Source identification of ambient PM$_{2.5}$ for inhalation exposure studies in Steubenville, Ohio using highly time-resolved measurements

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**ABSTRACT**

Recent epidemiological and toxicological studies have suggested that short-term elevations of ambient fine particle mass concentrations (aerodynamic diameter <2.5 µm, PM$_{2.5}$) can increase cardiac and pulmonary health risks. Thus, examining temporal variations of chemical changes in ambient PM$_{2.5}$ that could pose the greatest health risks and identifying its sources is critical so that the most toxic categories can be controlled. In this study we collected detailed air quality data in Steubenville, Ohio in August 2006 with the ultimate goal to evaluate associations between cardiovascular (CV) parameters measured in exposed laboratory animals and the chemical and elemental composition of PM$_{2.5}$. Current approaches using radiotelemetry to measure CV parameters in conscious laboratory animals are capable of collecting continuous recordings. To provide a robust and analogous dataset that can be better matched with CV responses, we have incorporated a highly time-resolved sampling method to characterize trace elements and thereby obtain more robust input data to determine potential emission sources. We applied positive matrix factorization (PMF) to trace element concentrations from 30-minute ambient PM$_{2.5}$ samples in Steubenville, Ohio, an area designated as a non-attainment area for the PM$_{2.5}$ National Ambient Air Quality Standards by the Environmental Protection Agency.

The average ambient PM$_{2.5}$ filter-based mass concentration during the 8-hour summer exposure study period was 26 ± 11 µg m$^{-3}$. Results from PMF indicated that six major factors contributed to the ambient PM$_{2.5}$ mass during this time: coal combustion/secondary (39 ± 46%), mobile sources (12 ± 14%), metal coating/processing (5 ± 5%), iron and steel manufacturing (5 ± 8%), and incineration/smelting (1 ± 3%). The objectives of this paper are (1) to present chemical composition of ambient PM$_{2.5}$ and its potential emission sources in Steubenville; and (2) to evaluate the PMF modeling results using observed meteorological data. These semi-continuous sampling approaches to determine potential emission sources have significant advantages over similar analyses using samples averaged over 8–24 h, and are being utilized by our group to determine associations of PM with acute CV responses from animal inhalation toxicology field studies.

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1. Introduction

The Ohio River Valley is characterized by numerous coal-fired power plants and other industrial facilities, and these sources are known to be significant contributors to ambient air pollution in the Eastern US (Kim et al., 2007; Pekney et al., 2006). In particular, the Steubenville, Ohio/Weirton, West Virginia area contains several large point sources, including coal-fired power plants, steel mills, coke facilities, metal processing operations, metal coating facilities, metal can industries, and tar production facilities and has been continuously designated as a PM$_{2.5}$ non-attainment area by the Environmental Protection Agency (EPA) for violations of both 1997 and 2006 National Ambient Air Quality Standards. Furthermore, Steubenville's air quality has been part of several historic epidemiological studies including the Harvard Six Cities and the American Cancer Society studies and has been consistently associated with an increased risk of morbidity and mortality (Krewski et al., 2003; Laden et al., 2000; Pope et al., 1995; Dockery et al., 1993; Schwartz and Dockery, 1992). More recently, health studies have reported that ambient PM$_{2.5}$ mass and sulfate concentrations in
Steubenville were associated with altered autonomic function (e.g., reduced heart rate variability (HRV)) (Luttmann-Gibson et al., 2006) and that ambient sulfate and ozone levels in the same location were associated with arrhythmia (Sarnat et al., 2006).

The intent of the overall Bi-City Concentrated Ambient Particle Study, which was conducted in Detroit, Michigan and Steubenville, Ohio, was to collect highly time-resolved exposure and outcome data on animals exposed to concentrated ambient PM at these two locations. Specifically, we collected HRV data; HRV varies with cardiac autonomic function, and reduced HRV is a widely-used clinical prognostic marker of increased risk of adverse cardiovascular (CV) effects (Tsuji et al., 1996). In animal studies, HRV data are typically collected using telemetric methods and continuous recordings. However the value of these highly time-resolved measurements is lost when evaluating associations with PM metrics that are typically averaged over 8–24 h. To provide a more analogous measure, a subsequent related report will describe the cardiac and elemental composition of ambient PM2.5 and subsequently to determine potential sources. The development and use of the SEAS has been described in detail (Pancrasa et al., 2006; Ogulei et al., 2006; Kidwell and Ondov, 2004). Trace elements are particularly useful constituents of ambient PM as they can serve as tracers for specific emission sources, and some do not transform significantly in the atmosphere (Henry, 1997). Moreover, numerous recent studies have reported that metals in PM derived from combustion sources may be closely associated with the adverse health impacts of ambient PM2.5 (Cavallari et al., 2008; Hirshon et al., 2008; Lippmann et al., 2006; Gavett et al., 2003), making semi-continuous monitoring of trace elements particularly important to our understanding of component-specific and source-specific morbidity and mortality.

