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The Impact of Three Recent Coal-fired Power Plant Closings on Pittsburgh Air Quality:

A Natural Experiment

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B.A.
Cornell University
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An abstract of
A thesis submitted to the Faculty of the
Rollins School of Public Health of Emory University
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Abstract

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Background: The region of southwestern Pennsylvania, including the metropolitan Pittsburgh area, suffers from high ambient concentrations of fine particulate matter ($PM_{2.5}$), relative to other areas in the United States. $PM_{2.5}$ is known to be associated with adverse respiratory and cardiovascular health impacts.

Purpose: The objective of this study is to evaluate whether the closing of three coal-fired power plants within the southwestern Pennsylvania region resulted in a significant decrease in fine particulate matter concentration.

Methods: Both $PM_{2.5}$ data obtained from 12 EPA ground stations in the study region, and aerosol optical depth (AOD) data retrieved from the MODIS instrument onboard the Aqua satellite, were used to estimate monthly averages of fine particulate matter concentration from January of 2009 through December of 2014. The significance of each plant shutdown in predicting $PM_{2.5}$ concentration was evaluated using a generalized linear regression model that controlled for seasonality.

Results: The ground station regression analysis shows that the closing of the Elrama plant in 2012 resulted in a significant decrease of 1.34 $\mu g/m^3$ in $PM_{2.5}$ concentration. Although there was a decrease in $PM_{2.5}$ concentration following the closing of Mitchell and Hatfield's Ferry power plants in 2013, this decrease was not significant at $\alpha = 0.05$. The satellite data regression analysis shows that both the Elrama closing and the joint closing of the Mitchell and Hatfield's Ferry plants resulted in a significant decrease in AOD: decreases were of 0.021 and 0.013, respectively.

Conclusion: The use of satellite-retrieved AOD data allows for greater spatial coverage than that provided by EPA ground station observations. In this study, the closing of two power plants in October of 2013 significantly decreased AOD levels throughout the study region, but did not significantly lower $PM_{2.5}$ measured from EPA ground stations. Further analysis is needed to determine how individual ground stations might be influenced by interfering sources of emissions.

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Introduction

1.1 Fine Particulate Matter and its Health Impacts

Particle air pollution is comprised of both solids and liquid droplets that are either emitted directly, or formed in the atmosphere when other pollutants react [1]. Fine particulate matter, or $PM_{2.5}$, refers to particles with an aerodynamic diameter less than or equal to 2.5 micrometers, and is derived primarily from direct combustion emissions, including motor vehicles, power plants, industrial processes, wood burning, and forest fires [2].

Elevated fine particulate matter concentrations in the ambient air can have detrimental health impacts. A 2009 study of 51 American metropolitan areas found that a decrease of 10 $\mu g/m^3$ in $PM_{2.5}$ concentration was associated with 0.61±0.20 year increase in life expectancy [3]. Fine particulate matter exposure has been shown to have adverse effects on cardiopulmonary health [2, 4-6]. More specifically, each 10 $\mu g/m^3$ increase in $PM_{2.5}$ concentration was associated with a 4% increased risk of all-cause mortality, a 6% increased risk of cardiopulmonary mortality, and an 8% increased risk of lung cancer [4]. There is also evidence of a causal relationship between $PM_{2.5}$ exposure and cardiovascular morbidity and mortality [7-10]. Increased risk of fatal coronary heart disease among women from the Nurses' Health Study was associated with each 10 $\mu g/m^3$ increase in annual fine particulate matter exposure (HR=2.02; 95% CI, 1.07-3.78) [9]. In addition, the risk of cerebrovascular events among postmenopausal American women was also found to be associated with increased levels of $PM_{2.5}$ (HR=1.35; 95% CI, 1.08-1.68) [8]. Those suffering from asthma, chronic obstructive pulmonary disease, pneumonia, other respiratory diseases, cardiovascular diseases, or diabetes are especially vulnerable to the negative health effects of fine particulate matter [11].

1.2 $PM_{2.5}$ in Pittsburgh, PA

The Clean Air Task Force estimates that the number of deaths attributable to fine particle pollution from US power plants has dropped from exceeding 24,000 in year 2004 to exceeding 7,500 in year 2014. Although emissions regulations have proven to be effective in reducing $PM_{2.5}$ concentration, certain areas of the county, such as southwestern Pennsylvania, still suffer a high number of annual deaths attributable to fine particle power plant pollution. As of 2012, Allegheny County, where Pittsburgh's population of over 305,500 resides [12], is estimated to experience 10 to 14 deaths per 100,000 people every year. The surrounding counties of Washington, Greene, Fayette, Butler, and Beaver have the same mortality estimate from power plant emissions as Allegheny County. Westmoreland and Armstrong Counties, located to the east of Allegheny, were assigned the highest estimate of mortality attributable to power plant emissions, which is greater than 14 deaths per 100,000 people each year. [13]

Ambient air pollutants released by coal-fired power plants include sulfur dioxide (SO_2), nitrogen oxides (NOx), carbon dioxide, hydrocarbons, and particulate matter (PM), including secondary sulfates-nitrates [14]. Coal-fired power plants have control technologies in place that are effective in removing large, massive particles from emissions, but submicron particles most harmful to human health are often able to escape into the ambient plumes [15]. Pittsburgh's air quality also suffers due to the high number of coal-burning sources in the Ohio River Valley. Ground-level concentrations of many pollutants, including acid aerosols, are higher in Pittsburgh when ground-level wind direction vectors indicate that wind is coming from the southwest [16].

1.3 Pittsburgh's Coal Industry: Past and Present

Since the eighteenth century, the coal industry has played an instrumental role in Pittsburgh's history. The first mining of bituminous coal in the United States began in Pittsburgh in 1762 on Coal Hill, presently known as Mt. Washington. Local residents began burning coal to heat their homes, but water and timber continued to be the primary sources of energy for much of the next century. Both production and use of coal increased tremendously by the mid-1800s, earning Pittsburgh its title of "The Smoky City." [17]

A brief hiatus in coal use occurred at the end of the nineteenth century due to George Westinghouse's work in promoting the production and distribution of natural gas. Reliance on natural gas was short-lived, however, and by the early 1920s, Pennsylvania's bituminous coal mines employed 170,000 people. In 1921, Seward Power Plant, the first mine-mouth, coal-fired power plant in the United States, was built near Johnstown, about 100 km east of Pittsburgh [18]. The plant had an original capacity of 196 MW, and was followed by the construction of several other Pennsylvania coal-fired power plants throughout the next fifty years [18]. In addition to the enforcement of Environmental Protection Agency (EPA) regulations, economic improvements, as well as heightened environmental awareness, encouraged many Pittsburgh residents to adopt natural gas as their source of energy. In 2012, the number of people working in Pennsylvania bituminous coal mines was less than 8,000. [17]

Recently, many coal-fired power plants across the United States have either closed or been scheduled to close in the near future because of the EPA's regulations [19]. The main regulations responsible for the recent plant closings are the Mercury and Air Toxics Standards, the proposed Cross State Air Pollution Rule, and the proposed regulation of carbon dioxide emissions outlined in the Clean Power Plan [19]. Since 2009, two coal-fired power plants and one combined coal/oil plant have closed near Pittsburgh [19]. Allegheny County's Elrama power plant, a coal-fired plant with a capacity of 510 MW located less than 22 km south of the city's center, was the first to close in October of 2012 [19, 20]. Washington County's Mitchell power plant, a combined coal/oil plant less than 25 km from Pittsburgh with a capacity of 374 MW, closed in October of 2013 [19, 21]. Hatfield's Ferry power plant, located less than 65 km south of Pittsburgh in Greene County, closed at the same time, shuttering 1728 MW of capacity, thus making it the highest capacity plant in the United States to recently close [19, 21].

