

## SYNOPTIC AND LOCAL WEATHER CONDITIONS ASSOCIATED WITH PM<sub>2.5</sub> CONCENTRATION IN CARLISLE, PENNSYLVANIA

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**ABSTRACT:** PM<sub>2.5</sub> concentration and local and synoptic meteorological data were examined for Carlisle, Pennsylvania, an area that is in non-attainment of the United States Environmental Protection Agency's 24-hour PM<sub>2.5</sub> standard. PM<sub>2.5</sub> concentrations are highest in summer and secondarily in winter. Wind speed is the dominant meteorological variable controlling seasonal differences. Local weather conditions on days with high PM<sub>2.5</sub> concentrations are generally characterized as warmer, more humid, less windy, higher pressure, and with less precipitation except for fall when temperature and humidity are actually lower for high PM<sub>2.5</sub> concentration days. High PM<sub>2.5</sub> concentration days are also associated with 500 hPa ridging and a resulting surface high pressure system located to the southeast. In fall the high is located to the northeast. The location of the high forces synoptically warmer and more humid conditions except for fall when it forces cooler and drier conditions. All seasons have weak southerly winds associated with high PM<sub>2.5</sub> concentration days. High PM<sub>2.5</sub> concentrations occur on days classified as Dry Tropical, Moist Moderate, or Moist Tropical in terms of air mass type. The air masses associated with high PM<sub>2.5</sub> concentration days occur 34 percent of the time in summer and relatively infrequently the rest of the year.

**Keywords:** Particulate matter, Synoptic meteorology, Air mass

### INTRODUCTION

Particulate matter (PM) pollution is one of the six criteria pollutants monitored by the U.S. Environmental Protection Agency (EPA) and consists of suspended solid particles and liquid droplets that are known to have adverse effects on the environment and human health. PM is typically classified based on its size with particles between 2.5 and 10  $\mu\text{m}$  referred to as PM<sub>10</sub> and particles less than 2.5  $\mu\text{m}$  referred to as PM<sub>2.5</sub>. Human exposure to PM<sub>2.5</sub> has been shown to decrease lung function (Sharma et al., 2004), aggravate asthma (Meng et al., 2010), increase rates of chronic bronchitis (Sunyer et al., 2006), and increase cardiopulmonary mortality (Ostro et al., 2010). The environmental impacts of PM<sub>2.5</sub> include decreased visibility (Wang et al., 2006), decreased environmental quality due to wind-based transport of PM<sub>2.5</sub> (Mugica et al., 2009; Sanchez de la Campa et al., 2009), and increased acid deposition (Wang et al., 2007).

Based on these health and environmental impacts, the EPA has established ambient air quality standards regarding the relative safety of various concentrations of PM<sub>2.5</sub>. In 2006 the EPA established annual (15  $\mu\text{g}/\text{m}^3$ ) and 24-hour (35  $\mu\text{g}/\text{m}^3$ ) standards of acceptable PM<sub>2.5</sub> concentrations (EPA, 2010). Based on these standards, regions are classified as being in attainment or non-attainment of the 2006 standard. Currently, Cumberland County, Pennsylvania is in non-attainment of the 24-hour standard.

Local production of pollution obviously contributes to PM<sub>2.5</sub> concentrations. However, PM<sub>2.5</sub> levels are also determined by specific meteorological conditions that impact locally generated pollution or transport remotely generated pollution. The details of the sources and causes of locally high concentrations of PM are unique to each location. In general however, high surface pressure and/or a thermal inversion layer contribute to increased PM concentrations (Buchanan et al., 2002; Lesniok et al., 2010; Wang et al., 2010). For Philadelphia, PA, Cheng et al., (1992) found that high pressure associated with maritime tropical and non-polar continental air masses produced the highest ozone and total suspended particulate concentrations. These air masses were characterized by high values of pressure, temperature, dew point, percent of clear sky, and stability. Often, the high pressure system establishes after the passage of a cyclonic system (Wang et al., 2009). Occasionally, low pressure systems, rather than high pressure, result in higher PM levels if the winds associated with the storm passage serve to stir up dust or other particulates (Dayan and Levy, 2005).

Terrain also interacts with specific weather patterns to increase PM levels. Canyons and mountains serve to increase atmospheric stability and therefore increase PM levels in the surrounding valleys due to cold air drainage into these valleys (Beaver et al., 2010). Enhanced stability in valleys is most prevalent under synoptic high pressure

conditions (Beaver et al., 2010). During unstable synoptic conditions, the opposite may be true as mountains serve to increase upward vertical motions in the atmosphere and therefore decrease surface PM concentrations. Mountains also can serve to enhance PM concentrations by trapping pollution that may otherwise have been advected away from the area (Chuang et al., 2008). Carlisle, Pennsylvania is located in the Cumberland Valley between Appalachian Mountain ridges and therefore PM concentrations in this area are subject to these mountain effects. The purpose of this study is to examine the meteorological conditions that contribute to high and low levels of  $PM_{2.5}$  pollution in Carlisle, PA. Data from local monitoring stations as well synoptic atmospheric data are used in this assessment.

## STUDY AREA

The borough of Carlisle, PA is centrally located in Cumberland County (Figure 1) and is positioned between two major interstates, I-81 and I-76. Due to the preponderance of warehouses in the area, both of these interstates carry a high volume of diesel-burning truck traffic that produces large amounts of  $PM_{2.5}$ . The situation is exacerbated by the fact that no interchange exists between the highways. Rather, trucks must exit one highway and travel approximately 5 km on a surface street before entering the other highway. Heavy traffic and multiple traffic lights force the trucks to idle and produce much larger quantities of  $PM_{2.5}$  than they would if an interchange existed.

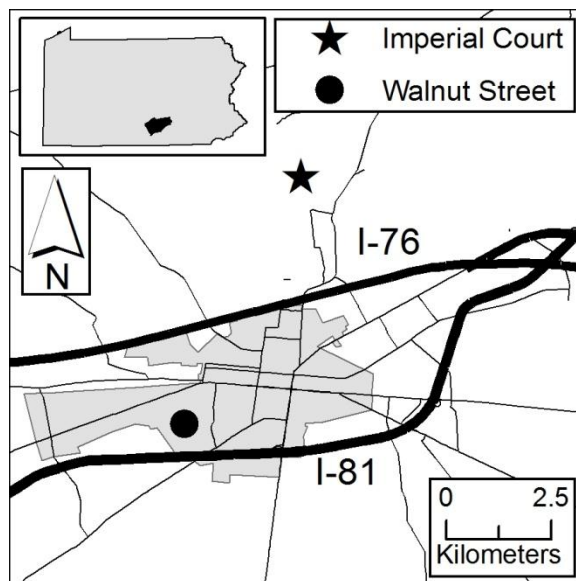


Figure 1. Carlisle, Pennsylvania. Shown are  $PM_{2.5}$  monitor locations, minor surface streets and two major interstate highways. The black polygon in the inset map of Pennsylvania is Cumberland County. Carlisle is centrally located in the county.

