# CLIMATOLOGICAL FACTORS IMPACTING SUMMER AIR POLLUTION IN THE PHILADELPHIA METROPOLITAN AREA

By

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ABSTRACT OF THE THESIS

Climatological Factors Impacting Summer Air Pollution in the Philadelphia Metropolitan Area

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This study examines two criteria atmospheric pollutants, ozone and particulate matter 2.5 μm (PM 2.5) within the Philadelphia-Camden-Wilmington (PCW) region and explores the relationship these pollutants may have with summer climatological factors and amongst themselves. Three synoptic types are found to be associated with high pollution concentrations, these synoptic types are mainly categorized by southerly winds, partly cloudy skies, and warm temperatures. Ozone and PM 2.5 were found to be strongly positively correlated between themselves, suggesting that as one pollutant increases or decreases, the other will as well. Future research would include the forecasting of poor air quality days, with a focus on the three synoptic types that are most strongly related to high pollution concentrations. As future climate changes, the relationship between synoptic climatology and pollutants may need to be further explored.

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## 1. Introduction

Air quality has long been an environmental topic of global importance. Communities worldwide have been concerned about their air quality, in international locations such as India, China, and London, England, and domestically in locations such as Donora, Pennsylvania and Los Angeles, California. Air quality in urban areas is primarily of concern, as larger populations exist in urban areas, increasing the potential for atmospheric pollution emissions (Wallace and Hobbs 2006, Appelhans et al 2013, Hou et al 2015).

Atmospheric pollutants are particles or gases that exist within the layers of the atmosphere, residing in the troposphere and the stratosphere, that produce harmful environmental and human health impacts (Ahrens 2005). Aerosols, minute liquid and solid particles suspended in the air, have natural and anthropogenic sources (Ahrens 2005, Allen 2017). Naturally occurring aerosols are those such as sea salt, dust, volcanic emissions, and organic carbon from forest fires. Human made aerosols, products of incomplete combustion, have well known sources, such as vehicle emissions, factories, and other fossil fuel intensive industries (Voiland 2010). Aerosols have both direct and indirect effects on the climate system through scattering and absorbing incoming solar radiation and through the modification of cloud properties, thus changing the reflective and absorptive properties of clouds (Remer et al 2009, Allen 2017). Aerosols scatter solar radiation, cooling the Earth, they also contribute to the production of adverse environmental and human health effects (Allen 2017).

Atmospheric pollution and climate, the long term conditions of a location such as average precipitation, temperature, and humidity (NOAA 2018) are intrinsically linked (Jacob and Winner 2009, Rasmussen et al 2012, Oswald et al 2015, Jing et al 2016). Six common air pollutants are the main focus of the US Environment Protection Agency, including ground-level ozone, particulate matter, carbon monoxide, lead, sulfur dioxide, and nitrogen dioxide (EPA 2019a). Earlier studies that examined synoptic climatology and air quality have a focus on criteria pollutants such as sulfur dioxide, and various locations (Kalkstein and Corrigan 1986, Beaver et al 2010, Lee et al 2012, Appelhans et al 2013, Jing et al 2016). Synoptic climatology examines the relationships between atmospheric circulation and a region's surface environment (Yarnal 1993). Synoptic climatology classifies the atmospheric circulation, creating individual categories of synoptic weather patterns, or air masses. This study examines two of the six criteria atmospheric pollutants, ozone and particulate matter 2.5 μm (PM 2.5) within the Philadelphia-Camden-Wilmington (PCW) region and explores the relationship these pollutants may have with climatological factors and amongst themselves.

Understanding the relationship between pollutants and climatology assists air quality managers and professionals in generating reliable air quality forecasts. Air quality forecasting tools are presently used by federal and state agencies, providing one to three-day forecasts. One such technique uses climatology to predict air quality based on the association of high pollution concentrations with certain meteorological conditions (National Science and Technology Council 2001). Applying the tenants of climatology to air quality problems can involve the development of an air mass classification scheme, such as a synoptic climatology, which identifies the recurring air masses that are associated with higher pollution levels. The National Weather Service defines air masses as, "…a large body of air with generally uniform temperature and humidity."(NOAA 2019). Classification tools can be used to classify air masses. Here a temporal synoptic index (TSI) is used to cluster air masses to further compare pollutant concentrations. A TSI is a fully automated synoptic classification tool wherein through the use of cluster analysis, similar air masses are categorized (Urban and Kysely 2018).

The climate system is responsible for the movement and dilution of pollutants (Mather 1968). Concentrations of pollutants vary based on local weather conditions, specifically temperature, surface winds, air pressure, cloud cover and the solar intensity. High atmospheric temperature, bright sunshine with limited cloud cover, light surface winds, and a stagnant high-pressure system over head are conditions in which pollution concentrations have greater potential of becoming detrimental to human health and the environment (Mather 1968, Ahrens 2005, Wallace and Hobbs 2006). While a light wind will promote increasing pollutant concentrations, a strong wind will produce turbulent air, mixing and diluting the pollutants, decreasing the localized concentration amounts. This study focuses on the pollutant levels during the summer months of June, July, and August (JJA), as pollutant concentrations are greatest during high temperatures and bright sunshine, typical of the summer months in the U.S. Mid-Atlantic region.

Periods of atmospheric stability and inversions are conditions in which air pollution is greatly affected (Wallace and Hobbs 2006, Dawson et al 2007). Inversions, representative of a stable atmosphere, act as a cap on vertical air motion (Ahrens 2005). During inversions the atmosphere is extremely stable, and warm air rests above cool air. Two inversions in particular, radiation inversions and subsidence inversions are commonly associated with major air pollution episodes (Ahrens 2005). Radiation inversions, also known as surface inversions, are common at night and early morning. Subsidence inversions are formed when the air above slowly sinks to the surface and warms. When this pattern persists for days major air pollution episodes can occur. During particularly severe air pollution episodes an ideal combination of many of the following environmental factors exists: a deep high-pressure system that persists over the region, light winds that are unable to disperse pollutants, a strong subsidence inversion, a shallow mixing layer, clear skies that promote night time radiational cooling, and strong sunlight necessary for photochemical reactions (Ahrens 2005, Dawson et al 2007).