In the present study, highly-time resolved fine PM samples were collected as part of the Bi-City Concentrated Ambient Particle Study to assess health effects of ambient PM2.5 in regions dominated by different sources. Detroit, MI and Steubenville, OH were selected because of its proximity to numerous anthropogenic air pollution sources in the Ohio River Valley. There are five large coal-fired utility boilers within a 50 km radius of the site and seventeen within 100 km (Keeler et al., 2006), as well as iron/steel manufacturing facilities, metal coating/processing facilities, smelters and incinerators. Fig. 1 presents overview and detail maps of the Steubenville area showing the location of AirCARE1 during the inhalation exposure studies. The overview map also indicates PM2.5 point sources in the area that are among the top 25 emitters in Pennsylvania, Ohio, and West Virginia (USEPA, 2002a).

2.2. Field campaign and exposure characterization

This study was conducted at the Franciscan University in Steubenville, OH from August 2–14, 2006, with exposure/sampling conducted from 7AM–3PM each day. Continuous ambient PM2.5 concentration data were collected using a Tapered Element Oscillating Microbalance (TEOM) Monitor (Rupprecht and Patashnick, Model 1400AB). A total of 221 ambient PM2.5 samples were collected at 30-minute intervals using the SEAS. The details of the SEAS have been previously described (Kidwell and Ondov, 2001, 2004). Briefly, ambient air was pulled into the sampling manifold at a flow rate of 90 L min\(^{-1}\). An aerosol concentrator was used to extract particles after steam injection and subsequent cooling that enables particle growth via condensation of water vapor. The water droplet or slurry samples were collected in an impactor and then transferred to a fraction collector every 30 min. Water slurry samples collected from SEAS were acidified to 10% nitric acid, refrigerated for a minimum of two weeks, and then analyzed for a suite of trace elements using inductively coupled plasma-mass spectrometry (ICP-MS) (ELEMENT2, Thermo Finnigan, San Jose, CA).

Particle samples collected on Teflon filters during 8-h exposure periods were used for morphological/chemical characterization using high-resolution transmission electron microscopy (HRTEM: JEOL 2010F). These filter samples were also acidified to 10% nitric acid, refrigerated for a minimum of two weeks, and then analyzed for a suite of trace elements using the ICP-MS. PM samples collected on quartz filters were analyzed for temperature-resolved carbon fractions (organic carbon (OC) and elemental carbon (EC)) by a thermal-optical analyzer using NIOSH Method 5040 (Sunset Labs, Forest Grove, OR). Black carbon concentrations in the exposure chamber were also monitored continuously using an aethalometer. In addition, ambient gaseous pollutants were measured continuously including oxygen (O\(_2\)), measured by a continuous UV photometric analyzer (TECO 49); sulfur dioxide (SO\(_2\)), measured by a pulsed fluorescence analyzer (TECO 435S); nitrogen oxides (NO\(_x\)), measured by a chemiluminescence detector (TECO 425S); and carbon monoxide (CO), measured by a non-dispersive infrared analyzer (TECO 48S). The continuous gaseous pollutant data along with the SEAS data were used to help identify primary emission sources during the study. An on-site 10-m meteorological tower was used to collect temperature, relative humidity, wind speed, and wind direction data.

2.3. Receptor modeling

EPA PMF 3.0 was utilized to determine the major emission sources that contributed to the ambient PM2.5 levels in Steubenville. PMF is based on factor analysis that constrains factor loadings and factor scores to nonnegative values and also allows for the inclusion of measurement uncertainties for elemental
PMF is a commonly used tool to extract factors from measurement data that can be used to help understand how sources can contribute to PM (Lee and Hopke, 2006; Hopke et al., 2006; Pekney et al., 2006). In this study, PMF was applied to 221 30-minute SEAS samples. The elemental concentrations and analytical uncertainties for each element for each sample together with the sampling uncertainties were used as input to the model. The sum of the analytical and sampling uncertainty, and method detection limit (MDL) were used to calculate the uncertainty \( U \) assigned to each measured concentration data point as follows:

\[
U = \sqrt{SC^2 + (AM)^2 \times \text{concentration}}^2 + \text{MDL}^2
\]

