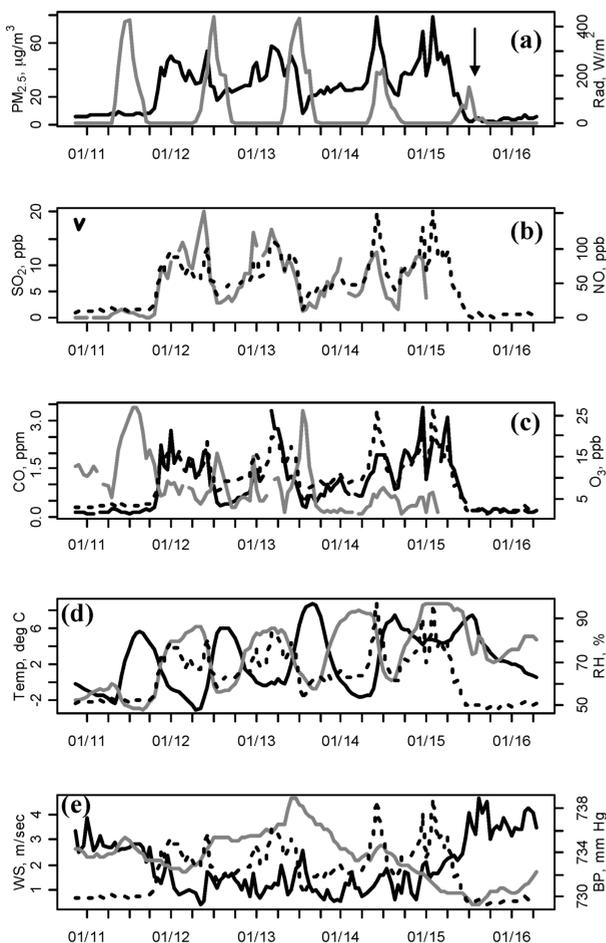
Not all PM<sub>2.5</sub> episodes during SCAMP exhibited the strong diurnal variations characteristic of nocturnal inversion-driven episodes. Figure 8 shows a summertime PM<sub>2.5</sub> episode (episode 12) that occurred during late July and early August 2001. PM<sub>2.5</sub> concentrations remained well above average levels during an extended period, ranging between 30.3 μg/m<sup>3</sup> and 72.6 μg/m<sup>3</sup> for 76 consecutive hours, but never reached the high levels observed during the episodes discussed above. Although strong diurnal cycles in PM<sub>2.5</sub> concentrations are not evident during the episode, the highest concentrations did occur



**Figure 8.** Time series of 1-hr average air monitoring data measured at the Steubenville station between 3:00 p.m. EST on July 29, 2001, and 6:00 p.m. EST on August 4, 2001 (episode 12). Plots are constructed as in Figure 5.

during the overnight hours on August 1–2, probably because of reduced nighttime mixing heights. Determinations of 24-hr average  $PM_{2.5}$  composition on July 30 and August 3 reveal that the  $PM_{2.5}$  mass on these days was dominated by sulfate (47.6%  $SO_4^{2-}$  on July 30; 46.2%  $SO_4^{2-}$  on August 3), suggesting a regional episode of secondary  $PM_{2.5}$  formation driven by warm temperatures, plentiful solar radiation, and high-pressure-induced stagnation. Such an episode affords the greatest opportunity for simultaneous exposure to elevated concentrations of  $PM_{2.5}$  and  $O_3$ ; however, concentrations of these species during the episode were considerably lower than concentrations examined by Brook et al.<sup>41</sup>

Some cooler season  $PM_{2.5}$  episodes also exhibited less pronounced diurnal patterns. The episode depicted in Figure 9 (episode 7) occurred during January 2001. In general,  $PM_{2.5}$  concentrations were elevated from late in the day on January 11 through early in the day on January 15. Nighttime local maxima are discernible, but dramatic daytime drops in concentration occurred less regularly



**Figure 9.** Time series of 1-hr average air monitoring data measured at the Steubenville station between 9:00 p.m. EST on January 10, 2001, and 7:00 a.m. EST on January 16, 2001 (episode 7). Plots are constructed as in Figure 5. A frontal system passed through the region within 6 hr of the arrow shown in plot (a).

during the episode. This episode has been described previously on the basis of daily data;<sup>9</sup> it was observed on a regional scale and occurred during a period of locally low wind speeds, suggesting sustained surface stagnation. The abrupt drop in  $PM_{2.5}$  concentration on January 15 coincides with the passage of an occluded front through the region between 7:00 a.m. and 7:00 p.m. EST, likely marking the arrival of a less polluted air mass.