Atmospheric stability determines the extent to which air will rise, thus affecting the amount of horizontal spreading for a parcel of air. For example, pollutants that are emitted into a stable atmosphere will spread horizontally, rather than mixing vertically, pollutant rich air will then accumulate at lower levels of the atmosphere, in turn increasing the pollutant concentrations for a region (Mather 1968). Within a stable atmosphere a parcel of air that becomes lifted or lowered will return to its original position, in an unstable atmosphere the parcel of air will move from its original position, favoring vertical air currents (Ahrens 2005). As a parcel of air rises it encounters surrounding air with lower atmospheric pressure, the air parcel then expands as the molecules within push outwards, cooling the air. When the parcels fall to the surface the atmospheric pressure increases, compressing the molecules within the air parcel, and warming the air. Stability of the atmosphere is then determined by comparing the temperature of the rising parcel of air to its surroundings. Rising air parcels that are cooler than the environment will sink - this is the stable condition (Ahrens 2005). Parcels that are warmer than their surrounding will rise within the atmosphere until it reaches equilibrium with the surrounding environment. Periods of changing atmospheric stability, from a stable atmosphere in the early morning to a conditionally unstable atmosphere in the afternoon, can have a large impact on the daily pollutant concentrations, as strong solar radiation during the afternoon will warm the surface, promoting an unstable atmosphere where mixing is feasible.

Of most concern regarding air pollution is the multitude of health effects that ozone and particulate matter (PM) have on the human body. Exposure to air pollutants creates long-term health challenges for the heart and lungs (Lippman 1989, Dawson et al 2007). Exposure is evident within hours; daily exposure to pollutants has the potential to exacerbate pre-existing health conditions such as asthma especially in young children and the elderly (Jing et al 2016). High levels of exposure also have the potential to increase mortality rates (Dawson et al 2007, Lee et al 2012, Hou et al 2015).

The greater Philadelphia region is an important location for this study, located within the Mid-Atlantic of the United States downwind of many pollution emitting sources further inland. It is also a city that generates many pollutants locally. Per 2017 U.S. population totals, Philadelphia ranked sixth overall, with an estimated population around 1.58

million people (US Census). Previous studies have analyzed the climatological relationship to air quality in Philadelphia alone (Cheng et al 1992), and between Philadelphia and other American cities (Greene et al 1999, Hou et al 2015, Oswald et al 2015, Simon et al 2016, Moghani et al 2018) during the summer.

Cheng et al (1992) developed a synoptic climatological categorization for the years 1955-1991 using the temporal synoptic index to compare to pollution concentrations of ozone and total suspended particulates – now referred to as particulate matter, concluding that high mean air temperatures, stable atmospheres, sunny skies and light winds translate into high pollution concentrations. Greene et al (1999) focused on the cities of Birmingham, Cleveland, Philadelphia and Seattle for their robust pollutant and meteorological data sets. Looking at ozone and total suspended particulates also. They found that for Philadelphia, higher temperatures and humidity, moderate cloud cover, and southerly winds are correlated with high pollution days. Hou et al (2015) used a photochemical transport model to explain the contributions that ozone and PM 2.5 have to mortality in Boston, New York, Philadelphia, Washington D.C., Atlanta, Chicago and Detroit during the summer. Their results proved that PM 2.5 is more deadly than ozone, with 2101 deaths from PM 2.5 compared to 909 from ozone. Oswald et al's (2015) study examined ozone throughout the Northeastern United States during 1993-2012, linking ozone to meteorological predictors and also large-scale teleconnections. Similar to the other studies, Oswald et al also examined a connection between high temperatures and ozone, but also precipitation and the amount of solar radiation flux. Simon et al (2016) used a photochemical model to assess the spatial gradient of ozone across urban areas from

2006-2008 for Atlanta, Philadelphia, and Chicago. Moghani et al (2018) modeled the transport of ozone to the Mid-Atlantic region for the cities of Wilmington, Baltimore, Philadelphia, D.C and New York City, finding that the main contributor of high ozone to the region is ozone transport. This study seeks to replicate previous studies with the focus on Philadelphia, though here I examine the relationship with climatology and air pollution rather than previous studies where individual meteorological variables were assessed alongside air pollutants. Following previous work, I seek to examine multiple locations, all while primarily focusing on the greater Philadelphia region to include the previously understudied surrounding suburban monitoring sites in New Jersey and Delaware.

The Philadelphia metropolitan region has several counties that are currently in nonattainment for the Clean Air Act's National Ambient Air Quality Standards (NAAQS) https://www3.epa.gov/airquality/greenbook/mapnpoll.html (Simon et al 2016). The EPA Green Book defines nonattainment as "Any area that does not meet (or that contributes to ambient air quality in a nearby area that does not meet) the national primary or secondary ambient air quality standard for a NAAQS." (EPA 2019a). This designation requires legislative action be taken by state and local governments to ensure cleaner air quality is achieved.

In 1963 the United States Congress enacted the Clean Air Act to combat air pollution. Seven years later an amendment to the Clean Air Act was made, setting more rigorous standards for air pollutants. The Clean Air Act of 1970 established the National Ambient

Air Quality Standards (NAAQS), which are a set of standards for pollutants that are harmful to human health and the environment. The NAAQS, monitored by the United States Environmental Protection Agency (EPA), distinguishes primary standards from secondary standards (Ahrens 2005). Primary standards are those that are directed at protecting human health, secondary standards provide protections against visibility and environmental damages to crops, animals, and buildings. Here, the focus is on ground-level ozone and particulate matter, as ozone is a secondary pollutant that requires the emissions of primary sources and a photochemical reaction. The focus on PM 2.5 concentrations in the summer can be attributed to air conditioning unit demand, as air conditioning units rely on fossil fuels, which worsen air quality (Abel et al 2018).