Several industrial facilities that produce  $PM_{2.5}$  are located in the borough of Carlisle and surrounding areas while agricultural practices, driving on dirt roads, and residential wood combustion generate  $PM_{2.5}$  in the surrounding rural areas. The impact of pollution production from multiple sources is enhanced by the fact that Carlisle (as well as I-81 in this area) is located in a valley of the Appalachian Mountains that serves to trap the pollution that is generated in the region. The collective result is that Carlisle has some of the poorest air quality in the region and Cumberland County has been designated as being in non-attainment of the 24-hour  $PM_{2.5}$  standard set by the EPA.

In response to Carlisle's poor air quality, in 2005 an advertisement was generated by local doctors and run in area newspapers to alert residents to the health impacts of high  $PM_{2.5}$  concentrations. Following the publication, the Clean Air Board of Central Pennsylvania (CAB) was founded in 2006 as a "faith-based citizens' initiative dedicated to achieving clear air to protect our health and quality of life." (CAB, 2010) Current and past members of CAB have included local residents, doctors, clergy, professionals, and government officials.

CAB has been involved in numerous initiatives to improve air quality in the region. Relevant to this study was CAB's petition to the Pennsylvania Department of Environmental Protection (DEP) to install a  $PM_{2.5}$  monitor

within the borough limits of Carlisle to better assess air quality in the borough. Prior to the petition, the nearest PM<sub>2.5</sub> monitor was located approximately 5 km north of the borough (Imperial Court; Figure 1). DEP monitored PM<sub>2.5</sub> for sixteen months within the borough limits (Walnut Street; Figure 1) and found that while PM<sub>2.5</sub> levels were on average 5 percent higher inside the borough, the difference was not statistically significant (DEP, 2009). Both sites were deemed to be in non-attainment of the 24-hour PM<sub>2.5</sub> standard. To continue monitoring within the borough, CAB, in conjunction with the Carlisle Regional Medical Center and the local newspaper *The Sentinel*, purchased and installed on the Sentinel building an EPA quality PM<sub>2.5</sub> monitor (The Sentinel, 2011). Currently, the data record is not long enough to be of assistance in this study.

## DATA AND METHODS

Daily PM<sub>2.5</sub> data were obtained for the Imperial Court and Walnut Street monitoring sites. Data for the temporary DEP monitor at Walnut Street existed from May 2007 to September 2008. The permanent station at Imperial Court began monitoring in April 2001. To coincide with the Walnut Street data, Imperial Court data were only gathered through September 2008 as well. Data from both sites were plotted and correlated. Based on the correlation analysis, Imperial Court with its longer record was deemed as representative and was solely used for the remaining analyses. Monthly and seasonal averages of the data were calculated. The seasons were defined as winter: December to February, spring: March to May, summer: June to August, and fall: September to November. For each season, a subset of days (hereafter referred to as extreme days) was selected based on the highest and lowest 1 percent of the PM<sub>2.5</sub> data.

Daily meteorological data were collected for the same time period from Harrisburg airport which is located approximately 40 km east of Carlisle and is the nearest first-order weather station. Data used in the analysis included average temperature, dew point, wind speed, precipitation, and sea level pressure (SLP). Averages of these data were calculated for the extreme days. To assess the relationship between weather elements of the Harrisburg data, a factor analysis was performed to remove the redundancy in the dataset and to determine which Harrisburg variables were most correlated.

Composite synoptic atmospheric maps were created for the extreme PM<sub>2.5</sub> days using data from the National Center for Environmental Prediction/National Center for Atmospheric Research reanalysis dataset (Kalnay et al., 1996) which is served by the National Oceanic and Atmospheric Administration's Earth System Research Laboratory (ESRL, 2011). Composite maps for extreme PM<sub>2.5</sub> days were created for surface temperature, specific humidity, wind speed and direction, 500 hPa height, and sea level pressure. Difference maps between the extreme high and low PM<sub>2.5</sub> days were also created.

Daily air mass type was obtained for Harrisburg airport from the Spatial Synoptic Classification data set (SSC) (Kalkstein et al., 1996; Sheridan, 2002) available from Kent State University (SSC, 2011). The SSC uses surface meteorological conditions to develop seed days for each air mass type for each season. Seed days are days that are meteorologically most representative of each air mass type. Actual meteorological conditions are then compared to the seed day conditions to determine the air mass type for each day at a given location. For each season and for each air mass, the average daily PM<sub>2.5</sub> concentration was calculated. Meteorological data from Harrisburg were also averaged using these same subdivisions. A series of t-statistics was calculated to assess the significance of the differences between PM<sub>2.5</sub> concentrations associated with each air mass. Correlations were calculated between PM<sub>2.5</sub> concentrations and the Harrisburg meteorological data for the total dataset as well as using the air mass type to create subsets of the data.

## RESULTS AND DISCUSSION

Explained variance between the overlapping PM<sub>2.5</sub> data for Imperial Court and Walnut Street was 93 percent. While the Walnut Street PM<sub>2.5</sub> levels were 5 percent higher during this time period (DEP, 2009), due to the high level of explained variance between the sites, Imperial Court, with its longer data record was deemed acceptable for the remaining analyses. Figure 2 shows the average monthly PM<sub>2.5</sub> concentrations for Imperial Court. The summer months have the highest PM<sub>2.5</sub> concentration with a three-month average of 18.5 µg/m<sup>3</sup> and a July maximum of 19.2 µg/m<sup>3</sup>. Winter has the second highest concentration with a three-month average of 14.1 µg/m<sup>3</sup> and a February maximum of 15.2 µg/m<sup>3</sup>. Climatologically, these months and seasons represent the extreme times of year. The transition seasons of spring and fall have the lowest three-month average PM<sub>2.5</sub> concentrations at 12.5 and 12.3 µg/m<sup>3</sup> respectively with minimum concentrations in April and October of 11.4 and 10.8 µg/m<sup>3</sup> respectively. It's

likely that seasonal PM<sub>2.5</sub> concentration differences are the result of both differences in production of PM<sub>2.5</sub> as well as prevailing weather and climate conditions. The focus of this work is on the latter.

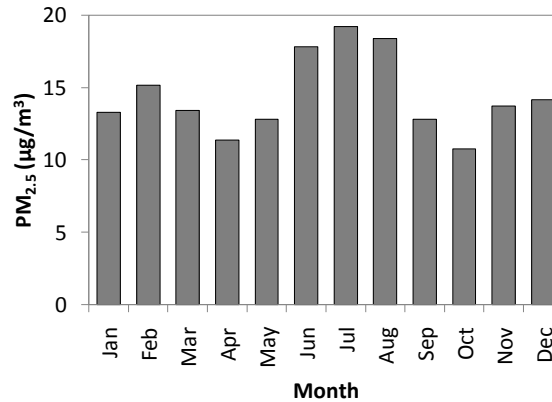


Figure 2. Monthly average PM<sub>2.5</sub> concentrations for Imperial Court.