Some southwestern Pennsylvania residents are concerned about how the recent coal-fired power plant closings will affect the local economy. When asked about the pollution from the plants, Washington County resident, Jeff Heidelbach, explained, "We tolerate it because it provides jobs" [20]. The closing of the three power plants has resulted in the loss of 310 employees' jobs: 80 from Mitchell [20], 60 from Elrama [22], and 170 from Hatfield's Ferry [21]. Ryan Sullivan, a young former employee at Hatfield's Ferry power plant, doesn't know how he will ever pay back the loan he borrowed to pay for his education in power plant operations [21]. Still, there are some supporters of the plant closings. Robert Leach, the son of a former Mitchell employee, justified the loss of jobs as “good news for the long-term future of the environment” [20].

1.4 Using Natural Experiments to Assess Air Quality Improvements

While the economic value of coal-fired power plants can be easily quantified, assessing the impacts of coal-fired power plants on air quality is more difficult. Much of the complexity stems from the fact that Pittsburgh’s $PM_{2.5}$ concentration is influenced by both regional and local sources of emissions [23]. A previous study assessed sources of $PM_{2.5}$ at the National Energy Technology Laboratory in urban Pittsburgh using Positive Matrix Factorization (PMF2) and potential source contribution function analysis, particulate pollutant component concentrations, and Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) back-trajectory information [23]. It was found that while transport to the Pittsburgh area from the west or southwest accounts for 10.0 $\mu g/m^3$ of the ambient $PM_{2.5}$ concentration, emissions from two coal-fired power plants, approximately 12 km southeast of the National Energy Technology Laboratory, account for 0.50 $\mu g/m^3$ of the ambient $PM_{2.5}$ concentration [23]. In another effort to quantify the influence of power plants on Pittsburgh air quality, a hybrid multivariate receptor model was used to estimate pollution from individual sources, accounting for geographic relation to the receptor site and wind direction during sampling [24]. The model was able to predict SO_2 concentrations with excellent agreement between observed and predicted values ($r = 0.92$), but did not produce an estimate for the concentration of $PM_{2.5}$ [24].

When quantifying the effect of coal combustion on ambient $PM_{2.5}$ levels, the use of a natural or quasi-experimental design can be very informative [10]. In such an experiment, there is an exposed group and an unexposed group, but exposure status is the result of politics, an accident, or a regulatory action, such as the recent power plant closings [10, 25]. It is appropriate to use a natural experiment when an intervention's proposed health impacts are plausible, but uncertainty remains about the size or nature of the effects [25]. A natural experiment is further justified when the intervention that defines exposure status is likely to occur again [25]. Since many coal-fired power plants are scheduled to close in the near future, an analysis of the observational data in Pittsburgh before and after the plant closings is useful to environmental policy makers.

Air pollution control is an important area of public health policy where natural experiments have already contributed convincing evidence [25]. One of the most well-known air pollution natural experiments took advantage of the ban of coal sales in Dublin in 1990 [26]. Air pollution concentration and death rates were compared for the 72 months before and after the ban. It was found that black smoke concentration was reduced by 35.6 $\mu g/m^3$, or 70%, and it was estimated that 116 fewer respiratory deaths and 243 fewer cardiovascular deaths were observed each year after coal was banned [26]. A recent natural experiment from Tongliang County, China found that the closure of a coal burning power plant in 2004 resulted in benefits to children's health. A 2002 birth cohort and a 2005 birth cohort from the same hospital were each followed for 2 years. Mothers were restricted to those of nonsmoking status, with twenty or more years of age and residence within 2.5 km of the Tongliang power plant. Polycyclic aromatic hydrocarbons (PAH) were the exposure of interest due to their negative impacts on children's neurodevelopment. Levels of PAH-DNA adducts were measured in the subjects' umbilical cords, along with levels of brain-derived neurotrophic factor (BDNF), a protein involved in neuronal growth. All of the subjects were tested according to the Gesell Developmental Schedules at age two. Lower levels of PAH-DNA adducts, higher levels of BDNF, and higher developmental quotient scores were observed in the post-closure cohort when compared to the pre-closure cohort. [27]

Since the negative health impacts of fine particulate matter are already well-established [3-11], the central focus of air quality natural experiments is often to quantify the impact of an intervention on ambient $PM_{2.5}$ concentration. In the Columbia River Gorge National Scenic Area, 14 years of aerosol data spanning from 1993-2006 were analyzed to determine the impact of a coal-fired power plant in Boardman, Oregon on regional air quality [28]. Significantly higher $PM_{2.5}$ concentrations were observed when the plant was operating, compared to when it was closed for repairs [28]. The estimated $PM_{2.5}$ contribution of the Boardman power plant to the Columbia River Gorge was 0.90 $\mu g/m^3$ averaged over the whole year [28]. A more recent study used 2005-2010 concentration data to evaluate the impact of a coal-fired power plant shutdown in the spring of 2008 on air quality in Rochester, NY, a city of 207,294 people [29]. A positive matrix factorization model and a conditional probability function were used to calculate that the coal-fired power plant had contributed 3.9% of Rochester's ambient $PM_{2.5}$ concentration; regional transport contributed 84.8% and O_3-rich secondary aerosol contributed 11.3% [29].

1.5 Study Objectives and Hypotheses

The region of southwestern Pennsylvania suffers a high health burden from air pollution, relative to the rest of the United States [13], and the air quality of metropolitan Pittsburgh is especially concerning due to its high human population. The recent closings of three coal-fired power plants in the area offer a unique opportunity to assess the impact of point-source emissions on the surrounding population.

Fine particle concentration data from EPA ground stations in the study region were analyzed and supplemented with aerosol optical depth (AOD) data from MODIS instruments on board the Aqua satellite in order to improve spatial coverage. We used a generalized linear model to test if the plant closings had significant impacts on $PM_{2.5}$ concentration after controlling for seasonal differences. It is expected that both the closure of Elrama power plant in October of 2012 and the closure of Mitchell and Hatfield's Ferry power plants in October of 2013 have lowered the regional ambient $PM_{2.5}$ concentration.

Data and Methods

The datasets used in this study consist of remotely sensed aerosol optical depth (AOD), ground measured fine particulate matter ($PM_{2.5}$), and ground measured temperature data. All analyses were done using general linear regression models in SAS version 9.4 (Cary, N.C).

2.1 Study Area

Since the main objective of the study was to evaluate recent expected improvements in Pittsburgh's air quality, the study domain was defined by the three coal-fired power plants closest to Pittsburgh (40.4397°N, 79.9764°W) that have shut down since 2009 according to records from the Institute for Energy Research [19]. Of the Elrama, Mitchell, and Hatfield's Ferry power plants, Mitchell was located between Elrama and Hatfield's Ferry, and was the second-closest to Pittsburgh. Therefore, the study domain was defined as a 1° x 1° square that is centered on Mitchell Power Station: 40.221°N, 79.969°W [30]. The domain includes coordinates from latitude 39.72083°N to 40.720833°N and from longitude 79.46889°W to 80.46889°W; it contains the metropolitan Pittsburgh area in the north, and a portion of the Appalachian Mountains in the southeast corner (Figure 1).

2.2 Remote Sensing Data

Collection 6 level 2 AOD data were downloaded for the study area from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument aboard the Aqua satellite using http://ladsweb.nascom.nasa.gov/data [31].

The Aqua earth science satellite mission is a part of the National Aeronautics and Space Administration (NASA)'s international Earth Observing System (EOS). It was designed to monitor the earth's water cycle by collecting information about evaporation from the oceans, water vapor in the atmosphere, clouds, precipitation, soil moisture, ice, and snow cover. Aqua also measures aerosols among other variables, including temperatures, radiative energy fluxes, land vegetation cover, and phytoplankton in the oceans. The satellite was launched in May of 2002, and although it was originally designed for a six year lifetime, it is currently expected to operate successfully into the early 2020s. Aqua is sun synchronous and passes the equator at 1:30pm, repeating the same pathway every 16 days. It carries 6 Earth-observing instruments, four of which still transmit high quality data. MODIS is among the four instruments still in operation. [32]

MODIS acquires data in 36 spectral bands [33] and uses spectral relationships between its blue (470 nm), red (660 nm), and shortwave infrared (2.13 μm) wavelength bands to retrieve aerosol information over land [34]. AOD is a unitless, column-integrated measurement of aerosol loading that can be used to estimate ground-level $PM_{2.5}$ measurements [35]. Cloud-free conditions and low surface reflectance from ice or snow on the ground are required in order to retrieve AOD measurements from MODIS; these conditions are often associated with deep boundary layers, low relative humidity, low wind speed, and high air temperature [35].