Real time data collected from monitoring sites operated by either the EPA or state agencies are used in this study to compare to NAAQS, creating a rating system of air quality, the Air Quality Index (AQI), adapted from the EPA. The AQI has a measured numerical value ranging from 0 to 500 (Figure 1) with a corresponding color code going from green to maroon. Satisfactory air quality is rated as Good or Moderate, Good AQI values range from 0 to 50, with a green color code, and Moderate levels are expressed as yellow and range from 51 to 100. An increasing AQI and associated color code represent unhealthy air quality, where the orange Unhealthy for Sensitive Groups code, has an AQI in the 101 to 150 range. An Unhealthy AQI level has a range from 151 to 200, and is colored red. Becoming increasingly dangerous, next highest AQI is Very Unhealthy, with a range from 201 to 300. The most dangerous AQI level is considered Hazardous, with an unsettling range of 301 to 500.

| AQI Level of Health Concern | Numerical Value | Meaning | Color Code |
|---|---|---|---|
| Good | 0 to 50 | Air quality is considered satisfactory, and air pollution poses little or no risk. | Green |
| Moderate | 51 to 100 | Air quality is acceptable; however, for some pollutants there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution. | Yellow |
| Unhealthy for Sensitive Groups | 101 to 150 | Members of sensitive groups may experience health effects. The general public is not likely to be affected. | Orange |
| Unhealthy | 151 to 200 | Everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects. | Red |
| Very Unhealthy | 201 to 300 | Health warnings of emergency conditions. The entire population is more likely to be affected. | Purple |
| Hazardous | 301 to 500 | Health alert: everyone may experience more serious health effects. | Maroon |

**Figure 1** Air Quality Index values and associated meanings (adapted from EPA).

### 1.1 Ozone

Ozone exists within two layers of the atmosphere. Stratospheric ozone is naturally occurring, protecting the Earth from incoming solar radiation and is important for skin protection in humans and ultraviolet radiation protection for plants and animals (EPA 2019b). Within the troposphere, ozone, also referred to as ground-level ozone, can become dangerous, causing numerous health effects in humans, damaging the respiratory system and potentially the bloodstream (Lippman 1989).

Ozone is a secondary air pollutant that is created through a photochemical process between primary pollutants and the sun (Ahrens 2005). Ozone relies on the emission and concentrations of primary pollutants such as nitric oxides (NO), carbon monoxide (CO) and organic compounds that are required to initiate the atmospheric chemical reaction with sunlight to transform into ground-level ozone (Wallace and Hobbs 2006). NO is naturally produced by lightning and anthropogenically produced from fossil fuels, combustion processes, biomass burning, and various forms of transportation; CO is produced by the oxidation of methane, biomass burning, and fossil fuel combustion (Wallace and Hobbs 2006). Because of the photochemical reaction necessary in the formation of ozone, ozone levels are generally highest during hot sunny weather, where higher temperatures will speed up the photochemical reactions.

Primary and secondary standards for ground-level ozone exist to protect human health (primary) in sensitive populations such as the elderly and asthmatic, or environmental health (secondary). The primary and secondary air quality standards are the same for tropospheric ozone (NJDEP 2017). For a one-hour period, the most up-to-date primary standard in New Jersey is 0.12 parts per million (ppm), nationally no standard exists. The 8-hour average daily maximum primary and secondary standard nationally sits at 0.070 ppm. To comply with the NAAQS, a design value for ozone is calculated from the past three-year's data (NJDEP 2017). Design values are used to designate areas that are in nonattainment. First, the fourth-highest daily maximum 8-hour average concentration at each monitoring site location is calculated from the most recent three years. The determined values at each site are then used to calculate a three-year average. Compliance is determined by three-year average values, where values that exceed the NAAQS for a site are said to be in nonattainment. This statistic describes the air quality of a location compared to the NAAQS. Values that are below the NAAQS for a site are in attainment.

**1.2 PM 2.5**

Particulate matter with an aerodynamic diameter less than or equal to 2.5 μm i.e. PM 2.5 is a fine inhalable pollution particle, existing in solid and liquid forms (Liu et al 2017). Categorized by size, particulate matter is studied at 10μm (PM 10) or 2.5 μm (PM 2.5), with PM 2.5 causing the most risks (NJDEP 2017). Particulates may be naturally occurring, such as dust, smoke, volcanic ash, and sea salt, or anthropogenically created, from fossil fuel combustion, unpaved roads, and industrial processes (NJDEP 2017 and EPA 2019c). Particulates that are directly emitted into the atmosphere are categorized as primary pollutants, whereas those that form from a chemical reaction, such as the reaction between water vapor and a primary pollutant, are classified as secondary pollutants (Ahrens 2005, NJDEP 2017, EPA 2019c).

Fine particulates are the most visible form of air pollution, reducing visibility through the production of haze when particles absorb sunlight (Ahrens 2005, NJDEP 2017, EPA 2019c). Due to the small size of particles and their ability to enter the respiratory tract, PM 2.5 has the potential to cause many deleterious health effects including increased mortality and increased risks for those with cardiovascular and respiratory diseases (Ahrens 2005, Dawson et al 2007, Liu et al 2017), potentially entering the bloodstream.

Two National Ambient Air Quality Standards (NAAQS) exist for PM 2.5, primary standards whose aims are human health based, and secondary standards whose goals are environmental based (NJDEP 2017). The current primary standard for PM 2.5 over an average annual period is 12.0 $\mu g/m^3$, the secondary standard is set to 15.0 $\mu g/m^3$. Over a

24-hour averaging period, both the primary and secondary standard is presently at 35 μg/$m^3$. Similar to other pollutants, standard compliance is determined from the design value. The design value for the annual period is the "highest statewide 3-year average of each site's annual average concentrations"; within a 24-hour period the design value is calculated from the 98$^{th}$ percentile of 24-hour concentrations from each monitoring site, which are then averaged over the last three years, the highest value is the set design value (NJDEP 2017).

Few studies have examined both ozone and PM 2.5 pollutants, for ozone is a predominately summertime pollutant and PM 2.5 is presented as a year-round pollutant (Greene et al 1999, Jacob and Winner 2009, Hou et al 2015). Ozone is a secondary pollutant that requires particular meteorological conditions in order to form, and PM 2.5 during the summer can be attributed to air conditioning units. While no obvious seasonality may exist for PM 2.5, prolonged use of fossil fuel combustion intensive activities, such as air conditioning units, will increase the amount of PM 2.5 emitted during the summer months. Either of these pollutants on their own are detrimental to human and environmental health, however when combined, the effects have greater potential to become hazardous.

### 1.3 Research Objectives

This thesis will examine ozone and PM 2.5 concentrations as they may be associated with synoptic climatological conditions and how this knowledge can be applied towards forecasting high pollution events. An extended study from 1990-2017 (monitoring site and pollutant specific) is conducted to generate a nearly 30-year climatology for the Philadelphia-Camden-Wilmington (PCW) region. Here I take a closer look at pollution for the suburban and urban areas that make up the PCW study region, with a focus on the spatial and temporal distribution of the two pollutants. Southern New Jersey has not previously been the focus of regional ozone or PM 2.5 concentration distributions or air quality research, and Delaware has only recently been the focus of studies (Moghani et al 2018, Veron et al 2018).