Table 1 shows seasonal PM<sub>2.5</sub> concentrations and meteorological conditions at Harrisburg airport for extreme PM<sub>2.5</sub> days. Generally speaking, high PM<sub>2.5</sub> concentrations occurred when conditions were less windy, had less precipitation, and had higher SLP. Winter precipitation and summer SLP were the exceptions to this generality but the differences between the high and low concentration days in these two instances were the lowest observed for any season.

Table 1. Meteorological conditions associated with the five highest and lowest PM<sub>2.5</sub> conditions for each season.

|                                        | Winter |        | Spring |        | Summer |        | Fall   |        |
|----------------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|
|                                        | high   | low    | high   | low    | high   | low    | high   | low    |
| PM <sub>2.5</sub> (µg/m <sup>3</sup> ) | 43.0   | 2.0    | 43.8   | 2.2    | 53.9   | 2.6    | 42.7   | 1.4    |
| Wind (m/s)                             | 1.3    | 8.8    | 2.9    | 5.4    | 1.7    | 3.4    | 2.1    | 3.3    |
| Precip (cm)                            | 0.2    | 0.0    | 0.2    | 0.6    | 0.0    | 0.2    | 0.3    | 1.7    |
| SLP (hPa)                              | 1018.5 | 1017.3 | 1015.3 | 1012.5 | 1016.0 | 1017.4 | 1017.2 | 1010.2 |
| T <sub>avg</sub> (°C)                  | -0.8   | -2.5   | 10.3   | 10.3   | 27.1   | 19.1   | 8.2    | 11.4   |
| T <sub>d</sub> (°C)                    | -3.3   | -12.8  | 7.3    | -0.4   | 20.9   | 9.7    | 5.9    | 9.7    |

Higher wind speeds serve to mix the atmosphere, transport less polluted air, and therefore reduce PM<sub>2.5</sub> concentrations in Carlisle where much of the PM<sub>2.5</sub> is locally produced. For the high PM<sub>2.5</sub> days, winter and summer experienced the least windy conditions which help to explain why these seasons show the highest PM<sub>2.5</sub> concentrations (Figure 2).

Similarly, high precipitation values serve to “wash” particulates out of the atmosphere and therefore reduce PM<sub>2.5</sub> concentrations (Saliba et al., 2010). For all seasons, high PM<sub>2.5</sub> days had minimal average precipitation totals so little can be said about seasonal differences. Spring did however, have the largest percentage of days when precipitation occurred (34 percent) which helps explain the low spring PM<sub>2.5</sub> concentrations during this season (Figure 2). Fall however, the other low PM<sub>2.5</sub> season had the lowest percentage of days with precipitation (29 percent) suggesting that another mechanism may be causing lower PM<sub>2.5</sub> concentrations in fall.

Higher wind speeds and precipitation totals that result in lower PM<sub>2.5</sub> concentrations are typically associated with stormier conditions and therefore lower SLP. Winter, when PM<sub>2.5</sub> concentrations are higher (Figure 2) had SLP values for high pollution days that were larger than any other season. Summer, the season with highest PM<sub>2.5</sub> concentrations was the only season when lower PM<sub>2.5</sub> concentration days had higher SLP. During the summer, pressure is relatively uniform and wind and precipitation result more from convective thunderstorms.

Also in Table 1, temperatures and dew points are generally higher during high PM<sub>2.5</sub> days. Fall is the one season where the reverse is true. Warmer and more humid conditions are typically associated with the clear, calm, and high pressure conditions that are also associated with higher PM<sub>2.5</sub> concentrations. During fall, the synoptic situation that produces these conditions is different from the synoptic conditions during the other three seasons.

Local weather conditions result in part from sea level and upper atmospheric pressure patterns. Figure 3 shows the seasonal 500 hPa pattern on both the high and low PM<sub>2.5</sub> concentration days as well as the difference between those maps (high – low). For all maps, Pennsylvania and Carlisle are highlighted. High PM<sub>2.5</sub> concentration days are characterized by a relatively zonal pattern to the upper air flow with slight troughing over western and central North America and ridging over the Atlantic Ocean. This pattern is relatively similar for all seasons. However, during fall the ridge is located more to the northeast. Low PM<sub>2.5</sub> concentration days are characterized by strong troughing over eastern North America. For winter, spring, and summer, the axis of this trough is located east of Carlisle. In fall, the axis is located west of Carlisle. The result is a set of difference maps with strong centers of positive differences centered east of Carlisle in winter, spring, and summer and virtually no difference in 500 hPa heights in fall.

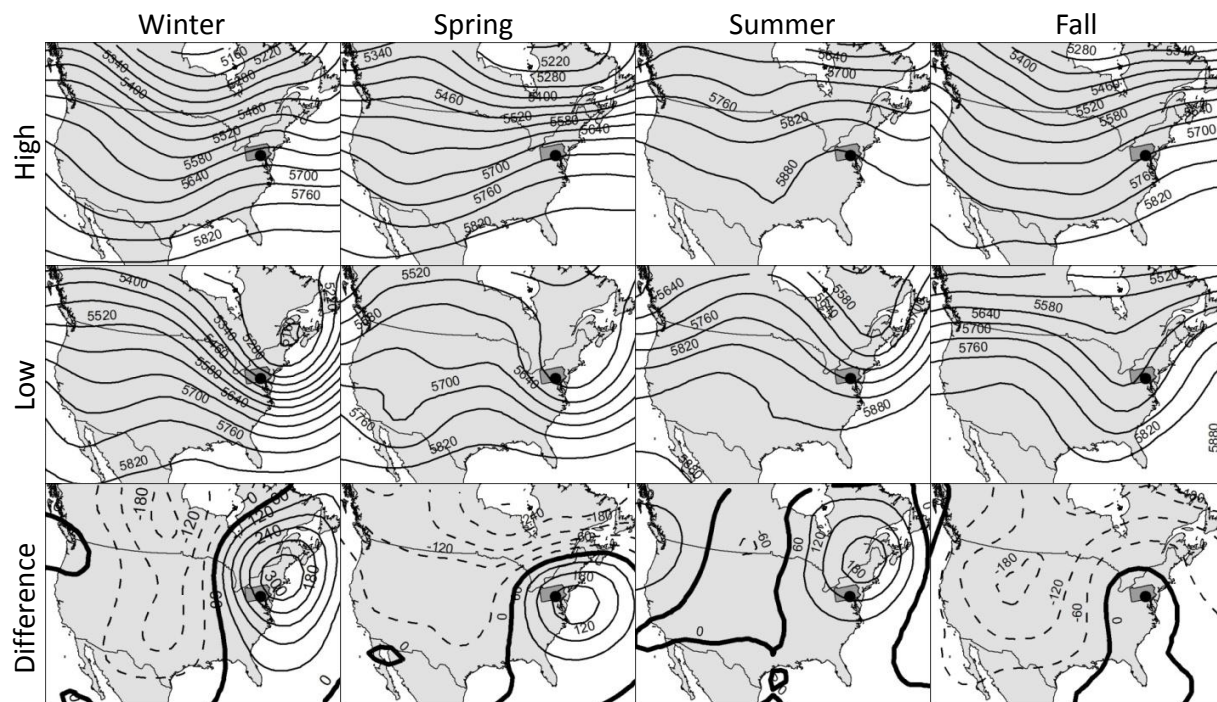


Figure 3. Seasonal 500 hPa heights for high and low PM<sub>2.5</sub> days and the difference between them. Units are m. For the differences, dashed lines indicate negative differences. Solid lines indicate positive differences. The thick solid line indicates zero difference.