(where SC = the uncertainty of sample collection, AM = the uncertainty of analytical measurement). Values below the MDL were replaced by half of the MDL for the measured data. Based on EPA’s PMF guidelines (2008b) and other references (Paatero and Hopke 2003; Paatero et al., 2005), signal-to-noise ratios were used to determine a species categorization. If the signal-to-noise ratio was less than 0.2, it was excluded from the analysis. If the signal-to-noise ratio was greater than 0.2 but less than 2, it was categorized as “weak” and down-weighted by tripling the calculated uncertainty. For this study, Ce, Sb, Mg, P, V, Ni, Cu, Zn, K and Ba were categorized as weak. The optimal solution was determined by multiple model runs to examine the effect on the numbers of factors assigned and the different FPEAK values on the range of results that were both physically reasonable and where the objective function Q value does not change substantially. The FPEAK value was set at zero, where the value of robust Q reaches a global minimum. The theoretical and calculated values were 2154 and 3920, respectively. An overall correlation between the reconstructed PM\(_{2.5}\) mass from all the sources \( Y \) and the observed PM\(_{2.5}\) mass concentrations \( X \) showed \( Y = 0.70X \) \( (R^2 = 0.54) \).

### 2.4. Meteorology and source directionality analysis

Each elemental concentration, PM\(_{2.5}\) mass concentration, gaseous pollutant concentration, and PMF-derived source factor contribution data set was matched with the average wind speed and direction at the sample site over the corresponding 30-minute time interval. These matched data were then grouped by wind direction and averaged over 10-degree wide sectors to produce study-averaged factor contributions by wind direction. In order to eliminate spurious results, half-hour samples with an associated wind speed of less than 1 m s\(^{-1}\) (9% of the total samples) were removed from the source directionality analysis (but were not removed from the PMF analysis), and time-averaged PMF source factor contributions for wind sectors containing less than 3 half-hour samples were suppressed from the final results.
3. Results and discussion

3.1. Air pollution during the Steubenville summer study

The mean ± standard deviation of ambient PM$_{2.5}$ mass concentration measured by TEOM during the 13-day exposure period was 25 ± 15 µg m$^{-3}$ (Table 1). Another recent study in the Steubenville region — the Steubenville Comprehensive Air Monitoring Program (SCAMP) — reported that from 2000 through 2002 the average PM$_{2.5}$ concentration measured in Steubenville was 18.4 µg m$^{-3}$. However, since the current study was conducted only during the daytime hours of 13 summer days, the average concentration cannot be regarded as representative.

Table 1 also summarizes gaseous pollutant concentrations. The average SO$_2$ concentration at the Steubenville site (8.9 ± 13.9 ppb) was approximately twice that of the 13-day Detroit exposure study (5.2 ± 4.1 ppb), and together with the maximum concentration (104 ppb, vs. 36 ppb in Detroit), these data show the close proximity of SO$_2$ sources to the Steubenville site.

Table 2 summarizes the 30-minute elemental concentrations measured by the SEAS and the total number of below-detection-limit samples for each species during the 13-day exposure study period. As shown in Table 1, some soil element concentrations measured by SEAS and filter samples were particularly large. Since most of the soil elements have a much lower water solubility than the anthropogenic elements (Connell et al., 2006), they were likely not collected as efficiently by the SEAS. Compared to the summer exposure study in Detroit (Morishita et al., 2011), Ti, V, Se and Cd concentrations were higher (2x, 1.5x, 1.5x, and 5x, respectively) during the Steubenville study.

3.2. Major sources of ambient PM$_{2.5}$ in Steubenville

PMF extracted six source factors from 221 30-minute ambient PM$_{2.5}$ samples including coal/secondary, motor source, iron/steel manufacturing, metal coating/processing, Pb factor and incineration/smelting (Table 3). Fig. 2 shows the reconstructed ambient PM$_{2.5}$ mass from all sources identified by PMF. The contribution from the coal/secondary sulfate factor (39%) was the highest, followed by mobile sources (12%), metal processing/industries (10%), iron/steel manufacturing (5%), and Pb factor (5%).