The Philadelphia region is presently in nonattainment for multiple pollutants covered under the NAAQS. The geographic position of the PCW region in the Eastern United States promotes higher pollutant concentrations due to the transport of pollution from westernmost locations. As westerly winds are carried across Pennsylvania and further into Delaware and New Jersey, the region experiences frequent unhealthy air quality days. Previous studies examined the air quality of Philadelphia, but none took a direct look at Southern New Jersey and Delaware. Air quality is not a singular environmental issue, climate factors are key in understanding how pollution is distributed, accumulated, and managed.

Here I answer the following questions: Under what climatological conditions is the air in the Philadelphia-Camden-Wilmington region unhealthy? Does a relationship exist between ozone and synoptic climatology for the application of improving air quality forecasts? Does a relationship exist between PM 2.5 and synoptic climatology? And between ozone and PM 2.5? How are pollutants spatially and temporally distributed within the Philadelphia-Camden-Wilmington region?

## 2. Methods: Data and Region

### 2.1. Ozone Data

Daily maximum 8-hour average ozone concentration data from 1990 to 2017 were obtained from the United States Environmental Protection Agency's Air Data portal (EPA 2019d) https://www.epa.gov/outdoor-air-quality-data/download-daily-data. Locations within the PCW region with the longest continuous collection period were chosen including Rider University, Ancora State Hospital, Air Management Services Laboratory, Norristown, and Lums Pond (Table 1 and Figure 2).

| AQS ID | Site Name | Latitude | Longitude | Ozone data period |
|---|---|---|---|---|
| 34-021-0005 | Rider University, NJ | 40.28 | -74.74 | 1990-2017 |
| 34-007-1001 | Ancora State Hospital, NJ | 39.68 | -74.86 | 1990-2017 |
| 42-101-0004 | Air Management Services Lab, PA | 40.01 | -75.09 | 1993-2017 |
| 42-091-0013 | Norristown, PA | 40.11 | -75.30 | 1990-2017 |
| 10-003-1007 | Lums Pond, DE | 39.55 | -75.73 | 1992-2017 |

**Table 1** Ozone monitoring site information. The AQS ID is an identification code for each location within the Air Quality System (AQS).

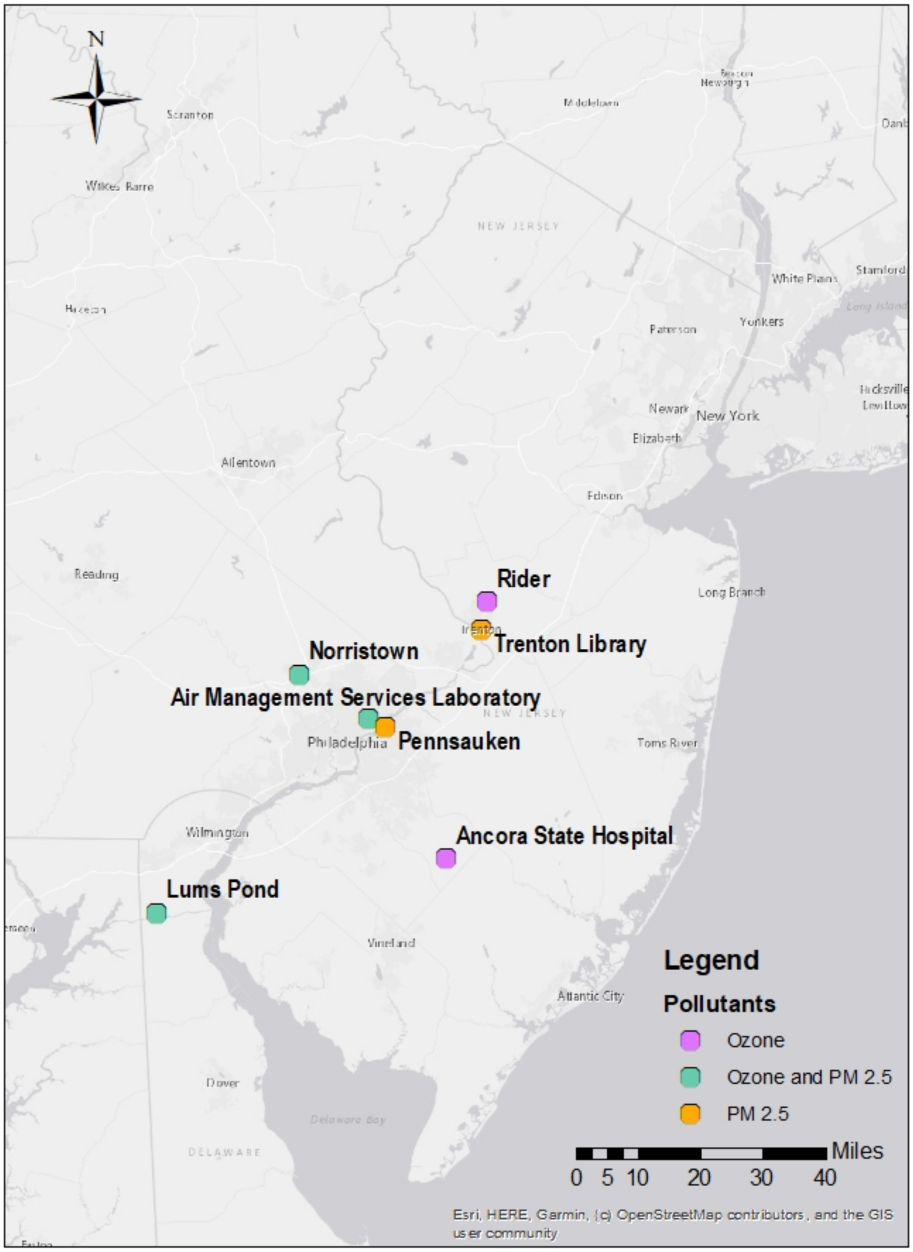



**Figure 2** Study site map of the Philadelphia-Camden-Wilmington (PCW) metropolitan region. Ozone monitoring sites in purple, PM 2.5 monitoring sites in orange, and monitoring sites that record both pollutants in teal.