Figure 4 shows similar maps for SLP. Patterns in SLP correspond to the upper air patterns. For high PM<sub>2.5</sub> concentration days during winter, spring, and summer, upper air ridging produces surface high pressure systems southeast of Carlisle. In the fall, this high is located northeast of Carlisle corresponding to the more northeasterly ridge location. The magnitudes of the high pressure centers are approximately equal for all seasons. Low PM<sub>2.5</sub> concentration days are characterized by surface low pressure centers located to the northeast of Carlisle and a high pressure center located to the west. In the fall, the low pressure center is located southeast of Carlisle with no well-defined high pressure center. The low is most intense in winter and least intense in summer. The resulting difference maps in SLP produce centers of positive differences in the vicinity of Carlisle. For winter, spring, and summer, these centers are either located to the east or northeast. In fall, this center is located to the southeast.

Pressure patterns at the surface and aloft help drive surface weather conditions. Figures 5 and 6 are synoptic maps of the differences between temperature, specific humidity, wind speed, and u and v wind direction components for the extreme days (high – low). For this set of maps, little information is gained from the synoptic patterns on the high and low PM<sub>2.5</sub> concentration days. Therefore, only difference maps are shown. Similar to the Harrisburg station data, temperature and specific humidity (Figure 5) are both higher in Carlisle during high PM<sub>2.5</sub> concentration days for all seasons except fall. Furthermore, the maps reveal that these warmer and more humid conditions are present over much of the eastern U.S. During the fall however, temperatures are cooler over all of



North America and approximately 6°C cooler in Carlisle during high PM<sub>2.5</sub> concentration days. Fall specific humidity is lower in Carlisle as well as much of the east coast on high PM<sub>2.5</sub> concentration days. More humid conditions do exist in a plume originating out of the Gulf of Mexico and extending northward. For fall, the more northerly location of the surface high during high PM<sub>2.5</sub> concentration days compared to other seasons serves to advect relatively cooler and drier air while the more southerly location of the low during low PM<sub>2.5</sub> concentration days serves to advect maritime air which is warmer and more humid than the continental air that is advected on low PM<sub>2.5</sub> concentration days during the other seasons. The end result is that fall differs from the other seasons in terms of temperature and humidity differences between high and low PM<sub>2.5</sub> concentration days.

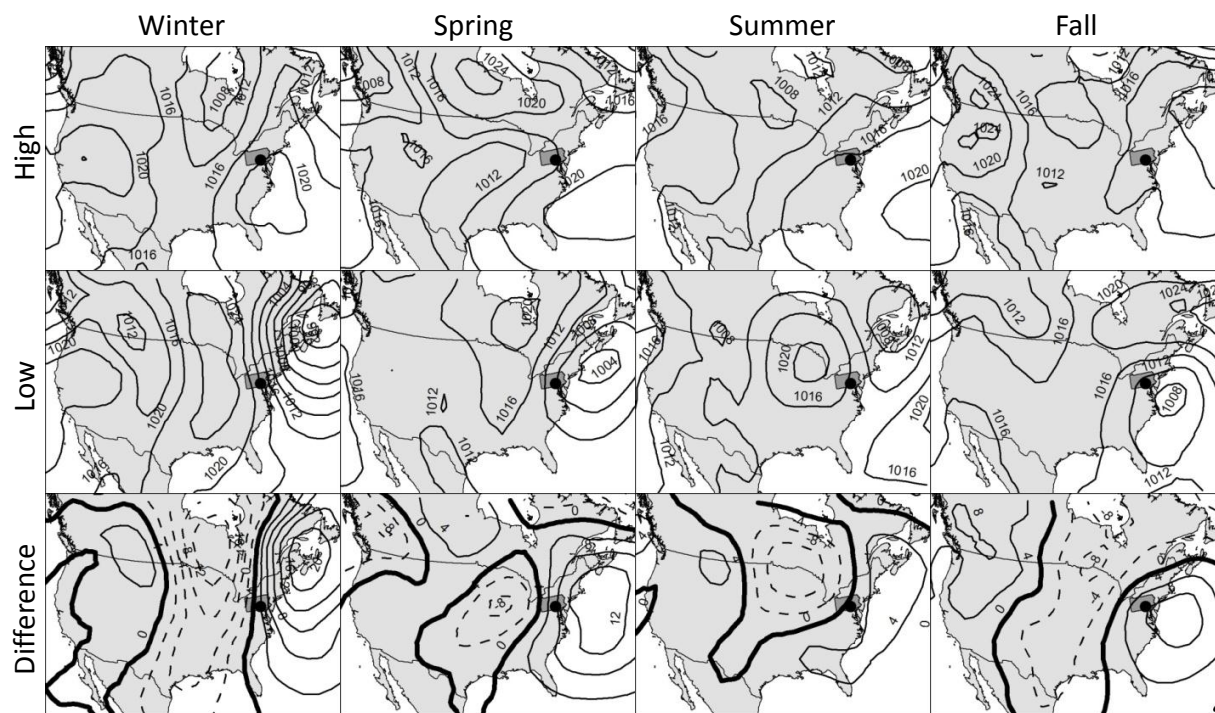


Figure 4. Seasonal sea level pressure for high and low PM<sub>2.5</sub> days and the difference between them. Units are hPa. For the differences, dashed lines indicate negative differences. Solid lines indicate positive differences. The thick solid line indicates zero difference.

Wind speed is lower for all seasons on high PM<sub>2.5</sub> concentration days (Figure 6). These results are in line with the Harrisburg station data. For u-wind components in Figure 6, positive values indicate that high PM<sub>2.5</sub> concentration days had more westerly winds compared to low PM<sub>2.5</sub> concentration days while negative values indicate more easterly winds for those days. Clear patterns are not as evident in the u-wind component compared with other maps. During winter and spring, high PM<sub>2.5</sub> concentration days have more easterly winds but the centers of strong easterly winds are well to the south during both seasons. For both summer and fall, Carlisle is located very close to the zero line indicating no difference in the u-wind component. For the v-wind components in Figure 6, positive values indicate that high PM<sub>2.5</sub> concentration days had more southerly winds compared to low PM<sub>2.5</sub> concentration days while negative values indicate more northerly winds for those days. For all seasons, high PM<sub>2.5</sub> concentration days had more southerly winds compared to low concentration days. Carlisle is located in the central core of these positive values. These wind direction differences are the result of southerly winds associated with the clockwise flow around the high on high PM<sub>2.5</sub> concentration days and more northerly winds associated with the counterclockwise flow around the low on low PM<sub>2.5</sub> concentration days.