The AOD data analyzed in this study were combined from the deep blue algorithm and dark target approach over the Pittsburgh study area for years 2009-2014. The 12 km Community Multiscale Air Quality (CMAQ) grid was used as a base grid for 10km x 10km MODIS data, resulting in little sacrifice of resolution [36]. Eighty-four CMAQ grid cells were at least partially included in the designated study region, and are highlighted in Figure 2.

2.3 Ground Station Data

Average daily ground-level $PM_{2.5}$ concentration measurements from 12 EPA ground stations were downloaded from http://www.epa.gov/airdata/ad_data_daily.html for the designated study area from 2009-2014 [37]. Eight stations with the following county-site codes were located in Allegheny County, which contains the city of Pittsburgh: 003-0002, 003-0008, 003-0064, 003-0067, 003-0093, 003-1008, 003-1301, and 003-3007. Three stations were located in Washington County: 125-0005, 125-0200, and 125-5001; and one station was located in Westmoreland County: 129-0008. Station locations are displayed in Figure 1. One station (125-5200) was excluded from the study because it only provided data from August of 2012 until June of 2014; it did not provide enough information prior to the closing of the Elrama plant in October of 2012 to determine whether the closing had an impact. Only observations with parameter code 88101 ($PM_{2.5}$ at local conditions) were included in the data set; observations of parameter 88502 (Acceptable $PM_{2.5}$ AQI and speciation mass) were excluded.

The temperature of the ambient air can affect $PM_{2.5}$ concentration in two ways. Firstly, outdoor temperature influences energy usage from heating and air conditioning systems, having a direct impact on the magnitude of $PM_{2.5}$ emitted from power plants. Secondly, sunlight and higher temperatures accelerate the photochemical reactions that produce secondary particulate matter species, such as sulfate, in the atmosphere [35]. Monthly average air temperatures measured by the weather station at Pittsburgh International Airport (40.4960°N, 80.2567°W) from 2009-2014 were downloaded from http://www.ncdc.noaa.gov/cdo-web/datatools/findstation [38].

2.4 Analysis

Monthly average AOD measurements from all 84 CMAQ grid cells during the study period were weighted by the number of days in the month that were used to calculate AOD for that specific month, year, and grid cell; there were about 5 AOD retrievals each month for each grid cell. Ground $PM_{2.5}$ measurements were also aggregated by month, year, and station; monthly averages were weighted by the average number of observations made each day for that specific month, year, and EPA ground station. Because certain EPA stations have multiple monitors, it was possible to have greater than one $PM_{2.5}$ observation for a single day at the same EPA ground station. Monthly averages from stations with multiple daily observations were considered to be more accurate, and therefore have a heavier influence on the model parameter estimates. Seasonal variables were created according to the methods of a previous study [26], in which winter was defined as December, January, and February; spring was defined as March, April, and May; summer was defined as June, July, and August; and fall was defined as September, October, and November.

Two dichotomous closing variables were created according to the documented dates of the power plant shutdowns. The first variable corresponds to the Elrama plant and switches from 0 to 1 beginning in November of 2012, marking the mid-October closure. The second variable corresponds to the Mitchell and Hatfield’s Ferry plants and switches from 0 to 1 beginning in November of 2013, after both plants closed during the previous October. These two variables divide the study into three periods. The first period is from January 2009 through October 2012, when all three plants were operating.

The second period is when Elrama was closed, but Mitchell and Hatfield's Ferry were still operating, from November 2012 through October 2013. The last period is from November 2013 through December of 2014, when all the plants were officially closed.

Both AOD and $PM_{2.5}$ levels were stratified by closing period, and two ANOVA tests were performed using Tukey's method to determine if AOD and $PM_{2.5}$ levels were different across closing periods, after controlling for seasonality, and weighting either by the average number of observations made each day for that specific month, year, and ground station; or by the number of days contributing to the AOD value of a specific month, year, and grid cell. The following general linear regression model reflects the ANOVA tests that were performed; this model was then applied to subsets of the $PM_{2.5}$ and AOD data, as well as to temperature data:

$$Y = \beta_0 + \beta_1 \text{ x Elrama} + \beta_2 \text{ x Mitchell\&Hatfield} + \beta_3 \text{ x Winter} + \beta_4 \text{ x Spring} + \beta_5 \text{ x Fall} + E \qquad \text{(Equation 1)}$$

Where Y = either monthly AOD, monthly $PM_{2.5}$, or monthly temperature

β_0 = the average Y variable during the summer season when all 3 plants are operating

Elrama = the closing of the Elrama plant (equals 0 up to October of 2012: operating plant; equals 1 beginning in November of 2012: closed plant)

Mitchell&Hatfield = the closings of the Mitchell and Hatfield's Ferry plants (equals 0 up to October of 2013: operating plants; equals 1 beginning in November of 2013: closed plants)

Winter = the winter season (equals 1 during December, January, and February; equals 0 during all other months)

Spring = the spring season (equals 1 during March, April, and May; equals 0 during all other months)

Fall = the fall season (equals 1 during September, October, and December; equals 0 during all other months)

E = random error term assumed ~ $N(0,\sigma^2)$

The statistical significance of each independent predictor variable was analyzed at $\alpha = 0.05$.

2.5 Sub-setting the AOD and $PM_{2.5}$ Data

After analyzing monthly fine particulate matter data from all of the EPA ground stations in the study area, each station was analyzed individually. In addition, the CMAQ grid cells were divided into different subsets to supplement the results of the full study area, consisting of 84 grid cells. Since all of the EPA ground stations were contained by 11 grid cells, these cells were identified as “Contains at least one ground station.” Fifty cells in the northern half of the study region were identified as “Near EPA ground stations.” The model results of these two data subsets were compared to the EPA ground stations results. (Figure 2)

In addition, subsets of grid cells were designated in the areas closest to the power plants. A 4 x 4 grid cell domain, roughly an area of 2,304 km squared, surrounding Hatfield’s Ferry power plant was designated as “Near Hatfield’s Ferry,” and a 3 x 3 grid cell domain, roughly an area of 1,296 km squared, surrounding the Mitchell and Elrama plants was designated as “Near Elrama and Mitchell.” The difference in areas surrounding the plants is due to their different levels of capacity. Together, Mitchell and Elrama have a capacity of 884 MW, while Hatfield’s Ferry has a capacity of 1,728 MW. The ratio of Hatfield’s Ferry capacity to Elrama and Mitchell capacity is 1.95. The ratio of “Near Hatfield’s Ferry” area to “Near Elrama and Mitchell” area is 1.78, and was intended to approximate the 1.95 ratio. (Figure 2)

Results

3.1 Descriptive Statistics

The EPA ground station data were approximately normally distributed with both skewness and kurtosis statistics below 1. The minimum monthly $PM_{2.5}$ concentration was 3.95 $\mu g/m^3$; the maximum was 24.53 $\mu g/m^3$; and the median was 11.07 $\mu g/m^3$, with a variance of 10.90 $\mu g/m^3$. Station 003-0002 was not in operation for all 12 months of 2009, and station 003-3007 did not have any recorded measurements for November of 2011; these deficiencies provide an explanation for the 13 missing values listed in Table 1. The mean $PM_{2.5}$ concentrations by each season and closing period, along with their corresponding standard deviations, are presented in Table 2. Fine particulate matter concentrations were consistently highest in the summer, followed by winter concentrations, with the lowest seasonal concentrations occurring in the spring or fall (Table 2). The average number of $PM_{2.5}$ concentration observations made in a month ranges from 4.4 to 49.0, depending on the ground station.