### 2.2 PM 2.5 Data

Daily mean PM 2.5 concentration data from 1999 to 2017 were obtained from the United States Environmental Protection Agency's Air Data portal https://www.epa.gov/outdoor-air-quality-data/download-daily-data. Locations and monitoring stations with the longest continuous collection period were chosen, including Trenton Library, Pennsauken, Air Management Service Laboratory, Norristown, and Lums Pond (Table 2 and Figure 2).

| AQS ID | Site Name | Latitude | Longitude | Ozone data period |
|---|---|---|---|---|
| 34-021-0008 | Trenton Library, NJ | 40.22 | -74.76 | 1999-2017 |
| 34-007-1007 | Pennsauken, NJ | 39.99 | -75.05 | 1999-2017 |
| 42-101-0004 | Air Management Services Lab, PA | 40.01 | -75.10 | 1999-2018 |
| 42-091-0013 | Norristown, PA | 40.11 | -75.31 | 1999-2015 |
| 10-003-1007 | Lums Pond, DE | 39.55 | -75.73 | 1999-2018 |

**Table 2** PM 2.5 monitoring site information. AQS ID is an identification code for the Air Quality System.

### 2.3 Study Region

Located on the eastern boundary of the United States, the Philadelphia, Pennsylvania-Camden, New Jersey –Wilmington, Delaware region, is commonly placed within the context of the Mid-Atlantic region (MAR) (Mather 1968 and Polsky et al 2000). The

MAR includes south-central New York to the north, North Carolina to the south, and West Virginia to the west, with Pennsylvania, portions of New Jersey, Virginia, and the Delmarva Peninsula as well. The MAR consists of rocky Piedmont, flat Coastal Plain, the Appalachian Plateau and Ridge and Valley regions. The Mid-Atlantic climate is modulated by the Atlantic Ocean to the east and the Appalachian Mountains to the west.

The climate of the PCW region is influenced by the eastward movement of western originating cyclones, the PCW region predominately experiences a continental climate regime (Mather 1968). Pennsylvania has a humid continental climate, where summers are generally warm, with the southeastern region around Philadelphia experiencing high temperatures 90°F or above on average 25 days during the summer (Pennsylvania State Climatologist 2019). The Philadelphia region is situated within the Southeastern Coastal Plain and Piedmont Plateau. The Southeastern Coastal Plain and Piedmont Plateau generally record abundant precipitation due to the influence of coastal storms. Average temperatures from 1990 to 2017 for the month of June range from 67.1-74.6°F, the July range is 71.2-78.8°F, and the August range is 69.3- 77.2°F. Delaware, south of Pennsylvania, is a transitional zone, with a humid subtropical climate in the south and a humid continental climate in the north **(**Office of the Delaware State Climatologist 2019). Summers in Delaware are warm, being influenced by adjacent water bodies that lessen temperature extremes. The mean temperature in Wilmington New Castle for June is 72.2°F, 76.8 °F in July, and 75.2°F in August. New Jersey can be divided into five climate zones, with the Central, Pine Barrens, and Southwest encompassed within the study area (Office of the New Jersey State Climatologist 2019). The climate of the Pine

Barrens is influenced by the sandy soil and proximity to the Atlantic Ocean. During the summer months, the Central region experiences about 15-20 days with temperatures 90°F or higher. The Southwest climate is influenced by the Delaware Bay, where the highest average daily temperatures within the state are found. This region also records less precipitation than other parts of the state for the lack or orographic features. This region experiences high humidity and moderate temperatures when winds originate from the south and east. Average temperatures for Mount Holly from 1994 - 2017 in June range from 68.2 – 75.3°F, from 72.2 -79.2°F in July, and from 70.0 – 77.4°F in August.

To represent the Philadelphia-Camden-Wilmington region, five air monitoring sites were chosen, with each monitoring site corresponding to a location north, east, south, or west of Philadelphia, along with a location in the city. The Air Management Services location is representative of city center in Philadelphia, where Trenton Library and Rider University represent locations north of Philadelphia. Ancora State Hospital and Pennsauken are representative of easternmost locations. Norristown was used as the location west of Philadelphia, and Lums Pond was used as the south location. The Air Management Services, Norristown and Lums Pond monitoring sites measure both ozone and PM 2.5.

## 3. Methods: Data Analysis

### 3.1 Temporal Synoptic Index

Synoptic climatology examines the relationships between atmospheric circulation and a region's surface environment (Yarnal 1993). Synoptic climatology is employed as a method of environmental analysis for air quality, hydrology, human health concerns, precipitation distribution, climatic change, and glacial accumulation and ablation, among other topics (Kalkstein et al 1996, Siegert and Leathers 2017). This methodology of synoptic weather classification defines each type by pressure or wind fields (Kalkstein et al 1996); these then represent unique flow patterns to a region. This procedure is ideal at a regional level. As synoptic climatology examines the relationship between the atmosphere and the surface environment, the characteristics of the Philadelphia-Camden-Wilmington region are important in understanding the distribution of pollutants. Recall that the Philadelphia region is situated within the Southeastern Coastal Plain and Piedmont Plateau, the land surface is flat, with sandy soil.

A fully developed temporal synoptic index (TSI) for the city of Philadelphia, Pennsylvania, provided by Dr. Zachary Suriano (University of Nebraska, Omaha), was used to represent climatic conditions during the study period. A temporal synoptic index is a fully automated synoptic classification tool wherein through the use of cluster analysis, similar air masses are categorized using a number of observational variables (Urban and Kysely 2018). The resultant clustering methodology produces a determined number of synoptic types where each type has similar meteorological conditions (Ellis and Leathers 1996, Leathers and Ellis 1996), which will be discussed in further detail below.