During the 13-day exposure period, the dominant wind directions were northeasterly ($N = 91$) and west southwesternly ($N = 75$) as shown in Fig. 3. Because of this uneven distribution of wind during the study, contributions from some large emission sources in the area were relatively low. For example, the relatively small magnitude of the iron/steel manufacturing factor is likely due to the relatively low fraction of time during which the wind came from the direction of those facilities during our study, despite the fact that the EPA listed those facilities as major sources of ambient PM$_{2.5}$, CO, and NO in the Steubenville-Wheeling area (2002a). Each factor profile and its associated wind rose plot for the factor contributions are discussed in detail next.

Factor 1 had the highest concentrations of S, Se, Al, and P and was identified as a coal combustion and secondary sulfate factor. As shown in Fig. 4, the highest ambient PM$_{2.5}$, S and Se concentrations were associated with southwesterly winds; this is consistent with the locations of multiple large coal-fired power plants in the Ohio Valley on a heading of 180–200° from the measurement site. The highest SO$_2$ concentrations were also associated with...
southwesterly winds, and Table 4 shows that Factor 1 had the highest correlation with SO$_2$. The SCAMP study also reported that many pollution episodes exhibited strong covariation between PM$_{2.5}$ and primary gaseous pollutants including CO, NOx and/or SO$_2$, although these episodes were frequently observed in cooler months (Connell et al., 2005). However, because of the lack of semi-continuous OC data, we could not evaluate the OC contribution to Factor 1. Based on 8-hour filter measurements, the average concentration of OC at the Steubenville site was 4.8 $\mu$g m$^{-3}$ (Table 2) and was approximately the same as that of the 13-day Detroit exposure study (5.1 $\mu$g m$^{-3}$). As discussed in the Detroit exposure paper (Morishita et al., 2011), this factor likely also contains secondary organic aerosol.

The wind rose plots of the time-averaged PMF factor contributions as a function of wind direction for the 30-minute SEAS data further confirmed probable locations of large coal-fired power plants (Fig. 5). These figures show how wind direction affected the contribution of each factor as observed at the Steubenville sampling site, and also confirm the probable locations of modeled sources. According to the EPA Facility Emission Report, four coal combustion utilities south of Steubenville were one of the largest sources of PM$_{2.5}$ in the region, emitting over 2000 tons of PM$_{2.5}$ per year (USEPA, 2005; Fig. 1).

The sampling site was often impacted by coal combustion during the exposure period; an example is presented in Fig. 6, which shows temporal variations of wind direction and factor contributions to ambient PM$_{2.5}$ during the 8-h exposure period on August 6. The highest ambient PM$_{2.5}$ concentration (80 $\mu$g m$^{-3}$) was observed during this 8-h exposure period, and this figure illustrates when each source factor (as derived from the SEAS data) impacted the site, something which cannot be determined from the integrated filter samples. In the early morning, the dominant wind direction was south-southeasterly (150–180°) and gradually shifted to the south-southwest (190–210°) by early afternoon. As the wind direction changed, the contribution of the coal/secondary factor increased significantly. 180–200° from the measurement site is again consistent with the locations of multiple large coal-fired power plants in the Ohio Valley.

In addition, although the relative contribution from local and regional coal-fired power plants could not be determined from this study, impact from local coal-fired power plants was likely observed on the afternoon of the 6th. Fig. 7 shows 30-minute temporal variations of Se and S concentrations measured by SEAS. As shown, levels of S and Se concentrations increased simultaneously, and the average ratio of S to Se between 10:00 and 15:30 was 551 (with a minimum of 290). Previous studies have reported S/Se ratios for coal-fired power plant stack emissions of <200 (Olmez et al., 1988) and <100 (England et al., 2007; Lee, 2001) for eastern U.S. coal (with electrostatic precipitation emission controls). Given that S/Se ratios in upwind regions or rural areas are reported to be >1500 and S/Se ratios in areas of strong SO$_2$ and Se sources drop to less than 1000 (Tuncel et al., 1987), the observed ratio on the 6th further confirms the impact from local coal-fired power plants.