The AOD data were roughly normally distributed with both skewness and kurtosis statistics below 1. Since MODIS does not have the sensitivity over land to retrieve aerosol better than +/-0.050, small negative AOD values were permitted in the dataset to avoid bias [39]. The minimum AOD was -0.050; the maximum was 0.588; and the median was 0.098, with a variance of 0.009. Average AOD values by grid cell for the full six-year study period ranged from 0.074 to 0.147. The grid cells with the highest AOD measurements (>0.130) were located in a cluster including Pittsburgh and the region immediately southeast of the city. Due to a high number of missing values in the winter (Table 1), the dataset was restricted to spring, summer, and fall; reducing the sample size from 5,289 to 4,404. The mean AODs by each season and closing period, along with their corresponding standard deviations, are presented in Table 4. The highest aerosol optical depth retrievals consistently occurred in the summer months; the spring months had lower values; and the fall AOD values were consistently lower than both spring and summer (Table 4). Each monthly AOD estimate per cell is based on an average number of 5.76 daily observations in the spring, 5.31 daily observations in the summer, and 6.81 daily observations in the fall.

3.2 ANOVA test results

The least squares means matrix for the EPA ground stations (Table 3) shows that although $PM_{2.5}$ concentration decreases with each closing, the concentration observed in Period 3 is not significantly different from that observed during Period 2. However, both Periods 2 and 3, taken separately, are significantly different from Period 1. Period 2 has a

$PM_{2.5}$ concentration that is 1.34 μg/m^3 less than that of Period 1, and Period 3 has a concentration is 1.74 μg/m^3 less than that of Period 1 (Table 3). According to the least squares means matrix for AOD (Table 5), aerosol optical depth decreases after each plant closing, and any pair of closing periods shows a significant difference in AOD. The AOD values measured during Period 2 are 0.021 lower than those measured during Period 1, and values measured during Period 3 are 0.035 lower than those measured during Period 1. The AOD measured in Period 3 is, on average, 0.014 lower than the AOD measured during Period 2 (Table 5).

3.3 Linear Regression Results and Data Subsets

Average monthly temperature data from Pittsburgh International Airport were analyzed according to Equation 1, and neither closing variable was a significant predictor of temperature. The three seasonal variables were significant, and accounted for about 81% of the variation in temperature. Since the seasonal variables were good indicators of variation in temperature, a temperature parameter was not added to the model.

The results of the linear regression for all EPA ground stations (Table 6) were in agreement with the ANOVA results. The Elrama closing resulted in a significant decrease of 1.34 μg/m^3 in $PM_{2.5}$ concentration, but the decrease in $PM_{2.5}$ concentration resulting from the closing of Mitchell and Hatfield's Ferry was not significant at $\alpha = 0.05$. The linear model was able to explain 31% of the variance in monthly $PM_{2.5}$ concentrations. Several outliers were identified by standard regression diagnostics (Figure 3), but all values were within a plausible range, so none of the observations were removed from the data set. The partial plots generated in Figure 4 did not reveal any gross violations of linearity. Variance inflation factors for each parameter were all < 2, indicating that collinearity was not a concern.

When the linear regression was restricted to one ground station at a time, the Elrama closing resulted in a significant decrease in $PM_{2.5}$ concentration at 7 different stations: 003-0002, 003-0008, 003-0064, 003-0067, 003-1008, 125-0005, and 129-0008 (Table 7, Figure 1). The joint Mitchell & Hatfield's Ferry closing resulted in a significant decrease in $PM_{2.5}$ concentration at station 129-0008 and a significant increase in $PM_{2.5}$ concentration at station 125-0005 (Table 7). The mean $PM_{2.5}$ concentrations by each season and closing period, along with their corresponding standard deviations, for station 125-0005 and station 129-0008 are presented in Table 8 and Table 9, respectively.

The results of the linear regression for the AOD data (Table 10) were also in agreement with the ANOVA results. Both the Elrama and the joint Mitchell & Hatfield's Ferry closings resulted in significant decreases in AOD at $\alpha = 0.05$. The Elrama closing resulted in a decrease of 0.021, and the joint Mitchell and Hatfield's Ferry closing resulted in a decrease of 0.013 (Table 10). The linear model was able to explain 51% of the variance in monthly $PM_{2.5}$ concentrations. Several outliers were identified by standard regression diagnostics (Figure 5), but since all AOD values were deemed plausible, none of the observations were removed from the data set. The partial plots generated in Figure 6 did not reveal any gross violations of linearity. Variance inflation factors for each parameter were all < 2, indicating that collinearity was not a concern.

When the linear regression was restricted to grid cells near Mitchell and Elrama, the Mitchell&Hatfield closing variable lost its significance (Table 11). When the linear regression was restricted to grid cells near Hatfield’s Ferry, both closing variables were significant, and the magnitude of the Mitchell&Hatfield parameter estimate increased, surpassing the magnitude of the Elrama parameter estimate (Table 11). When the linear regression was applied to the EPA ground station data, excluding winter, the Mitchell&Hatfield closing variable was significant at $\alpha = 0.10$, but not at $\alpha = 0.05$ (Table 12). When the same model was run for AOD data restricted to grid cells containing ground stations, and excluding winter, the Mitchell&Hatfield closing variable was again significant at $\alpha = 0.10$, but not at $\alpha = 0.05$ (Table 12). Once the AOD dataset was expanded to include all grid cells near EPA ground stations, the Mitchell&Hatfield closing variable became significant, with a p-value < 0.01 (Table 12).

Discussion

4.1 Notable EPA Ground Stations

Station 129-0008 in Westmoreland County showed a significant decrease in $PM_{2.5}$ concentration after both the closing of Elrama and the joint closing of Mitchell and Hatfield’s Ferry. Station 129-0008 also has the highest quality data among the 12 ground stations, with 3 different monitors and an average of 49.0 observations each month (Table 7). While station 129-0008 is not located within Allegheny County, it is still within an urban area according to the 2010 US Census (Figures 1&2). It is possible that station 129-0008’s location to the northeast of the Hatfield’s Ferry plant and along the foothills of the Appalachian Mountains (Figure 1) allowed for fine particulate matter to be transported to the station via prevailing winds. The mountains likely act as a barrier to dispersion, resulting in an accumulation of fine particulate matter at station 129-0008 prior to the shutdowns of nearby coal-fired power plants. A more thorough analysis of $PM_{2.5}$ transport by wind is needed.

Results from station 125-0005 in Washington County showed a significant decrease in $PM_{2.5}$ concentration after the Elrama closing, but a significant increase in $PM_{2.5}$ concentration was seen after the joint closing of Mitchell and Hatfield's Ferry power plants. Station 125-0005 has data of intermediate quality, with an average of 28.3 observations each month (Table 7). The increase in fine particulate matter concentration after the closing of Mitchell and Hatfield's Ferry in October of 2013 could be due to the opening, or significant increase in operation, of another emissions point source near station 125-0005. The fracking industry has recently brought air pollution to areas that were previously free of it [40]. Over 6,400 wells have been drilled in the Marcellus Shale in Pennsylvania, and Washington County is a particularly popular location for shale gas drilling [40]. Statewide shale gas development and production is estimated to result in 460-1400 metric tons of $PM_{2.5}$ emissions per year, most of which originates from compressor stations [41].

4.2 Using Satellite-retrieved AOD Measurements to Assess Improvements in Fine Particulate Matter Concentration

The use of AOD data retrieved from MODIS aboard the Aqua satellite allows for greater spatial coverage when assessing the impact of power plant closings on air quality. Hatfield's Ferry power plant, at 1728 MW, is the largest capacity plant in the United

States to close in the past 6 years, but there is not a single EPA ground station within a 15 km radius of the plant. It is only through remotely sensed AOD data that the impact of the Hatfield's Ferry closing on air quality can be adequately analyzed. The results presented in Table 11 show that the decrease in $PM_{2.5}$ concentration experienced in the grid cells near Hatfield's Ferry after the joint Mitchell & Hatfield's Ferry closing was larger than the decrease experienced by all the grid cells in the study area, taken as a whole.