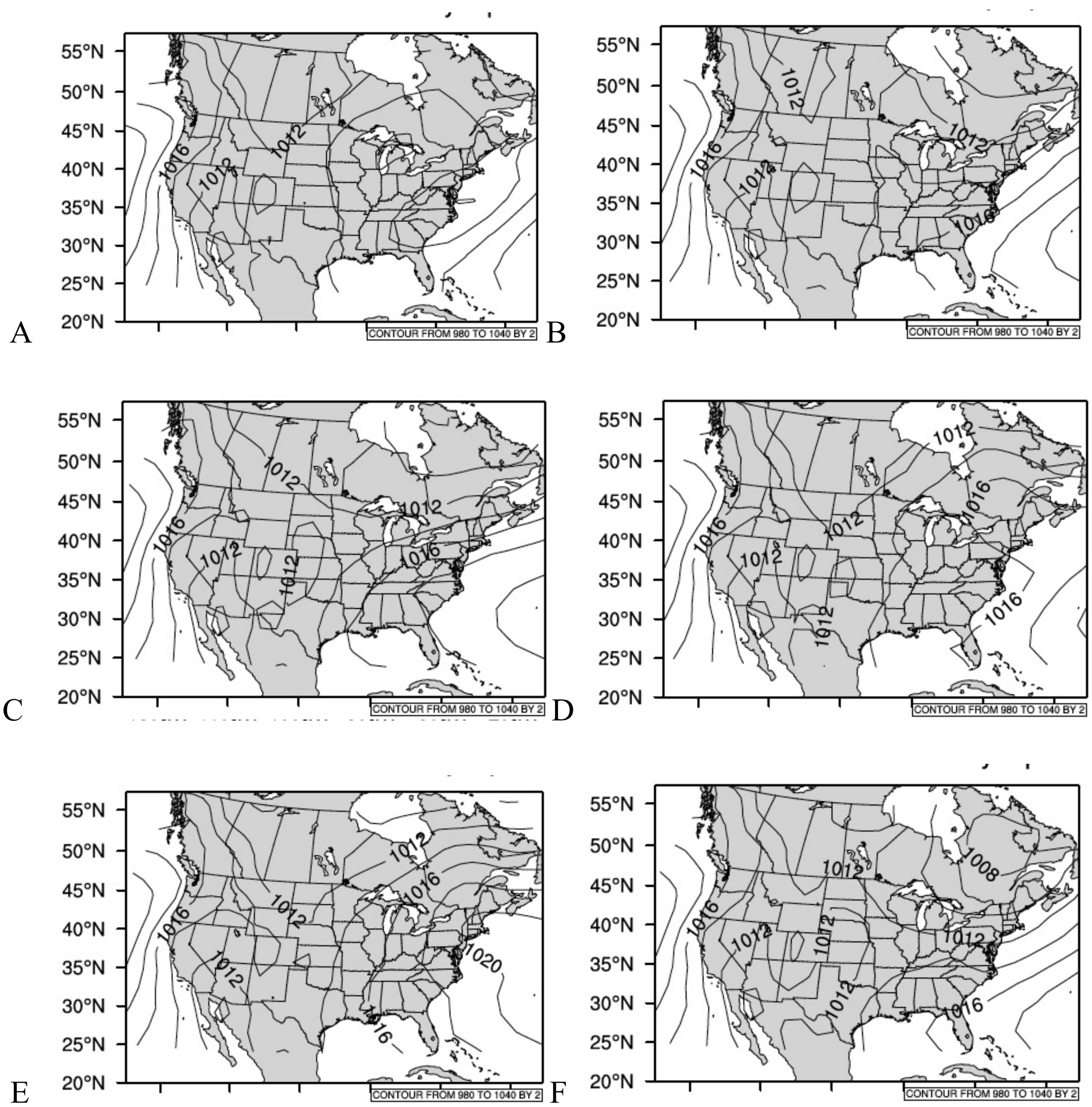
In generating the TSI categories, large-scale atmospheric patterns are identified using a principal component analysis of surface and atmospheric meteorological conditions obtained from weather station data (Ellis and Leathers 1996, Leathers and Ellis 1996, Siegert et al 2016, Suriano and Leathers 2017, Veron et al 2018). For this study weather station data were obtained from the National Centers for Environmental Information (NCEI) for the National Weather Service station located at Philadelphia International Airport in Philadelphia, PA (WBAN #13739: 39.87° N, 75.23° W) (Siegert et al 2016, Veron et al 2018). Temperature, dewpoint temperature, sea level pressure, u and v wind vectors, and cloud cover for four daily observation times (0900 UTC, 1500 UTC, 2100 UTC, 0300 UTC) were collected for every calendar day. U and V wind vectors are the zonal and meridional velocity components, respectively, where the u wind vector is the horizontal wind and the v wind vector is the vertical wind (Wallace and Hobbs 2006). Using a principal component analysis reduces the 24 variables corresponding to the four daily observations into daily components (Ellis and Leathers 1996, Leathers and Ellis 1996, Kalkstein and Corrigan 1986, Suriano and Leathers 2017, Urban and Kysely 2018). Daily component scores are then further calculated; days with similar meteorological conditions have similar component scores. Component scores are further clustered seasonally. Here, only summer season (JJA) conditions are analyzed.

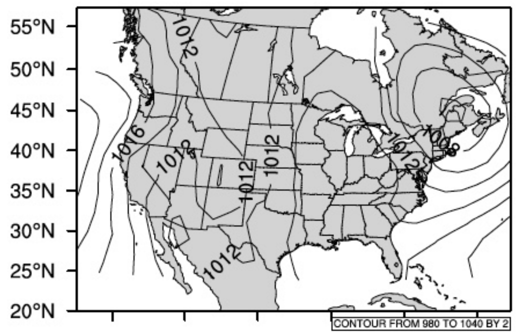
To better understand the synoptic type classifications generated with this TSI approach, descriptions of each type were created (Table 3). 3001 is a New England High system, 3031 Weak flow pattern, 3032 Southwest Flow with a classic Bermuda High system, 3033 weak Southwest Flow, 3034 Off-shore High, 3035 Hudson's Bay Low, Frontal Activity, 3036 New England Low, 3037 North-Northwest Flow, and 3038 Overhead High. Sea level pressure maps for each of the synoptic types are in Figure 3.