Collectively, these case studies illustrate the apparent substantial role of meteorology in causing variations in the diurnal pattern of  $PM_{2.5}$  concentrations in Steubenville.

## CONCLUSIONS

Hourly average  $PM_{2.5}$  concentrations were determined with a TEOM at a monitoring site in Steubenville, OH, between June 14, 2000, and May 14, 2002. Hourly average gaseous co-pollutant concentrations and meteorological conditions were also measured during this period.

Analysis of these data indicates that  $PM_{2.5}$  concentrations at Steubenville during SCAMP were typically low-to-moderate; half of the 14,682 hourly concentrations were  $\leq 8.6 \mu\text{g}/\text{m}^3$ , and 75% were  $\leq 17 \mu\text{g}/\text{m}^3$ . However, much higher concentrations were observed in some instances. One-hour average  $PM_{2.5}$  concentrations  $> 65 \mu\text{g}/\text{m}^3$  were observed 76 times during the program, and 1-hr changes in concentration  $\geq 20 \mu\text{g}/\text{m}^3$  were observed 154 times, indicating the possibility for transient exposure to elevated outdoor  $PM_{2.5}$  concentrations in Steubenville. Transport during periods containing these elevated concentrations was frequently from the southwest, south, or south-by-southeast, suggesting the possible influence of emission sources located along the Ohio River to the south of Steubenville.

$PM_{2.5}$  concentrations exhibited an overall average diurnal pattern consisting of higher nighttime and lower afternoon concentrations, with a morning maximum occurring at 8:00 a.m. EST, although this pattern varied considerably from day to day. It is more noteworthy that concentrations  $> 65 \mu\text{g}/\text{m}^3$  were never observed during the mid-afternoon between 1:00 p.m. and 5:00 p.m. EST; rather, the highest  $PM_{2.5}$  concentrations occurred during the evening, overnight, and morning hours.

Episodes containing these highest  $PM_{2.5}$  concentrations were studied, and several scenarios associated with elevated hourly  $PM_{2.5}$  concentrations at Steubenville were identified. For example, a case study of a summertime episode revealed that elevated  $PM_{2.5}$  concentrations occurred during a period marked by warm temperatures, high barometric pressure and above-average afternoon levels of ozone and solar radiation. These conditions are associated with the formation of secondary  $PM_{2.5}$  (e.g.,

sulfate). During the episode, hourly average PM<sub>2.5</sub> concentrations remained >30 µg/m<sup>3</sup> for a prolonged period (76 consecutive hours). Out of 22 PM<sub>2.5</sub> episodes identified during SCAMP, 5 occurred during the months of June through August. The maximum 1-hr PM<sub>2.5</sub> concentration measured during these months was 76.6 µg/m<sup>3</sup>.

The remaining 17 episodes occurred during climatologically cooler months (9 occurred during the months of September through November), and often included higher 1-hr PM<sub>2.5</sub> concentrations; 5 of these episodes included at least one concentration >95 µg/m<sup>3</sup>. In many cases, these episodes were characterized by strong associations between PM<sub>2.5</sub> concentrations and concentrations of CO, NO, NO<sub>2</sub>, or SO<sub>2</sub>; O<sub>3</sub> concentrations were negatively correlated with PM<sub>2.5</sub> concentrations in all cases for which sufficient data were available. This finding, coupled with similar overall average diurnal profiles exhibited by CO, NO<sub>x</sub>, and PM<sub>2.5</sub>, may indicate the influence of a common emission source of these pollutants. However, case studies of several cool season PM<sub>2.5</sub> episodes suggested the substantial importance of nocturnal surface-based temperature inversions in driving elevated nighttime concentrations of PM<sub>2.5</sub> and primarily emitted pollutant gases, including CO, NO<sub>x</sub>, and SO<sub>2</sub>. Afternoon concentrations of these species were generally substantially lower during inversion-driven episodes, which ended with the approach or passage of a frontal system.