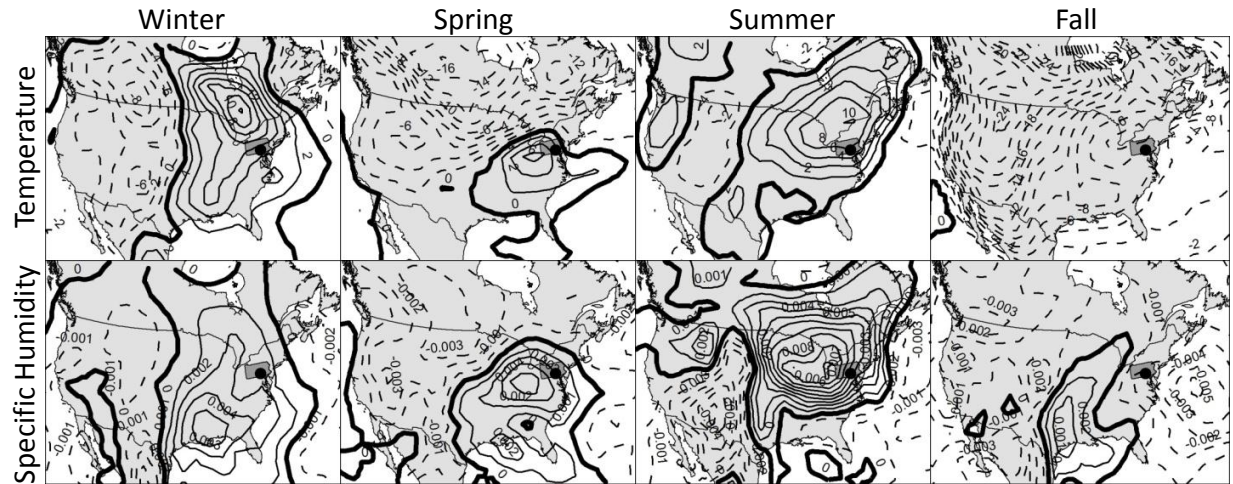


Figure 5. Seasonal temperature and specific humidity differences between high and low  $PM_{2.5}$  days. Temperature units are  $^{\circ}C$ . Specific humidity units are kg/kg. Dashed lines indicate negative differences. Solid lines indicate positive differences. The thick solid line indicates zero difference.

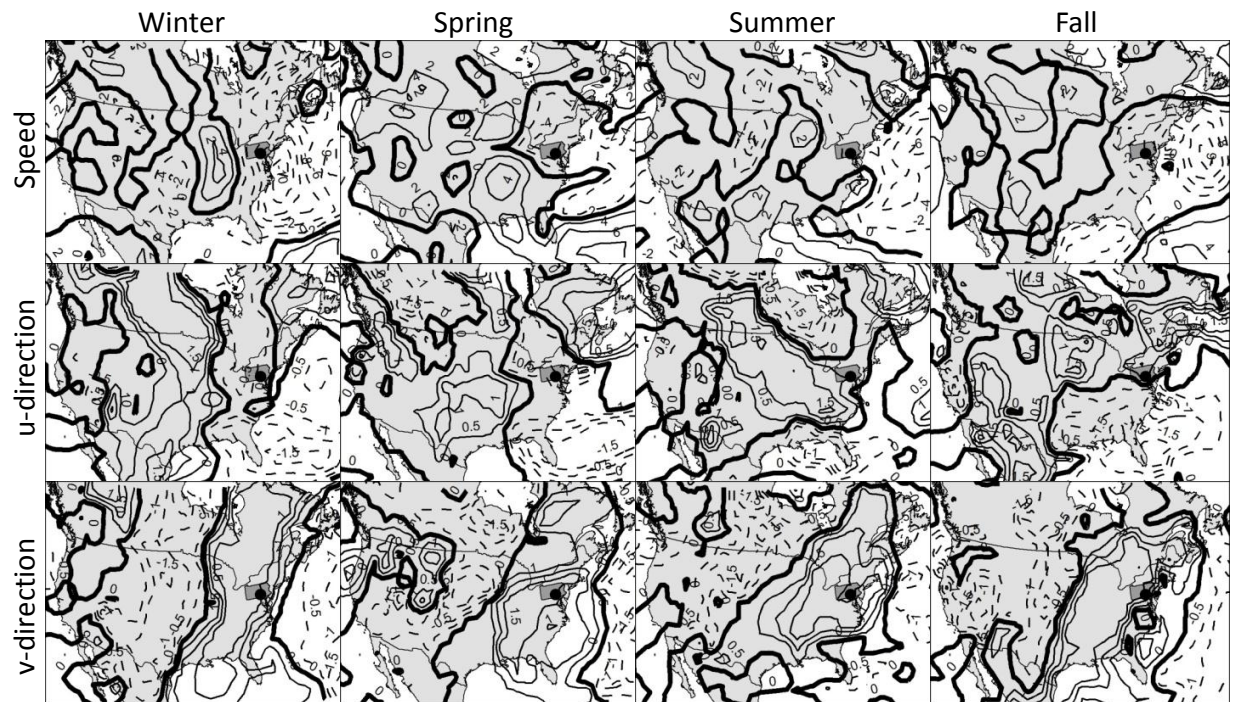


Figure 6. Seasonal wind speed, u-direction, and v-direction differences between high and low  $PM_{2.5}$  days. Wind speed units are m/s. Direction units are dimensionless. Dashed lines indicate negative differences. Solid lines indicate positive differences. The thick solid line indicates zero difference.

The previous analyses focused on the meteorological conditions associated with extreme  $PM_{2.5}$  concentration days. It is also possible to examine the  $PM_{2.5}$  concentration associated with different meteorological conditions or in this case different air masses. Figure 7 shows the seasonal  $PM_{2.5}$  concentrations for each of the air masses. Air mass abbreviations are defined in the caption for Figure 7. In general,  $PM_{2.5}$  concentration increases with temperature for both dry and moist air masses (darkest bars). Also in general, Dry Tropical (DT) air masses

produce the highest PM<sub>2.5</sub> concentrations. For spring Moist Moderate (MM) is 0.5 µg/m<sup>3</sup> higher than DT. DT air masses and often Moist Tropical (MT) air masses as well are associated with southerly winds on the western edge of a high pressure system located over eastern North America or the Atlantic Ocean similar to high PM<sub>2.5</sub> concentration days in Figure 4. Little rain or wind is associated with these pressure systems and therefore PM<sub>2.5</sub> concentrations increase. The highest PM<sub>2.5</sub> concentrations under these conditions occur in summer. For winter and spring, PM<sub>2.5</sub> concentrations are higher for MM air masses than MT air masses. As the high pressure moves eastward with an approaching cold front, MT conditions become associated with strong winds. During winter and spring these fronts are often more powerful and the associated faster wind speed reduce PM<sub>2.5</sub> concentrations. With the exception of summer, DT, MT, and MM conditions represent the days with highest PM<sub>2.5</sub> concentrations but also the air mass conditions least likely to occur. This is not true in summer where the two highest PM<sub>2.5</sub> concentration air masses (DT and MT) occur 34 percent of the time.