| **Synoptic Type** | **Description** |
| --- | --- |
| **3001** | New England High - Winds from the east into the region. |
| **3031** | Weak flow pattern - Thunderstorms likely. |
| **3032** | Southwest Flow - Sunny skies and warm. Potential for thunderstorms. |
| **3033** | Weak Southwest Flow - Southerly flow bringing warm air. Greater potential for precipitation than 3032. |
| **3034** | Off-shore High - Pleasant conditions with a high offshore, winds from the east. |
| **3035** | Hudson's Bay Low, Frontal - Cold front passage brings cooler air to the region. Rain likely. Winds from the west southwest (WSW) |
| **3036** | New England Low - Strong low pressure over New England. Winds from the west northwest (WNW) |
| **3037** | North- Northwest Flow - Weak flow with less intense pressure. Winds from the north northwest (NNW) |
| **3038** | Overhead High – Moderate high pressure – pleasant conditions. Winds are variable as direction changes greatly as the system moves over the |

| | |
|---|---|
| | region. |

**Table 3** The nine synoptic types and their meanings with descriptions from Siegert et al 2016



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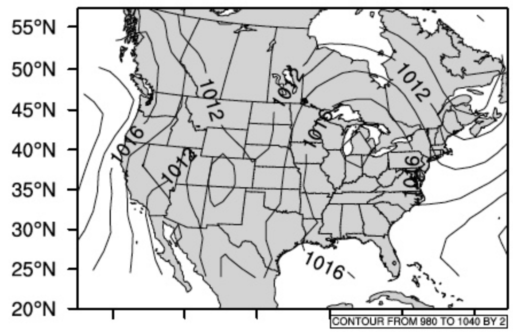


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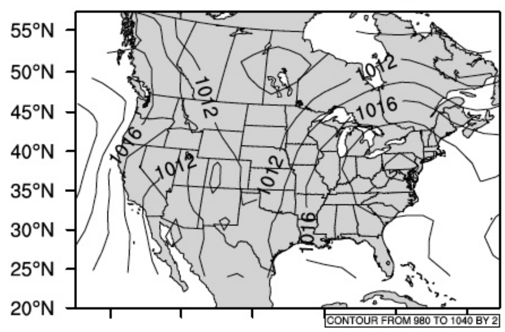


I

**Figure 3** The sea level pressure maps for the nine synoptic types, measured in millibars. From A to I are 3001, 3031, 3032, 3033, 3034, 3035, 3036, 3037 and 3038, respectively (adapted from Suriano and Leathers 2017).

Following the clustering of meteorological conditions and the calculation of component scores, a synoptic calendar is created. The synoptic calendar includes atmospheric variables that are assumed to classify the atmosphere based on several characteristics such as atmospheric structure, stability, and air mass origin, with each date assigned to a seasonally appropriate synoptic type (Siegert et al 2016). Gridded data from National Centers for Environmental Prediction (NCEP) are used in the creation of composite maps where sea level pressure, 500-mb heights, 850-mb heights, and temperature are collated (Ellis and Leathers 1996, Leathers and Ellis 1996, Siegert, Leathers and Levia 2016, Veron et al 2018). Composite maps are representative of atmospheric circulation characteristics (Veron et al 2018). End products of the temporal synoptic index include a synoptic calendar, composite maps, and information about each synoptic type. The synoptic calendar is used alongside pollutant concentrations, comparing synoptic types to AQI types. The AQI thus explains the severity of the pollution on any given day. Through the comparison of a severity index such as AQI with a daily synoptic climatology, an understanding of the association between climatology and pollution can be revealed.

**3.2 Statistical analysis**

Boxplots were created to calculate the average ozone and PM 2.5 concentrations at each of the five monitoring sites for each of the nine synoptic types. Used as a visual statistical representation to better understand the spatial distribution of the pollutants, boxplots were produced to display the ozone concentrations at each of the monitoring sites. Boxplots also display the average ozone concentrations across the nine synoptic types; boxplots were also created to display the average PM 2.5 concentrations for the synoptic types. The variance, or the spread of values from the average value, was determined for ozone and PM 2.5 concentrations, grouped by synoptic type. Boxplots were also made to display the variance for ozone and PM 2.5 concentrations.

To explore potential relationships between synoptic climatology and pollutant concentrations, the frequencies for each synoptic type were compared to the frequencies of poor air quality days. Across the study period the percentage of occurrence by synoptic type was plotted. With future uses geared towards forecasting high ozone/PM 2.5 days, the frequencies of days that met or exceeded the NAAQS were recorded across all synoptic types.

Following the guidance of Fealy and Sweeney 2007 and Jing et al 2016, a correlation analysis was performed to assess the existence of a relationship among synoptic types and ozone and PM2.5 concentrations. The synoptic typing used in this study is categorical, with nine categories; both ozone and PM 2.5 concentrations are continuous variables, whereas concentration amounts have a determined range, but amounts can vary within that range, into the thousandths of a part per million (ppm) for ozone, for example.

Daily adjustments for the pollutant concentrations were made, as pollutant concentrations are continuous variables, and the synoptic types are categorical variables. If the concentration at any of the five monitoring locations recorded an amount that met or exceeded the threshold for either pollutant, 0.07 ppm for ozone, and 35.4 $ug/m^3$ for PM 2.5, the site was listed as 1, or ‘yes’. Conversely, if a monitoring location did not record an exceedance amount, the site was listed as 0, or ‘no’.  The number of exceedance days per year was recorded for each of the 28 years of the research period. With the frequency of high ozone and high PM 2.5 days corresponding in variable type to the frequency of synoptic type per year, a correlation test was then run.

To determine whether a statistically significant relationship exists between synoptic types and pollutant concentrations, a correlation analysis was first conducted. A correlation test produces a correlation coefficient, a value with the range of -1 to +1, which signifies the strength and direction of the relationship amongst two variables. A value of +1 suggests a strong positive relationship exists, whereas a correlation coefficient of -1 suggests that a strong negative relationship exists. Under the strong positive relationship scenario, the relationship could be explained as such, as variable X increases, variable Y also increases, and the opposite could be said if the variables decreased. During the strong negative relationship scenario, the relationship could be explained as such, as variable X increases, variable Y decreases, and the opposite scenario is also true in a strong negative relationship, if X decreased, Y would increase. The correlation function and Pearson function in Excel produce the same results, confidence intervals for the correlation tests were not recorded. Both tools are used in the same manner. Here, the frequency of each of the nine synoptic types was compared against the frequency of high ozone days, and then again against the frequency of high PM 2.5 days, with 28 years of data representing the entire study period.