These findings have several important implications for areas of interest related to PM<sub>2.5</sub>. Studies assessing the possible health effects of PM<sub>2.5</sub> in Steubenville and similar cities should more closely consider potential differences between the effects of several-hour episodes of acutely elevated PM<sub>2.5</sub> concentrations (e.g., Figure 5) and the effects of more prolonged episodes of moderately elevated PM<sub>2.5</sub> concentrations (e.g., Figure 8). Moreover, the timing of short-term transient PM<sub>2.5</sub> episodes must be considered carefully. The highest PM<sub>2.5</sub> concentrations at Steubenville, especially those driven by nocturnal inversions during nonsummer months, tended to occur during the late evening through early morning hours. Many high 1-hr concentrations during SCAMP occurred overnight, when most people are sleeping indoors; other high 1-hr concentrations occurred near the time of morning rush hour. These factors must be accounted for when modeling human exposure to PM<sub>2.5</sub> of outdoor origin. Timing of emissions should also be considered when developing a PM<sub>2.5</sub> reduction strategy for Steubenville. Primary emissions during a nighttime surface-based temperature inversion likely have a much stronger immediate impact on PM<sub>2.5</sub> concentrations than primary emissions during an afternoon period of thorough vertical mixing. Furthermore, results presented here suggest that toxicology studies should focus more closely on potential interactions

between PM<sub>2.5</sub>, CO, NO<sub>x</sub>, and SO<sub>2</sub>, because elevated concentrations of these species often occurred simultaneously at Steubenville, especially during nocturnal inversion-driven pollution episodes.

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## REFERENCES

- Dockery, D.W.; Pope, C.A.; Xu, X.; Spengler, J.D.; Ware, J.H.; Fay, M.E.; Ferris, B.G.; Speizer, F.E. An Association Between Air Pollution and Mortality in Six U.S. Cities; *N. Engl. J. Med.* **1993**, *329*, 1753-1759.
- Pope, C.A.; Thun, M.J.; Namboodiri, M.M.; Dockery, D.W.; Evans, J.S.; Speizer, F.E.; Heath, C.W. Particulate Air Pollution as a Predictor of Mortality in a Prospective Study of U.S. Adults; *Am. J. Respir. Crit. Care Med.* **1995**, *151*, 669-674.
- Chow, J.C.; Watson, J.G.; Fujita, E.M.; Lu, Z.; Lawson, D.R. Temporal and Spatial Variations of PM<sub>2.5</sub> and PM<sub>10</sub> Aerosol in the Southern California Air Quality Study; *Atmos. Environ.* **1994**, *28*, 2061-2080.
- Vukovich, F.M.; Sherwell, J. Comparison of Fine Particles and the Relationship Between Particle Variations and Meteorology at an Urban Site and a Remote Site in the Eastern United States; *J. Air & Waste Manage. Assoc.* **2002**, *52*, 573-584.
- Fitz-Simons, T.S.; Mathias, S.; Rizzo, M. Analyses of 1999 PM Data for the PM NAAQS Review; available on U.S. Environmental Protection Agency Web site, <http://www.epa.gov/oar/oaqps/pm25/analyses.html> (accessed 2004).
- Chuersuwan, N.; Turpin, B.J.; Pietarinen, C. Evaluation of Time-Resolved PM<sub>2.5</sub> Data in Urban/Suburban Areas of New Jersey; *J. Air & Waste Manage. Assoc.* **2000**, *50*, 1780-1789.
- Weber, R.; et al. Short-Term Temporal Variation in PM<sub>2.5</sub> Mass and Chemical Composition During the Atlanta Supersite Experiment, 1999; *J. Air & Waste Manage. Assoc.* **2003**, *53*, 84-91.
- Connell, D.P.; Withum, J.A.; Winter, S.E.; Statnick, R.M.; Bilonick, R.A. The Steubenville Comprehensive Air Monitoring Program (SCAMP): Overview and Statistical Considerations; *J. Air & Waste Manage. Assoc.*, **2004**, *55*, 467-480.
- Connell, D.P.; Withum, J.A.; Winter, S.E.; Statnick, R.M.; Bilonick, R.A. The Steubenville Comprehensive Air Monitoring Program (SCAMP): Associations among Fine Particulate Matter, Co-Pollutants, and Meteorological Conditions; *J. Air & Waste Manage. Assoc.*, **2004**, *55*, 481-496.
- Hansen, D.A.; Edgerton, E.S.; Hartsell, B.E. PM and Precursor Sources and Process Inferences from High Temporal Resolution Aerometric Data; In *Proceedings of the International Conference on Air Quality III*; Arlington, VA, September 9-12, 2002.
- Triantafyllou, A.G.; Kiros, E.S.; Evagelopoulou, V.G. Respirable Particulate Matter at an Urban and Nearby Industrial Location: Concentrations and Variability and Synoptic Weather Conditions During High Pollution Episodes; *J. Air & Waste Manage. Assoc.* **2002**, *52*, 287-296.