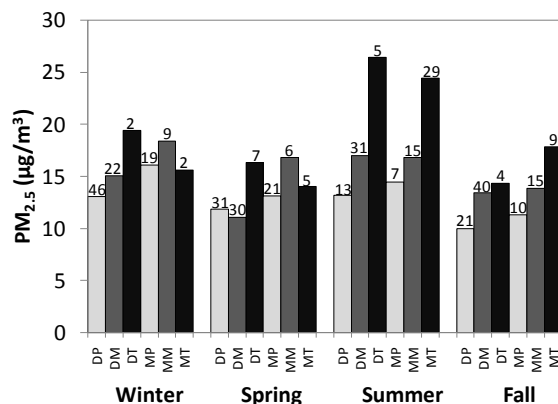


Figure 7. Seasonal PM<sub>2.5</sub> concentration by air mass. Labels on top of bars correspond to the percentage of days the air mass occurred during the study period for that season (seasons sum to 100 percent). DP=dry polar, DM=dry moderate, DT=dry tropical, MP=moist polar, MM=moist moderate, MT=moist tropical.

Lower PM<sub>2.5</sub> concentrations are associated with polar and moderate air masses. Depending on the weather conditions, these air masses occur ahead of a low pressure system and are advected from the Atlantic Ocean or occur behind a low pressure system and are advected from the central plains of North America. In either case, precipitation likely occurred relatively recently and winds were likely relatively stronger. Both would serve to reduce PM<sub>2.5</sub> concentrations.

Table 2 presents t-statistics to assess the significance of the seasonal PM<sub>2.5</sub> concentration differences between air masses. The table should be read across the rows. Because they are based on the same data, the grey and white shading shows the same pattern of differences as Figure 7. In winter significant differences exist between DP and DT, MP, and MM. DP is the coldest, driest, and lowest PM<sub>2.5</sub> concentration air mass. DT, MP, and MM all have significantly higher PM<sub>2.5</sub> concentrations. Similarly, for spring, significant differences exist in PM<sub>2.5</sub> concentrations between the coldest and warmest air masses: DP, DM (cooler) and DT, MM, and MT (warmer). For summer, numerous significant differences exist because in summer, the air masses show the most difference in terms of PM<sub>2.5</sub> concentration. Finally, for fall significant differences in PM<sub>2.5</sub> concentration exist between the extreme air masses. DP has significantly lower concentrations than all air masses except MP which is has the same sign but is not significant. MT has significantly higher concentrations than all other air masses.

To assess the relative importance of various meteorological parameters on PM<sub>2.5</sub> concentrations, correlations were run between the PM<sub>2.5</sub> concentration data and the Harrisburg meteorological data (Table 3). Without subdividing by air mass type (top rows for each season) all variables except for wind speed are positively correlated with PM<sub>2.5</sub> concentration. Most of these correlations are significant as well. With the exception of summer, wind speed shows the strongest correlation with PM<sub>2.5</sub> concentration. For summer, dew point which is a good indicator of air mass type and therefore pressure patterns is most strongly correlated with PM<sub>2.5</sub> concentrations. When examining the data by air mass, the same general nature of the correlations exists although far fewer of the correlations are significant due to the decreased sample size. Precipitation however, does not show a clear pattern of correlation signs due in part to the large number of zero values in the dataset. For individual air masses, winter is not as consistent in the signs of the correlations as the other seasons. For the other seasons higher SLP values are



generally associated with warmer, more humid and calmer conditions and therefore increases in PM<sub>2.5</sub> concentrations. In winter however, for many of the air masses, cooler conditions due to intrusions of Canadian air are actually associated with higher pressure and therefore negative correlations.

Table 2. T statistics for comparisons between PM<sub>2.5</sub> concentrations associated with different air masses. Grey cells indicate that the row air mass has a higher concentration than the column air mass. White cells indicate that the row air mass has a lower concentration than the column air mass. Black cells indicate no difference. Larger, bold font indicates differences are significant at the 95% confidence level. DP=dry polar, DM=dry moderate, DT=dry tropical, MP=moist polar, MM=moist moderate, MT=moist tropical.

|    | Winter      |             |              |             |             |              | Spring     |             |             |            |             |             |
|----|-------------|-------------|--------------|-------------|-------------|--------------|------------|-------------|-------------|------------|-------------|-------------|
|    | DP          | DM          | DT           | MP          | MM          | MT           | DP         | DM          | DT          | MP         | MM          | MT          |
| DP |             | -2.0        | <b>-6.4</b>  | <b>-3.0</b> | <b>-5.4</b> | -2.6         |            | 0.8         | <b>-4.4</b> | -1.2       | <b>-5.0</b> | -2.2        |
| DM | 2.0         |             | -4.4         | -1.0        | -3.4        | -0.6         | -0.8       |             | <b>-5.2</b> | -2.0       | <b>-5.8</b> | <b>-3.0</b> |
| DT | <b>6.4</b>  | 4.4         |              | 3.3         | 1.0         | 3.8          | <b>4.4</b> | <b>5.2</b>  |             | 3.2        | -0.5        | <b>2.3</b>  |
| MP | <b>3.0</b>  | 1.0         | -3.3         |             | -2.3        | 0.5          | 1.2        | 2.0         | -3.2        |            | -3.7        | -0.9        |
| MM | <b>5.4</b>  | 3.4         | -1.0         | 2.3         |             | 2.8          | <b>5.0</b> | <b>5.8</b>  | 0.5         | 3.7        |             | <b>2.8</b>  |
| MT | 2.6         | 0.6         | -3.8         | -0.5        | -2.8        |              | 2.2        | <b>3.0</b>  | -2.3        | 0.9        | -2.8        |             |
|    | Summer      |             |              |             |             |              | Fall       |             |             |            |             |             |
|    | DP          | DM          | DT           | MP          | MM          | MT           | DP         | DM          | DT          | MP         | MM          | MT          |
| DP |             | <b>-3.9</b> | <b>-13.3</b> | -1.3        | <b>-3.6</b> | <b>-11.3</b> |            | <b>-3.4</b> | <b>-4.3</b> | -1.3       | <b>-3.9</b> | <b>-7.8</b> |
| DM | <b>3.9</b>  |             | <b>-9.4</b>  | 2.6         | 0.2         | <b>-7.4</b>  | <b>3.4</b> |             | -0.9        | 2.1        | -0.5        | <b>-4.4</b> |
| DT | <b>13.3</b> | <b>9.4</b>  |              | <b>11.9</b> | <b>9.6</b>  | 2.0          | <b>4.3</b> | 0.9         |             | 3.0        | 0.5         | <b>-3.5</b> |
| MP | 1.3         | -2.6        | <b>-11.9</b> |             | -2.3        | <b>-10.0</b> | 1.3        | -2.1        | -3.0        |            | -2.5        | <b>-6.5</b> |
| MM | <b>3.6</b>  | -0.2        | <b>-9.6</b>  | 2.3         |             | <b>-7.7</b>  | <b>3.9</b> | 0.5         | -0.5        | 2.5        |             | <b>-4.0</b> |
| MT | <b>11.3</b> | <b>7.4</b>  | -2.0         | <b>10.0</b> | <b>7.7</b>  |              | <b>7.8</b> | <b>4.4</b>  | <b>3.5</b>  | <b>6.5</b> | <b>4.0</b>  |             |