The first two columns of Table 12 show that when winter observations are excluded from $PM_{2.5}$ ground station data, and AOD data, excluding winter observations, is restricted to grid cells containing ground stations, both linear models are in agreement on the level of significance ($0.05<\text{p-value}<0.1$) of the joint Mitchell and Hatfield's Ferry closing. This agreement suggests that the increase in the same closing's significance when the AOD data is expanded to include a greater number of grid cells (Table 12) is the result of increased spatial coverage, rather than a mere disagreement between the accuracy of AOD and $PM_{2.5}$ data.

4.3 Limitations

The AOD data used in this study was gridded to a 12km x 12km CMAQ grid. Higher spatial resolution of either 3km x 3km or 1km x 1km would allow for a more accurate analysis of the impact of the three power plant closings on regional air quality. Limited AOD data during the winter season is likely due to snow cover.

In this study, monthly averages of $PM_{2.5}$ and AOD were used to limit extreme values due to meteorological conditions. Further studies using daily measurements and accounting for daily meteorological conditions, such as temperature, precipitation, wind direction, and humidity, would have a much greater sample size and more statistical power. Allowing for more time after the joint closure of the Mitchell and Hatfield's Ferry plants, and thus, more data collection, could also be beneficial.

In addition, a more thorough investigation of fine particulate matter point sources near station 125-0005 is needed. Discovery of interference due to a new source of emissions after October of 2013 at station 125-0005 may justify removal of that station from this natural experiment.

Conclusion

In this study, generalized linear regression models were used to assess the impact of three coal-fired power plant shutdowns on air quality in and around the Pittsburgh metropolitan area. Although EPA ground stations provided reliable data throughout all seasons of the year, the twelve stations were not evenly spread throughout the study region. Satellite-retrieved aerosol optical depth data was analyzed to improve spatial coverage. The closing of the Elrama plant in October of 2012 was found to significantly decrease $PM_{2.5}$ concentration throughout the study region according to data retrieved from both satellites and ground stations; while the joint closing of the Mitchell and Hatfield's Ferry plants was only found to significantly decrease $PM_{2.5}$ concentration throughout the study region according to satellite-retrieved AOD. As more power plants close due to failure to meet the standards of EPA regulations, aerosol optical depth will continue to be a useful supplement to ground station data in assessing impacts on air quality.

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Tables and Figures

Table 1: Descriptive statistics for fine particulate matter and AOD data.

	EPA Ground Stations Monthly $PM_{2.5}$ Averages by Season				AOD Monthly Averages by Season			
	Mean ($\mu g/m^3$)	SD	N	Missing	Mean	SD	N	Missing
Winter	11.37	2.61	213	3	0.022	0.046	885	627
Spring	9.70	2.45	213	3	0.101	0.064	1,508	4
Summer	13.90	3.25	213	3	0.195	0.083	1,504	8
Fall	9.58	2.84	212	4	0.051	0.068	1,392	36
Total			851	13			5,289	675

Table 2: Average $PM_{2.5}$ concentrations by season and closing period (N=851).

Season	Period 1* mean(sd) units= $\mu g/m^3$	Period 2** mean(sd) units= $\mu g/m^3$	Period 3*** mean(sd) units= $\mu g/m^3$
Winter	11.99(2.33)	10.84(1.93)	10.92(2.25)
Spring	10.56(2.21)	8.54(0.96)	9.07(2.01)
Summer	14.58(3.08)	12.34(1.22)	12.17(1.71)
Fall	10.18(2.73)	10.25(1.59)	8.21(1.92)

*Period 1 spans from January 2009 through October 2012, when all 3 plants were open.

**Period 2 spans from November 2012 through October 2013, when Elrama was closed, but Hatfield’s Ferry and Mitchell were still open.

***Period 3 spans from November 2013 through December of 2014, when all 3 plants were closed.

Table 3: ANOVA least squares means matrix for $PM_{2.5}$ (N=851).

	Period 1* mean = 11.84 μg/m^3	Period 2** mean = 10.50 μg/m^3	Period 3*** mean = 10.10 μg/m^3
Period 1* mean = 11.84 μg/m^3	NA	<0.0001	<0.0001
Period 2** mean = 10.50 μg/m^3	<0.0001	NA	0.1609
Period 3*** mean = 10.10 μg/m^3	<0.0001	0.1609	NA

*Period 1 spans from January 2009 through October 2012, when all 3 plants were open.
**Period 2 spans from November 2012 through October 2013, when Elrama was closed, but Hatfield's Ferry and Mitchell were still open.
***Period 3 spans from November 2013 through December of 2014, when all 3 plants were closed.

Table 4: Average AOD by season and closing period (N=4,404).

Season	Period 1* mean(sd)	Period 2** mean(sd)	Period 3*** mean(sd)
Spring	0.111(0.162)	0.102(0.074)	0.073(0.154)
Summer	0.213(0.171)	0.181(0.113)	0.159(0.150)
Fall	0.055(0.175)	0.034(0.078)	0.040(0.073)

*Period 1 spans from January 2009 through October 2012, when all 3 plants were open.
**Period 2 spans from November 2012 through October 2013, when Elrama was closed, but Hatfield's Ferry and Mitchell were still open.
***Period 3 spans from November 2013 through December of 2014, when all 3 plants were closed.

Table 5: ANOVA least squares means matrix for AOD, excluding winter observations (N=4,404).

	Period 1* mean = 0.128	Period 2** mean = 0.107	Period 3*** mean = 0.093
Period 1* mean = 0.128	NA	<0.0001	<0.0001
Period 2** mean = 0.107	<0.0001	NA	<0.0001
Period 3*** mean = 0.093	<0.0001	<0.0001	NA

*Period 1 spans from January 2009 through October 2012, when all 3 plants were open.
**Period 2 spans from November 2012 through October 2013, when Elrama was closed, but Hatfield's Ferry and Mitchell were still open.
***Period 3 spans from November 2013 through December of 2014, when all 3 plants were closed.

Table 6: General linear regression model estimates for monthly average $PM_{2.5}$ concentrations from all EPA ground stations (N=851).

Parameter	Estimate*	SE	P-value	R^2
Intercept	14.27	0.20	<.0001	0.31
Elrama	-1.34	0.24	<.0001	
Mitchell&Hatfield	-0.40	0.28	0.1609	
Winter	-2.06	0.26	<.0001	
Spring	-3.79	0.26	<.0001	
Fall	-3.88	0.26	<.0001	

*Units = μg/m^3

Table 7: Model estimates for each closing variable* by ground station.

Station ***	Monthly Weight ****	Elrama			Mitchell&Hatfield			R^2
		Estimate *****	SE	P-value	Estimate *****	SE	P-value	
003-0002	14.8	**-4.40**	**1.08**	**0.0002**	0.37	1.35	0.7850	0.56
003-0008	33.2	**-1.32**	**0.52**	**0.0144**	0.08	0.63	0.8977	0.57
003-0064	32.9	**-2.58**	**0.82**	**0.0024**	0.31	0.99	0.7532	0.34
003-0067	8.9	**-1.55**	**0.60**	**0.0115**	-0.10	0.72	0.8877	0.63
003-0093	4.4	-0.71	0.74	0.3454	-0.60	0.90	0.5078	0.43
003-1008	9.0	**-2.02**	**0.61**	**0.0014**	-0.08	0.73	0.9178	0.60
003-1301	8.7	-0.88	0.76	0.2523	-0.10	0.91	0.9126	0.46
003-3007	4.6	-1.35	0.88	0.1315	-0.06	1.05	0.9524	0.30
125-0005	28.3	**-1.34**	**0.61**	**0.0324**	**2.14**	**0.74**	**0.0053**	0.51
125-0200	47.2	-0.70	0.51	0.1759	-0.18	0.59	0.7665	0.53
125-5001	38.3	1.20	0.76	0.1185	-1.09	0.85	0.2037	0.19
129-0008	49.0	**-1.84**	**0.66**	**0.0070**	**-1.69**	**0.70**	**0.0182**	0.55

*Statistics for closing variables that are significant at $\alpha=0.05$ are listed in bold font.