Factor 2 was characterized by the highest loadings of K and As along with moderate loadings of Fe, Sb, Zn, S, Mo, and Pb, all of which are associated with motor vehicle roadway emissions (Lough et al., 2005). Furthermore, factor 2 had the second highest correlation with CO and moderate correlations with both NO and EC, all of which are primary pollutants from mobile sources (Gertler et al., 2002; McDonald et al., 2004). In addition, Fig. 2 shows that this factor was present in more wind sectors than any other factor. Thus this factor was identified as mobile source-related. Fe, Mn, Pb and Sb are present in brake wear dust; Pb can also be emitted from motor and fuel oil combustion; Fe, Zn, As, K and Mo are all present in tailpipe emissions; and Zn is present in tire wear dust as well as in tailpipe emissions due to its use in motor oil (Schauer et al., 2006; Garg et al., 2000; Iijima et al., 2008). However, Fig. 5 shows that this factor appears to have picked up fugitive dust emitted from iron/steel industries since the directionality analysis shows the contribution peak from the south, where those industries are located. The Ohio EPA has reported that the mobile source emission inventory estimates for the Jefferson–Weirton non-attainment areas show emissions of 25 tons of PM$_{2.5}$ per year (State of Ohio, 2008). This is consistent with relatively small contributions of motor vehicle/diesel to ambient PM$_{2.5}$ compared to other emission sources surrounding the site (e.g., coal fired power plants, metal industries). Furthermore, as Graham (2008) discussed in a recent review article, the study location at the Franciscan University is located over 100 m above Ohio Route 7 and other major roads, and this may have resulted in an under-estimate of the contributions from motor/diesel emission, and may have resulted in increased mixing with other sources such as iron/steel manufacturing.

![Fig. 2. Average factor contributions to ambient PM$_{2.5}$ during the 13-day exposure period: Results from 221 30-minute SEAS samples collected in August 2006.](image-url)

![Fig. 3. Wind frequency during the 13-day exposure period.](image-url)
Factor 3 had the highest V, Cr, Ti, Mo, La, and Ce concentrations, as well as elevated levels of As, Ca, P and Al, and the wind direction data for this factor shown in Fig. 5 indicate that probable sources are located northeast of Steubenville. Ti and Al are used in paint operations, and Mo and Cr are used in non-ferrous rolling/drawing operations (Pekney et al., 2006; Suarez and Ondov, 2002). It is notable that over 20 years ago Koutrakis and Dpengler (1987) also reported strong correlations among Ti, Cr and V and identified the factor as Ti production, which at that time represented 1.5% of fine particle mass. The EPA has reported that several metal coatingrocessing facilities and metal can production industries are located in this area (Fig. 1) and again the wind rose plot for the factor contributions confirmed probable locations of those facilities.

Factor 4 is attributed to iron/steel manufacturing due to the highest concentrations of Fe, Mn, Ni, Sr, Sb, Ca, Rb, Mg, and Ba as well as moderate loadings of S, K and Zn. This factor profile is consistent with the SCAMP study (Connell et al., 2006). However, Pb – one of the hazardous air pollutants typically emitted from iron/steel manufacturing – was absent in this factor. As described below, it appears that Pb factor was separately extracted from PMF since there are multiple large Pb emission sources in this area. This factor also had the highest correlation with the primary pollutants CO and NO. There are multiple iron/steel facilities in this area, but the larger ones are located within ten miles to the north-northeast and south-southeast, and the directionality analysis in Fig. 5 shows that the highest contributions come from those directions. The impact from these local sources is further evidenced by the HAADF-STEM images of the ambient PM_{2.5} samples from the 8-hour sampling period on August 4th. Fig. 8 shows numerous spherical nano-scale Fe, Cr, and Ni particles that are typically associated with iron/steel manufacturing processes. HAADF-STEM images of multiple filters showed that these ultrafine particles (<100 nm in size), likely emitted locally from high-temperature combustion processes, frequently impacted the study site. This factor accounted for about 5% of ambient PM_{2.5} (Fig. 2).

Factor 5 accounts for over 80% of Pb, 40% of Cu, and 20% of K, and is believed to result from numerous Pb emission sources in this area including smelting/incineration and iron/steel manufacturing (USEPA, 1995, 2002a, 2005). Fig. 5 indicates two probable source directions. One direction is south, where iron/steel manufacturing and metal processing facilities are all located. This factor also showed increased contributions when the winds were coming from the west-southwest at approximately 250°, where a local airport (Jefferson County Airport) is located. Currently, tetraethyl lead is still added to aviation gasoline which is used in most piston-engine powered aircraft (EPA, 2008a), and the 2002 National Emissions Inventory estimates that lead emissions from the use of leaded aviation gasoline could account for 29% of the air emissions. The EPA reported that it is estimated that Jefferson County Airport