To better understand the seasonal differences in PM<sub>2.5</sub> concentration and the relative importance of individual meteorological variables, a factor analysis for each season was performed on the Harrisburg data. Table 4 shows the results from the factor analysis. Factors with eigenvalues greater than one were retained resulting in two factors for each season except summer which had three. Percent variance explained in the input data by the factors ranged from 73.6 percent in winter to 83.7 percent in summer. For each season, all the temperature variables and dew point loaded on to the first factor. SLP, wind speed and precipitation loaded onto the second factor or in the case of summer, second and third factor. Note that when the analysis was rerun and forced to produce either two or three factors and not rely on eigenvalues (not shown); the pattern of loadings was identical for all seasons suggesting that the data behave in essentially the same manner for each season. As the variables on factor two and/or three (SLP, wind, and precipitation) drive the variables on factor one (temperature and humidity), factor two and/or three was named the forcing factor(s) and factor one was named the resulting factor. The factor analysis indicates how the forcing variables are correlated while correlations (Table 3) indicate that of these forcing variables wind speed is most important.

Figure 8 shows seasonal scatter plots of wind speed versus PM<sub>2.5</sub> concentration differentiated by air mass. Each season exhibits a discernable negative trend where increased wind speed results in decreased PM<sub>2.5</sub> concentration although the relative positioning of air masses on the plots differs from season to season. Summer, the season with highest PM<sub>2.5</sub> concentration (Figure 2) has the lowest average wind speed (open circle on plot) and the least variation in wind speeds between air masses. Many of the low and middle PM<sub>2.5</sub> concentration air masses in summer have concentrations higher than most air masses from other seasons as a result of these low wind speeds. Winter, which has the next highest PM<sub>2.5</sub> concentration (Figure 2) actually has the highest average wind speed but also has the largest variation in wind speed between the air masses. The three highest PM<sub>2.5</sub> concentration air masses (DT, MM, and MT) have very low wind speeds, especially DT which is the lowest of any in Figure 8. These air masses only occur 13 percent of the time during winter (Figure 7) and therefore the average wind speed is increased despite the strong presence of the negative relationship.

Table 3. Spearman rank correlations between PM<sub>2.5</sub> concentration and meteorological conditions at Harrisburg airport separated by season and air mass classification. Grey cells are positive correlations; white cells are negative correlations; and black cells are zero correlation. Larger, bold font indicates correlations are significant at the 95% confidence level. Air mass abbreviations are the same as Figure 2. T<sub>mx</sub>=maximum daily temperature, T<sub>mn</sub>=minimum daily temperature, T<sub>av</sub>=average daily temperature, T<sub>d</sub>=average daily dew point, SLP=sea level pressure, WS=wind speed, PCP=precipitation.

|       | Winter          |                 |                 |                |             |              |             | Spring          |                 |                 |                |             |              |              |
|-------|-----------------|-----------------|-----------------|----------------|-------------|--------------|-------------|-----------------|-----------------|-----------------|----------------|-------------|--------------|--------------|
|       | T <sub>mx</sub> | T <sub>mn</sub> | T <sub>av</sub> | T <sub>d</sub> | SLP         | WS           | PCP         | T <sub>mx</sub> | T <sub>mn</sub> | T <sub>av</sub> | T <sub>d</sub> | SLP         | WS           | PCP          |
| all   | <b>0.17</b>     | -0.01           | <b>0.09</b>     | <b>0.32</b>    | <b>0.15</b> | <b>-0.71</b> | <b>0.13</b> | <b>0.23</b>     | <b>0.20</b>     | <b>0.23</b>     | <b>0.42</b>    | 0.07        | <b>-0.46</b> | <b>0.16</b>  |
| DP    | <b>0.30</b>     | 0.01            | <b>0.16</b>     | <b>0.55</b>    | <b>0.19</b> | <b>-0.72</b> | <b>0.27</b> | 0.06            | 0.03            | 0.05            | <b>0.37</b>    | 0.11        | <b>-0.56</b> | <b>0.32</b>  |
| DM    | <b>0.38</b>     | <b>-0.32</b>    | 0.06            | <b>0.26</b>    | 0.22        | <b>-0.65</b> | 0.07        | 0.19            | 0.10            | 0.16            | <b>0.42</b>    | 0.17        | <b>-0.33</b> | <b>0.32</b>  |
| DT    | -0.16           | -0.13           | -0.32           | 0.20           | -0.43       | -0.12        |             | 0.31            | 0.15            | 0.25            | <b>0.56</b>    | <b>0.40</b> | -0.23        | 0.33         |
| MP    | -0.08           | -0.20           | -0.16           | 0.22           | <b>0.30</b> | <b>-0.66</b> | -0.01       | 0.07            | 0.04            | 0.07            | <b>0.23</b>    | 0.18        | <b>-0.53</b> | 0.09         |
| MM    | <b>0.40</b>     | 0.13            | 0.31            | 0.34           | <b>0.48</b> | <b>-0.46</b> | 0.08        | 0.09            | 0.08            | 0.09            | 0.07           | 0.23        | -0.39        | 0.24         |
| MT    | -0.32           | -0.12           | -0.38           | 0.26           | 0.26        | <b>-0.94</b> | -0.21       | 0.27            | 0.35            | 0.32            | 0.28           | 0.07        | -0.35        | 0.22         |
| Trans | -0.18           | -0.19           | -0.21           | 0.00           | 0.01        | <b>-0.63</b> | 0.06        | <b>0.34</b>     | 0.28            | <b>0.33</b>     | <b>0.57</b>    | -0.23       | <b>-0.53</b> | 0.13         |
|       | Summer          |                 |                 |                |             |              |             | Fall            |                 |                 |                |             |              |              |
|       | T <sub>mx</sub> | T <sub>mn</sub> | T <sub>av</sub> | T <sub>d</sub> | SLP         | WS           | PCP         | T <sub>mx</sub> | T <sub>mn</sub> | T <sub>av</sub> | T <sub>d</sub> | SLP         | WS           | PCP          |
| all   | <b>0.25</b>     | <b>0.21</b>     | <b>0.24</b>     | <b>0.67</b>    | 0.01        | <b>-0.33</b> | 0.16        | <b>0.25</b>     | 0.11            | <b>0.19</b>     | <b>0.37</b>    | 0.13        | <b>-0.59</b> | 0.06         |
| DP    | <b>0.55</b>     | <b>0.52</b>     | <b>0.60</b>     | <b>0.66</b>    | -0.01       | <b>-0.32</b> | 0.01        | <b>0.32</b>     | <b>0.19</b>     | <b>0.27</b>     | <b>0.37</b>    | 0.06        | <b>-0.53</b> | -0.04        |
| DM    | <b>0.64</b>     | <b>0.52</b>     | <b>0.66</b>     | <b>0.85</b>    | 0.19        | <b>-0.50</b> | 0.04        | 0.08            | 0.02            | 0.07            | <b>0.31</b>    | -0.02       | <b>-0.46</b> | <b>0.34</b>  |
| DT    | <b>0.33</b>     | <b>0.45</b>     | <b>0.45</b>     | <b>0.55</b>    | 0.10        | <b>-0.30</b> | -0.15       | 0.12            | -0.06           | 0.02            | 0.12           | 0.13        | <b>-0.60</b> | <b>-0.28</b> |
| MP    | <b>0.59</b>     | 0.06            | 0.31            | 0.34           | 0.38        | -0.25        |             | <b>0.66</b>     | 0.43            | <b>0.63</b>     | <b>0.55</b>    | 0.12        | -0.19        |              |
| MM    | <b>0.62</b>     | <b>0.58</b>     | <b>0.61</b>     | <b>0.54</b>    | 0.00        | -0.19        | -0.21       | 0.10            | 0.14            | 0.13            | 0.30           | 0.23        | <b>-0.80</b> | -0.01        |
| MT    | <b>0.43</b>     | <b>0.24</b>     | <b>0.44</b>     | <b>0.35</b>    | 0.04        | -0.17        | -0.14       | 0.27            | 0.16            | 0.23            | 0.16           | 0.18        | -0.29        | -0.09        |
| Trans | <b>0.66</b>     | <b>0.63</b>     | <b>0.71</b>     | <b>0.71</b>    | 0.12        | <b>-0.50</b> | 0.02        | 0.17            | 0.10            | 0.15            | <b>0.36</b>    | 0.08        | <b>-0.52</b> | 0.30         |