***All 3 season variables (winter, spring, fall) were included in each station-specific model, even though seasonal statistics are not presented in this table.

****Average number of observations per month

*****Units = μg/m^3

Table 8: Average $PM_{2.5}$ concentrations by season and closing period at site 125-0005

Season	Period 1* mean(sd) units=μg/m^3	Period 2** mean(sd) units=μg/m^3	Period 3*** mean(sd) units=μg/m^3
Winter	12.37(1.61)	9.89(1.36)	12.71(1.98)
Spring	11.28(1.90)	9.45(0.45)	12.36(1.21)
Summer	15.08(2.10)	12.97(0.68)	15.79(0.45)
Fall	9.81(2.11)	10.69(0.96)	10.98(3.04)

*Period 1 spans from January 2009 through October 2012, when all 3 plants were open. N= 46 monthly averages.
**Period 2 spans from November 2012 through October 2013, when Elrama was closed, but Hatfield's Ferry and Mitchell were still open. N= 12 monthly averages.
***Period 3 spans from November 2013 through December of 2014, when all 3 plants were closed. N= 14 monthly averages.

Table 9: Average $PM_{2.5}$ concentrations by season and closing period at site 129-0008

Season	Period 1* mean(sd) units=μg/m^3	Period 2** mean(sd) units=μg/m^3	Period 3*** mean(sd) units=μg/m^3
Winter	12.44(2.23)	11.48(2.24)	10.39(3.01)
Spring	11.25(2.61)	8.66(2.57)	7.77(2.14)
Summer	16.27(4.06)	13.01(2.50)	10.83(0.65)
Fall	10.70(2.97)	10.31(1.86)	7.53(1.91)

*Period 1 spans from January 2009 through October 2012, when all 3 plants were open. N= 46 monthly averages.
**Period 2 spans from November 2012 through October 2013, when Elrama was closed, but Hatfield's Ferry and Mitchell were still open. N= 12 monthly averages.
***Period 3 spans from November 2013 through December of 2014, when all 3 plants were closed. N= 14 monthly averages.

Table 10: General linear regression model estimates for monthly average AOD for all grid cells at least partially included in the study area, excluding winter observations (N=4,404).

Parameter	Estimate	SE	P-value	R^2
Intercept	0.208	0.0018	<.0001	0.51
Elrama	-0.021	0.0026	<.0001	
Mitchell&Hatfield	-0.013	0.0034	<.0001	
Spring	-0.096	0.0024	<.0001	
Fall	-0.150	0.0023	<.0001	

Table 11: Comparison of all partially-included grid cells (full study domain) to power plant-centered subsets, excluding winter observations.

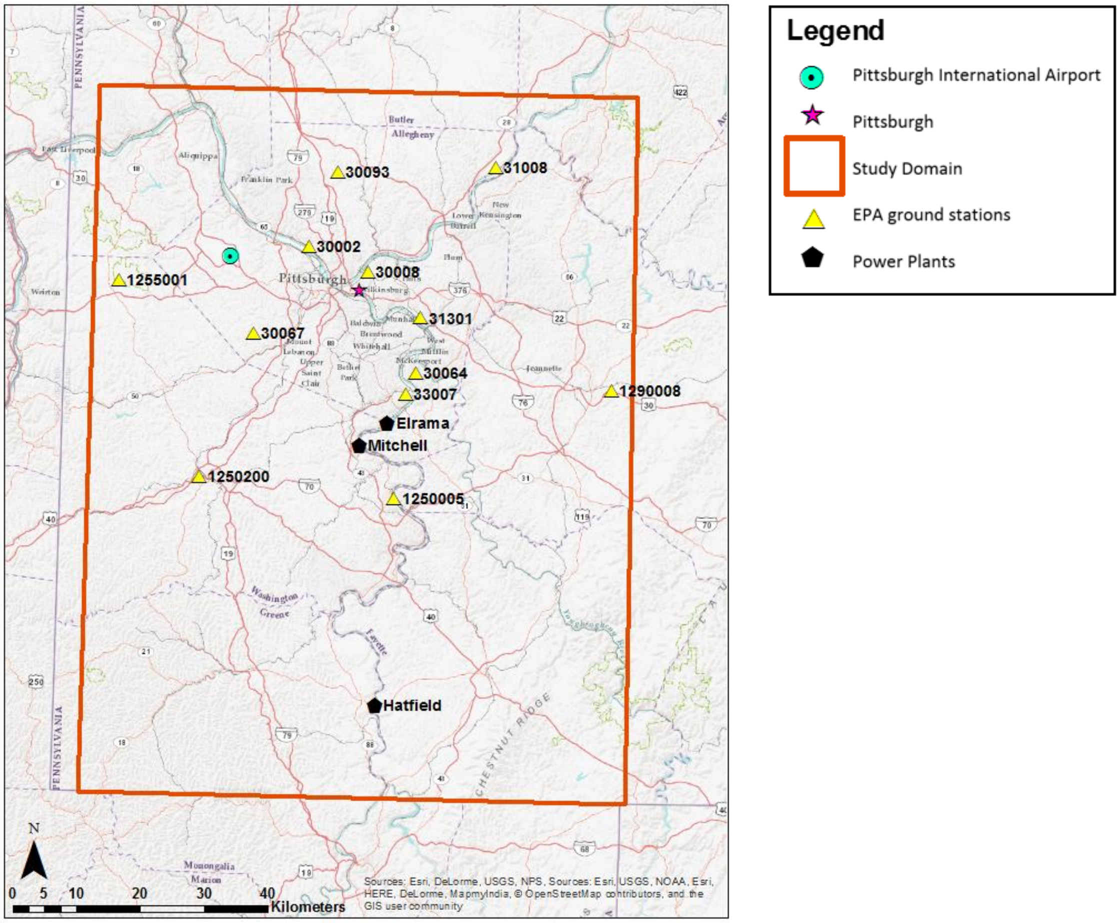
Variable	Full Study Domain N=4,404 R^2=0.51	Near Mitchell and Elrama N=474 R^2=0.57	Near Hatfield's Ferry N=848 R^2=0.60
Intercept	0.208***	0.237***	0.219***
Elrama	-0.021***	-0.024***	-0.018***
Mitchell&Hatfield	-0.013***	-0.012	-0.023***
Spring	-0.096***	-0.099***	-0.120***
Fall	-0.150***	-0.169***	-0.169***

*0.05<p-value<0.1
**0.01<p-value<0.05
***p-value<0.01

Table 12: Comparison of $PM_{2.5}$ results from all EPA ground stations to the AOD results from the grid cells containing ground stations, and to the AOD results from the cells near ground stations, excluding winter observations.