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### Table 4

<table>
<thead>
<tr>
<th>Source Type</th>
<th>Coal secondary</th>
<th>Mobile source</th>
<th>Metal coating/processing</th>
<th>Iron steel</th>
<th>Pb</th>
<th>Incineration smelting</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>0.16</td>
<td>0.56</td>
<td>0.12</td>
<td>-0.06</td>
<td>0.01</td>
<td>0.28</td>
</tr>
<tr>
<td>SO_{2}</td>
<td>0.50</td>
<td>-0.14</td>
<td>-0.15</td>
<td>0.01</td>
<td>0.24</td>
<td>-0.07</td>
</tr>
<tr>
<td>NO</td>
<td>-0.07</td>
<td>0.39</td>
<td>0.36</td>
<td>0.08</td>
<td>-0.14</td>
<td>0.26</td>
</tr>
<tr>
<td>BC</td>
<td>0.18</td>
<td>0.43</td>
<td>0.09</td>
<td>-0.02</td>
<td>0.04</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Fig. 4. Average PM_{2.5}, SO_{2}, Se and S concentrations as a function of wind direction from 221 data points collected in August 2006.
emits 0.042 tons of Pb per year. However, there was no significant correlation with any primary gaseous pollutants, and more investigation is required to determine relative contributions of Pb sources.

Finally, Factor 6 is characterized by the highest concentrations of Zn and Cd. The directionality analysis indicates that probable sources for this factor are located northeast of Steubenville. The largest Zn smelting facility in the country is located in this direction within 30 miles of the sampling site and EPA records show that the facility emits approximately 50 tons of PM$_{2.5}$ per year. Furthermore, the northeast region of Steubenville has a number of relatively small (emitting <10 tons per year) metal processing plants and waste incinerators, which reported Cd and/or Zn air emissions to EPA TRI (Connell et al., 2006; USEPA, 2002b). Fig. 5 supports the locations of probable sources by showing the highest contribution from the northeast direction. Therefore, this factor is likely to represent various industries including incineration and nonferrous metal processing.

PMF was unable to attribute all of the measured fine mass using the data collected from SEAS; in fact, 28% of the mass was not apportioned to a source factor. This was due in part to several 30-minute SEAS samples with below-detection-limit elemental concentrations that corresponded to the lowest PM$_{2.5}$ mass concentrations. More samples together with greater temporal variability may have helped identify more emission sources. In addition to the identified source factors, the Steubenville area also contains numerous chemical production and processing facilities that emit relatively large amounts of organic compounds; these were not measured by SEAS in our study. Similarly, biogenically-derived secondary organic aerosol, likely to be significant in Steubenville in the summer, was not measured or included in PMF. Furthermore, since the PM$_{2.5}$ mass was determined using a TEOM, the physical differences in the actual collection of the fine particles between TEOM and SEAS were also likely responsible for the differences between the measured and calculated masses. For example, some of the PM$_{2.5}$ mass should be from wind blown soil,

**Fig. 5.** Average factor contributions versus wind direction from 221 SEAS samples collected in August 2006.
Fig. 6. Temporal variations of wind direction (above) and factor contributions to measured PM$_{2.5}$ (below) during the 8-h exposure period on August 6, 2006.

Fig. 7. Temporal variations of Se and S concentrations from SEAS samples collected on August 6, 2006.
often referred as a crustal component. However, a clearly identifiable crustal factor was not observed in the SEAS data, and we believe that since most of the soil elements have a much lower water solubility than the anthropogenic elements (Connell et al., 2006), they were likely not collected as efficiently by the SEAS.

4. Conclusions

Utilizing highly time-resolved elemental concentration data and receptor modeling, along with source directionality analysis, six factors for the ambient PM$_{2.5}$ observed in Steubenville were identified and the contributions from each factor were determined. Primary sources included (1) coal combustion/secondary, (2) mobile sources, (3) metal coating/processing, (4) iron and steel manufacturing, (5) Pb factor, and (6) incineration/smelting. The identified factors contributing the most mass to ambient PM$_{2.5}$ (calculated using 30-minute data) were coal/secondary sulfate (39%), followed by mobile sources (12%). These results from the semi-continuous sampling method concur with the results from previous studies and identified similar emission sources around the Steubenville site.

Furthermore, the highly time-resolved elemental concentration data and receptor modeling showed temporal variations in the 30-minute samples that cannot be observed in the 8-hr samples. The results presented on source-specific PM exposure are being used to investigate the associations between the identified sources and a number of real-time cardiopulmonary endpoint; the results of this investigation will be presented in a separate publication. Although the exposure was only 13 days long and may not accurately reflect long-term average conditions, this study has advanced our understanding of temporal PM source-receptor relationships in a complex urban air shed. These methods have been shown to be useful for health studies, particularly those focusing on acute health effects of PM.

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