Table 4. Loadings of individual meteorological variables for different seasonal factors. Shaded values indicate largest magnitude loading. Also shown are the percent variance explained in the data by the factors and the total percent variance explained for each season.

| Factor           | Winter<br>(73.6%) |         | Spring<br>(74.6%) |         | Summer<br>(83.7%) |         |         | Fall<br>(78.2%) |         |
|------------------|-------------------|---------|-------------------|---------|-------------------|---------|---------|-----------------|---------|
|                  | 1                 | 2       | 1                 | 2       | 1                 | 2       | 3       | 1               | 2       |
|                  | (54.4%)           | (19.2%) | (54.4%)           | (20.2%) | (48.3%)           | (19.2%) | (16.2%) | (54.8%)         | (23.4%) |
| T <sub>max</sub> | 0.903             | -0.160  | 0.920             | -0.156  | 0.861             | -0.119  | -0.288  | 0.936           | -0.133  |
| T <sub>min</sub> | 0.927             | 0.080   | 0.943             | 0.104   | 0.924             | 0.165   | 0.033   | 0.956           | 0.101   |
| T <sub>avg</sub> | 0.976             | -0.053  | 0.980             | -0.040  | 0.974             | 0.013   | -0.155  | 0.988           | -0.022  |
| T <sub>d</sub>   | 0.951             | -0.084  | 0.937             | 0.116   | 0.860             | -0.013  | 0.284   | 0.968           | 0.007   |
| SLP              | -0.400            | -0.752  | -0.211            | -0.798  | -0.155            | -0.828  | 0.049   | -0.194          | -0.836  |
| Wind             | -0.228            | 0.795   | -0.431            | 0.537   | -0.265            | 0.705   | -0.420  | -0.269          | 0.758   |
| Precip           | 0.255             | 0.324   | 0.058             | 0.663   | 0.023             | 0.346   | 0.876   | 0.145           | 0.580   |

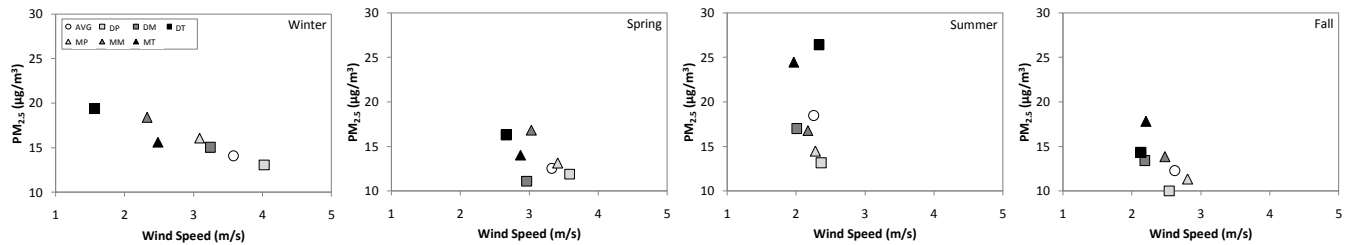


Figure 8. Scatter plots of seasonal wind speed versus PM<sub>2.5</sub> concentration by air mass.

## CONCLUSION

PM<sub>2.5</sub> concentration and local and synoptic meteorological data were examined for Carlisle, Pennsylvania, an area that is in non-attainment of the EPA 24-hour PM<sub>2.5</sub> standard. Results of the analysis can be summarized as follows.

- PM<sub>2.5</sub> concentrations are highest in summer and secondarily in winter. Spring and fall have relatively low concentrations. Wind speed is the dominant meteorological variable controlling this seasonality.
- Local weather conditions on days with high PM<sub>2.5</sub> concentrations are generally characterized as warmer, more humid, less windy, higher pressure, and with less precipitation. Temperature and humidity are actually lower for high PM<sub>2.5</sub> concentration days in fall.
- High PM<sub>2.5</sub> concentration days occur due to ridging in the upper atmosphere and a resulting surface high pressure system to the southeast except for fall when the high is located to the northeast. The location of the high forces synoptically warmer and more humid conditions except for fall when it forces cooler and drier conditions. All seasons have weak southerly winds associated with high PM<sub>2.5</sub> concentration days.
- High PM<sub>2.5</sub> concentrations occur on days classified as DT, MM, or MT in terms of air mass. These air mass days occur 34% of the time in summer and relatively infrequently the rest of the year.

The results suggest that close monitoring of PM<sub>2.5</sub> conditions in this area should be continued and perhaps expanded to include other pollutants that tend to be prevalent in higher concentrations under similar weather conditions as presented in this study. It is also important to continue to use synoptic meteorological conditions and forecasts to inform the public about potentially hazardous air quality conditions. Future work should investigate the relative contributions of locally produced PM<sub>2.5</sub> and PM<sub>2.5</sub> that is transported into the region and the synoptic weather conditions that contribute to both sources.

## ACKNOWLEDGEMENTS

This work was partially funded by the Center for Land Use at Shippensburg University. Thank you to Tom Au for helpful comments.

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