12. Strohm, D.E.; Dye, T.S.; MacDonald, C.P. The Influence of Meteorological Phenomena on Midwest PM<sub>2.5</sub> Concentrations: A Case Study Analysis; Presented at the 2004 American Meteorological Society Annual Meeting, AMS Sixth Conference on Atmospheric Chemistry: Air Quality in Megacities, Seattle, WA, January 11-15, 2004.
13. Huntzicker, J.J.; Hoffman, R.S.; Cary, R.A. Aerosol Sulfur Episodes in St. Louis, Missouri; *Environ. Sci. Technol.* **1984**, *18*, 962-967.
14. Turpin, B.J.; Huntzicker, J.J. Secondary Formation of Organic Aerosol in the Los Angeles Basin: A Descriptive Analysis of Organic and Elemental Carbon Concentrations; *Atmos. Environ.* **1991**, *25A*, 207-215.
15. Turpin, B.J.; Huntzicker, J.J. Identification of Secondary Organic Aerosol Episodes and Quantitation of Primary and Secondary Organic Aerosol Concentrations During SCAQS; *Atmos. Environ.* **1995**, *29*, 3527-3544.
16. Tan, P.V.; Evans, G.J.; Tsai, J.; Owega, S.; Fila, M.S.; Malpica, O.; Brook, J.R. On-Line Analysis of Urban Particulate Matter Focusing on Elevated Wintertime Aerosol Concentrations; *Environ. Sci. Technol.* **2002**, *36*, 3512-3518.
17. Lim, H.-J.; Turpin, B.J. Origins of Primary and Secondary Organic Aerosol in Atlanta: Results of Time-Resolved Measurements During the Atlanta Supersite Experiment; *Environ. Sci. Technol.* **2002**, *36*, 4489-4496.
18. Schwartz, J.; Dockery, D. Particulate Air Pollution and Daily Mortality in Steubenville, Ohio; *Am. J. Epidemiol.* **1992**, *135*, 12-19.
19. Schwartz, J.; Dockery, D.W.; Neas, L.M. Is Daily Mortality Associated Specifically With Fine Particles? *J. Air & Waste Manage. Assoc.* **1996**, *46*, 927-939.
20. Delfino, R.J.; Zeiger, R.S.; Seltzer, J.M.; Street, D.H. Symptoms in Pediatric Asthmatics and Air Pollution: Differences in Effects by Symptom Severity, Anti-Inflammatory Medication Use and Particulate Averaging Time; *Environ. Health Perspect.* **1998**, *106*, 751-761.
21. Peters, A.; Dockery, D.W.; Muller, J.E.; Mittleman, M.A. Increased Particulate Air Pollution and the Triggering of Myocardial Infarction; *Circulation.* **2001**, *103*, 2810-2815.
22. Wilson, W.E.; Suh, H.H. Fine Particles and Coarse Particles: Concentration Relationships Relevant to Epidemiologic Studies; *J. Air & Waste Manage. Assoc.* **1997**, *47*, 1238-1249.
23. Jakab, G.J.; Clarke, R.W.; Hemenway, D.R.; Longphre, M.V.; Kleeberger, S.R.; Frank, R. Inhalation of Acid Coated Carbon Black Particles Impairs Alveolar Macrophage Phagocytosis; *Toxicol. Lett.* **1996**, *88*, 243-248.
24. Kleinman, M.T.; Bufalino, C.; Rasmussen, R.; Hyde, D.; Bhalla, D.K.; Mautz, W.J. Toxicity of Chemical Components of Ambient Fine Particulate Matter (PM<sub>2.5</sub>) Inhaled by Aged Rats; *J. Appl. Toxicol.* **2000**, *20*, 357-364.
25. Schlesinger, R.B. Interaction of Gaseous and Particulate Pollutants in the Respiratory Tract: Mechanisms and Modulators; *Toxicology.* **1995**, *105*, 315-325.
26. Patashnick, H.; Rupprecht, E.G. Continuous PM<sub>10</sub> Measurements Using the Tapered Element Oscillating Microbalance; *J. Air & Waste Manage. Assoc.* **1991**, *41*, 1079-1083.