Variable	All ground stations (μg/m^3) N=638 R^2=0.36	Grid cells containing ground stations N=573 R^2=0.49	Grid cells near ground stations N=2,610 R^2=0.48
Intercept	14.33***	0.214***	0.208***
Elrama	-1.40***	-0.021***	-0.019***
Mitchell&Hatfield	-0.59*	-0.018*	-0.015***
Spring	-3.79***	-0.080***	-0.087***
Fall	-3.87***	-0.144***	-0.142***

*0.05<p-value<0.1
**0.01<p-value<0.05
***p-value<0.01



Sources: Esri, DeLorme, USGS, NPS, Sources: Esri, USGS, NOAA, Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community

Figure 1: Topographical map of study domain with EPA ground stations

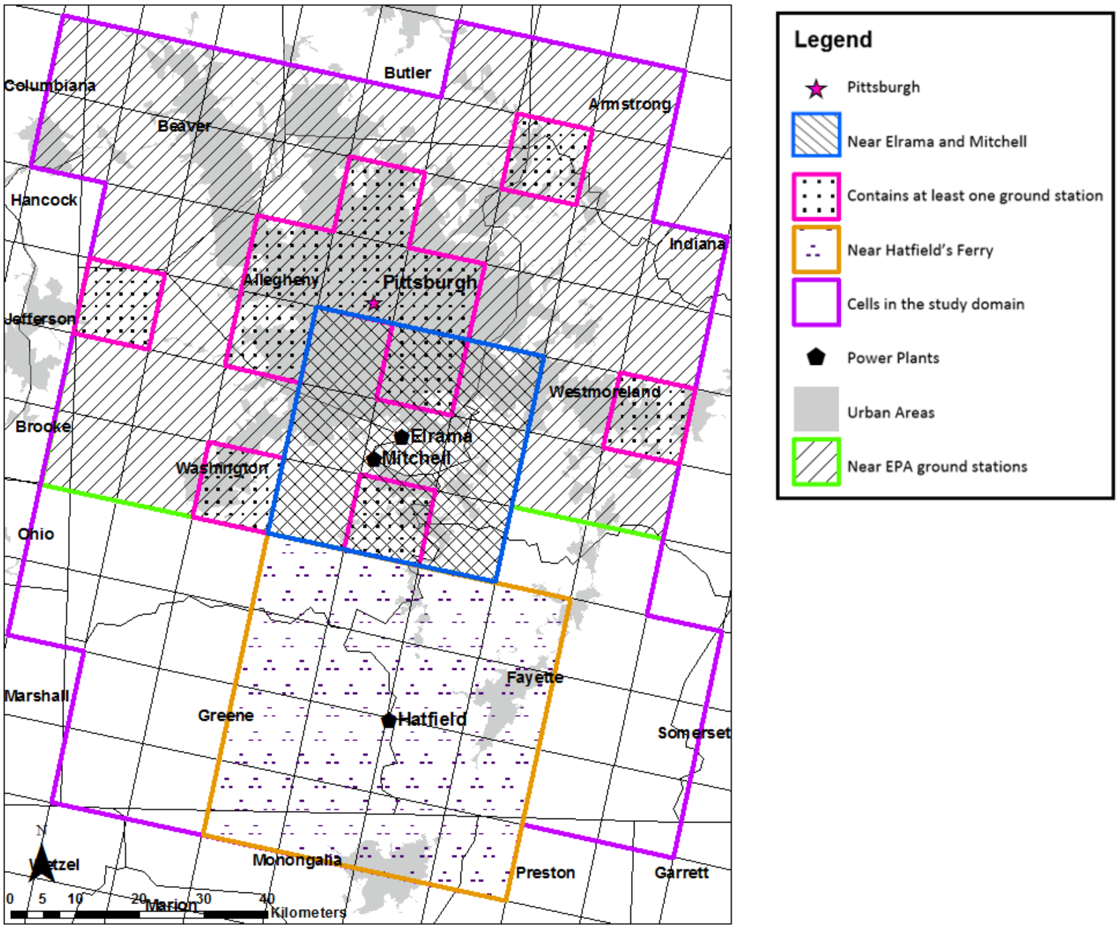
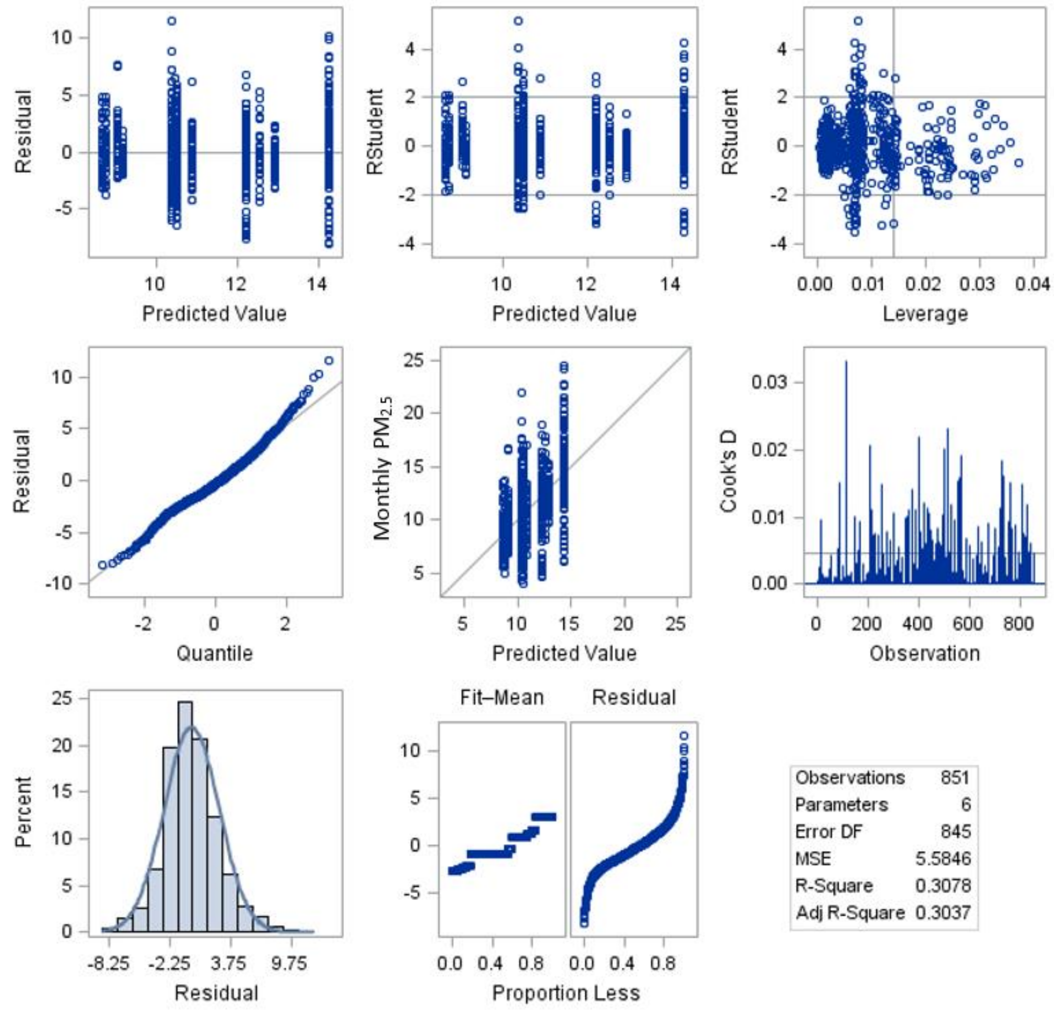


Figure 2: Map of CMAQ grid study domain and grid cell subsets

*The base layer is "USA Urban Areas" from ArcGIS online. Gray areas represent urbanized areas and urban clusters, according to the 2010 US Census.



Observations	851
Parameters	6
Error DF	845
MSE	5.5846
R-Square	0.3078
Adj R-Square	0.3037

Figure 3: Monthly $PM_{2.5}$ Fit Diagnostics

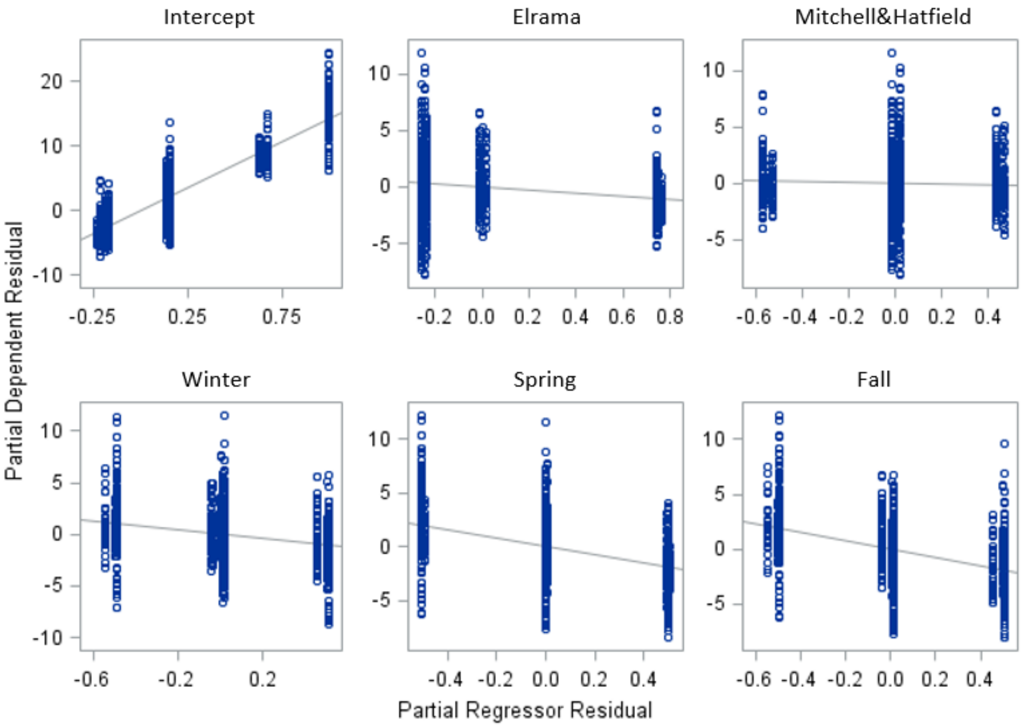
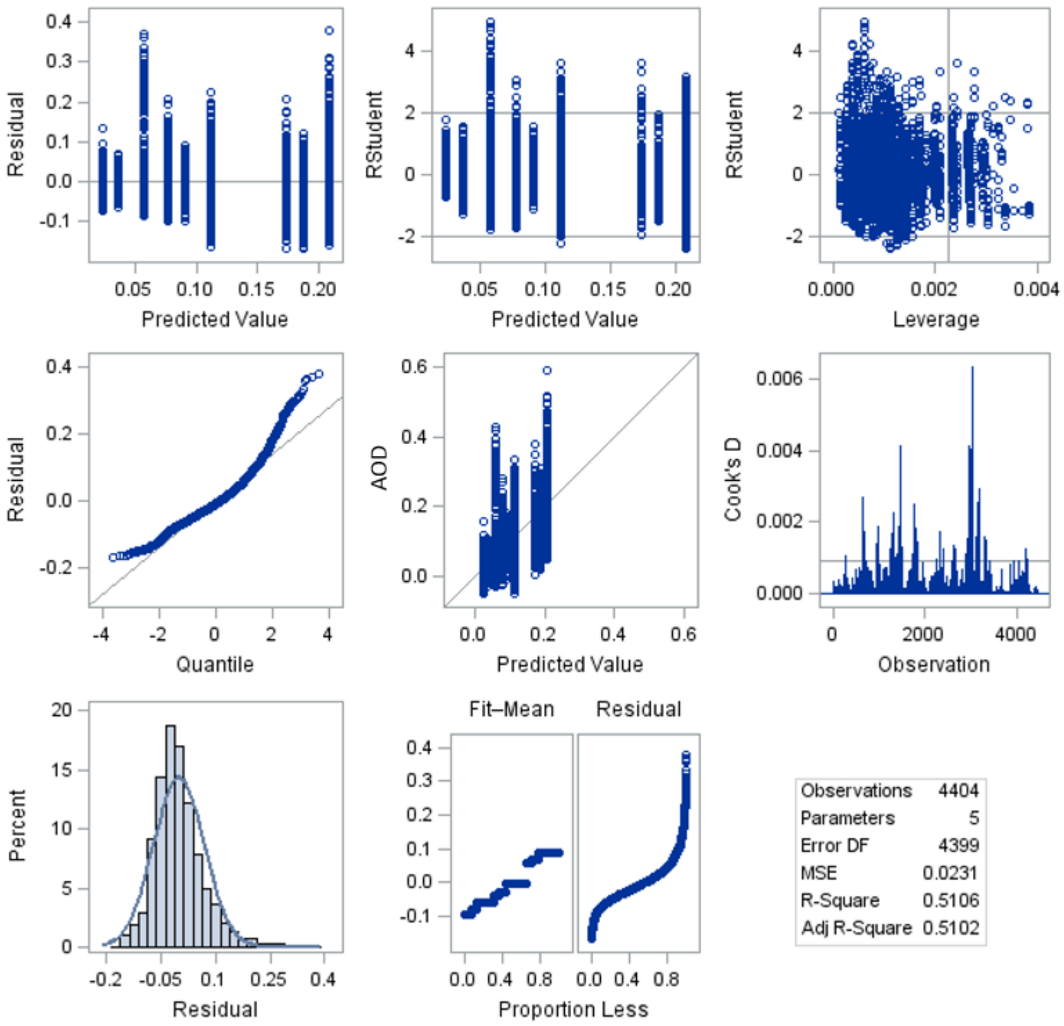


Figure 4: Monthly PM2.5 Partial Plots



Observations	4404
Parameters	5
Error DF	4399
MSE	0.0231
R-Square	0.5106
Adj R-Square	0.5102

Figure 5: Monthly AOD Fit Diagnostics

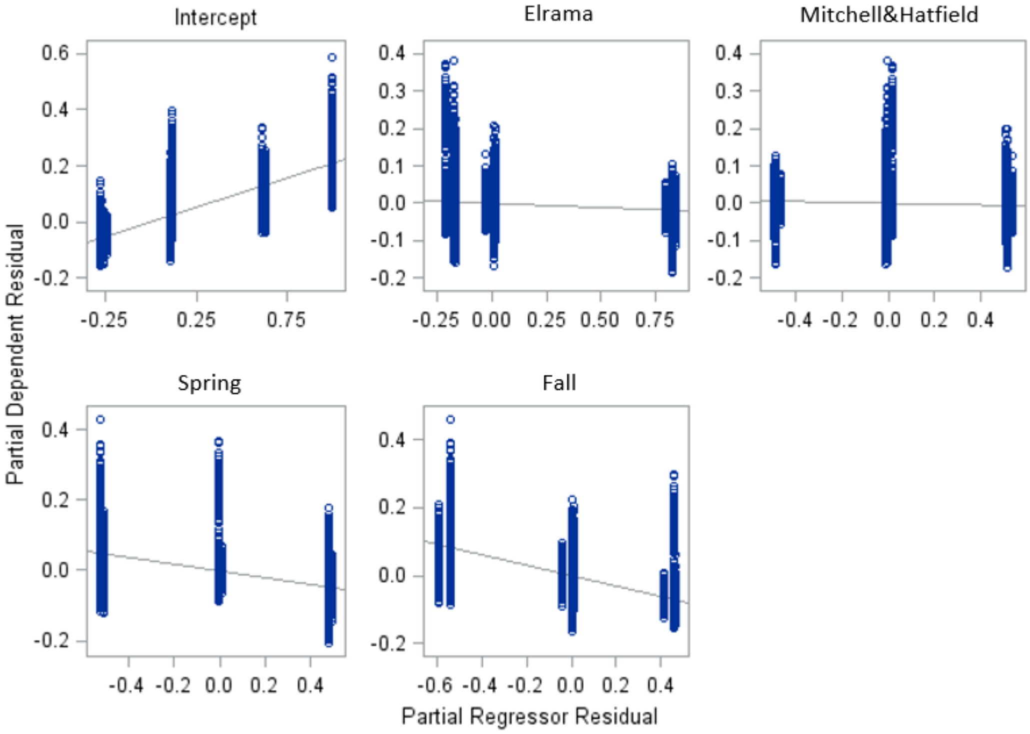


Figure 6: Monthly AOD Partial Plots