27. Allen, G.; Sioutas, C.; Koutrakis, P.; Reiss, R.; Lurmann, F.W.; Roberts, P.T. Evaluation of the TEOM Method for Measurement of Ambient Particulate Mass in Urban Areas; *J. Air & Waste Manage. Assoc.* **1997**, *47*, 682-689.
28. Ayers, G.P.; Keywood, M.D.; Gras, J.L. TEOM vs. Manual Gravimetric Methods for Determination of PM<sub>2.5</sub> Aerosol Mass Concentrations; *Atmos. Environ.* **1999**, *33*, 3717-3721.
29. Operating Manual TEOM Series 1400a Ambient Particulate (PM<sub>10</sub>) Monitor (AB Serial Numbers); Revision B; Rupprecht & Patashnick Co., Inc.: Albany, NY, 1992.
30. U.S. Environmental Protection Agency. *Quality Assurance Handbook for Air Pollution Measurement Systems, Volume II: Ambient Air Specific Methods*; EPA-600/R-94-038b, 1994.
31. Protection of Environment. Chapter I-Environmental Protection Agency. Part 58-Ambient Air Quality Surveillance. Appendix B-Quality Assurance Requirements for Prevention of Significant Deterioration (PSD) Air Monitoring. Code of Federal Regulations, Part 58.61, Title 40, 1999.
32. Jansen, J.J.; Edgerton, E.S.; Hansen, D.A.; Hartsell, B.E. Sampling Artifacts in the Federal Reference Method for PM<sub>2.5</sub>; In *Proceedings of the International Conference on Air Quality III*; Arlington, VA, September 9-12, 2002.
33. Rizzo, M.; Scheff, P.A.; Kaldy, W. Adjusting Tapered Element Oscillating Microbalance Data for Comparison with Federal Reference Method PM<sub>2.5</sub> Measurements in Region 5; *J. Air & Waste Manage. Assoc.* **2003**, *53*, 596-607.
34. Draxler, R.R.; Rolph, G.D. HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) Model; available on the NOAA Air Resources Laboratory Web site, <http://www.arl.noaa.gov/ready/hysplit4.html> (accessed 2004).
35. Unisys Weather: Image and Map Archive; available on the Unisys Web site, <http://weather.unisys.com/archive/index.html> (accessed 2004).
36. Seinfeld, J.H. *Atmospheric Chemistry and Physics of Air Pollution*; Wiley: New York, 1986.
37. Milionis, A.E.; Davies, T.D. Regression and Stochastic Models for Air Pollution-II. Application of Stochastic Models to Examine the Links Between Ground-Level Smoke Concentrations and Temperature Inversions; *Atmos. Environ.* **1994**, *28*, 2811-2822.
38. Monn, C.H.; Braendli, O.; Schaeppli, G.; Schindler, C.H.; Ackermann-Liebrich, U.; Leuenberger, P.H. Particulate Matter < 10 μm (PM<sub>10</sub>) and Total Suspended Particulates (TSP) in Urban, Rural, and Alpine Air in Switzerland; *Atmos. Environ.* **1995**, *29*, 2565-2573.
39. *Atmospheric Soundings*; available on the University of Wyoming, College of Engineering, Department of Atmospheric Science Web site, <http://weather.uwyo.edu/upperair/sounding.html> (accessed 2004).
40. Thatcher, T.L.; Lunden, M.M.; Revzan, K.L.; Sextro, R.G.; Brown, N.J. A Concentration Rebound Method for Measuring Particle Penetration and Deposition in the Indoor Environment; *Aerosol Sci. Technol.* **2003**, *37*, 847-864.
41. Brook, R.D.; Brook, J.R.; Urch, B.; Vincent, R.; Rajagopalan, S.; Silverman, F. Inhalation of Fine Particulate Air Pollution and Ozone Causes Acute Arterial Vasoconstriction in Healthy Adults; *Circulation.* **2002**, *105*, 1534-1536.

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