Following results of the correlation test, the nine synoptic types and pollutant concentrations are further compared via a simple linear regression analysis. In regression analysis certain outputs provide a strong supportive part in estimating the relationship between two variables. For example, the $R^2$ value explains how closely the data fits a regression line, where larger values closer to 1 correspond to best fit for a line. Similar to correlation coefficients mentioned above, the significance F provides an idea of how statistically significant the results are, as the p-value. With a significance F value of 0.05 or less the model is dependable, when the value is greater than 0.05 the model is not dependable. Multiple R is the same as the correlation coefficient. Lastly, the sum of squares (SS) is an important descriptor of the data, providing a statistical understanding of how the model fits the data, where a smaller residual SS compared to the total SS means the better the model fits the data

A simple linear regression model provides additional information regarding the potential application of these data towards forecasting future air quality action days. A key aspect of a simple linear regression analysis lies in the ability of the analysis to estimate the relationship amongst variables, providing further guidance to extrapolate the relationship in the use of forecasting models. A regression analysis was performed between the frequency of high ozone days and the frequency for each of the nine synoptic types, a regression between PM 2.5 and the synoptic types was also calculated. When used as a forecasting tool, regression can explain how the dependent variable (high ozone or high PM 2.5) changes in response to changes in the independent variable (synoptic types). Lastly, a correlation test was run between the frequency of high ozone days and the frequency of high PM 2.5 days for the years 1999 to 2015 to determine the existence of a relationship between the two pollutant types.

## 4. Results and Discussion

Three synoptic types, 3031, 3032 and 3035 are linked to high ozone and PM 2.5 concentrations, as will be seen below (Figure 4 and Table 5, Figure 9 and Table 8).

The characteristics of the types are as follows: 1) Type 3031, the Weak flow pattern, is associated with air mass thunderstorms that are generally weak. 2) Type 3032, a Southwest Flow pattern, Bermuda High, has warm air advection that draws moisture from the Gulf of Mexico into the region. The process of warm air advection increases the precipitation potential 3) Type 3035, a Hudson's Bay Low with an associated cold front passage, air is colder and low pressure aloft is situated directly over the PCW region.

Average temperature, precipitation, wind speed, wind direction and cloud cover were collected for all TSIs (Table 4). The synoptic types with highest average temperature are the Southwest Flow and Hudson's Bay Low, with the Weak Flow also recording high average temperatures. As precipitation is an important factor in understanding pollutant concentration, average precipitation amounts were collected, with highest averages attributed to the weak Southwest Flow and New England High systems. Wind speed data, also being a key factor in understanding pollutant dispersion, shows that during the New England High and Southwest Flow patterns average winds were 3.0 m/s, though the highest average wind speeds are attributed to New England Low. Wind direction to the PCW region determines the conditions of the region, with winds from the south or southwest bringing in warmer air. Cloud cover contributes to the development of ozone as a secondary pollutant, requiring low to no cloud cover for optimal ozone development.

Cloud cover was recorded on a scale from 0 to 10, where a score of 0 correlates to no clouds, and a score of 10 correlates to an overcast, cloudy sky. The New England High, Weak pattern, and Off-shore High experience greatest amounts of cloudiness.

| **Synoptic Type** | **Average Temperature (°C)** | **Average Precipitation (inches)** | **Average wind speed (m/s)** | **Average wind direction** | **Cloud cover (0 to 10)** |
|---|---|---|---|---|---|
| 3001 | 20.2 | 0.52 | 3.0 | NNE/NE | 8.4 |
| 3031 | 24.8 | 0.44 | 1.5 | SW/WSW | 8.0 |
| 3032 | 25.5 | 0.32 | 3.0 | SW | 5.3 |
| 3033 | 22.8 | 0.68 | 2.8 | ENE/E | 7.8 |
| 3034 | 22.1 | 0.34 | 1.9 | ESE | 8.3 |
| 3035 | 25.6 | 0.39 | 2.5 | WSW | 5.2 |
| 3036 | 21.4 | 0.17 | 3.8 | WNW/NW | 4.0 |
| 3037 | 23.7 | 0.34 | 2.7 | NNW | 3.4 |
| 3038 | 22.3 | 0.10 | 1.5 | variable | 3.0 |

**Table 4** Meteorological conditions for the synoptic types, where temperature is measured in Celsius, precipitation in inches, wind speed in meters per second, and cloud cover on a scale from 0 to 10, from no clouds to an overcast sky.

From the meteorological characteristics alone, one would expect the Overhead High and Southwest Flow to favor higher pollution concentrations. The Overhead High is associated with low wind speeds, little cloud cover, and low precipitation rates, however the winds are variable, which disperse pollutants. The Southwest Flow also has low wind speed, a favorable wind direction from the southwest and higher average temperatures. Other types such as the New England High would be expected to be associated with lower pollution concentrations as the average temperatures are low, average precipitation is around one half of an inch, wind speeds are stronger than most other types and from the North, and cloud cover is considerable. Similar conditions experienced during the New England Low could be expected to have lower pollution concentrations, as temperatures are again low and winds are stronger and from the North.

**4.1 Ozone and synoptic climatology**

Average ozone concentrations were calculated for each synoptic type, seen in Figure 4. By comparing the average ozone concentrations of each synoptic type the entirety of the study period is represented as a single value, with the range of values expressed as a boxplot (Figure 4). The concentrations under the Southwest Flow 3032 and Hudson's Bay Low 3035 synoptic types are the greatest on average, with the Overhead High condition also recording high concentrations. The average ozone concentrations associated with the Southwest Flow 3032 and Hudson's Bay Low 3035 reach into the range of 0.070 ppm, which is a range that is unhealthy, labeled in the AQI system as being 'Unhealthy for Sensitive Groups'. During the Southwest Flow 3032 type, warm air is brought to the area from a Bermuda High, providing the heat necessary to transform primary pollutants into ozone. Pollutants are then carried into the PCW region from the Ohio Valley by the prevailing southwest winds. With the Hudson's Bay Low 3035 a low pressure system resides over the Hudson Bay. Low pressure systems have lower atmospheric pressure at the center, with rising air and water vapor that condenses to form clouds, which in turn precipitate out. Prior to the passage of the cold front associated with the Hudson's Bay Low, the winds are from the south-southwest, providing warm air; cloud cover builds as the front moves into the region. The general wind direction and warm air seen with the Hudson's Bay Low prior to the passage of the cold front promotes the creation of ozone. With an Overhead High, wind speeds are low, cloudiness is minimal, and precipitation is light, promoting the production of ozone. While the winds for an Overhead High are variable, the meteorological conditions act as catalysts for ozone production, perhaps a local pollution source rather than a distant source. The conditions under these three synoptic types promote the development of ozone.

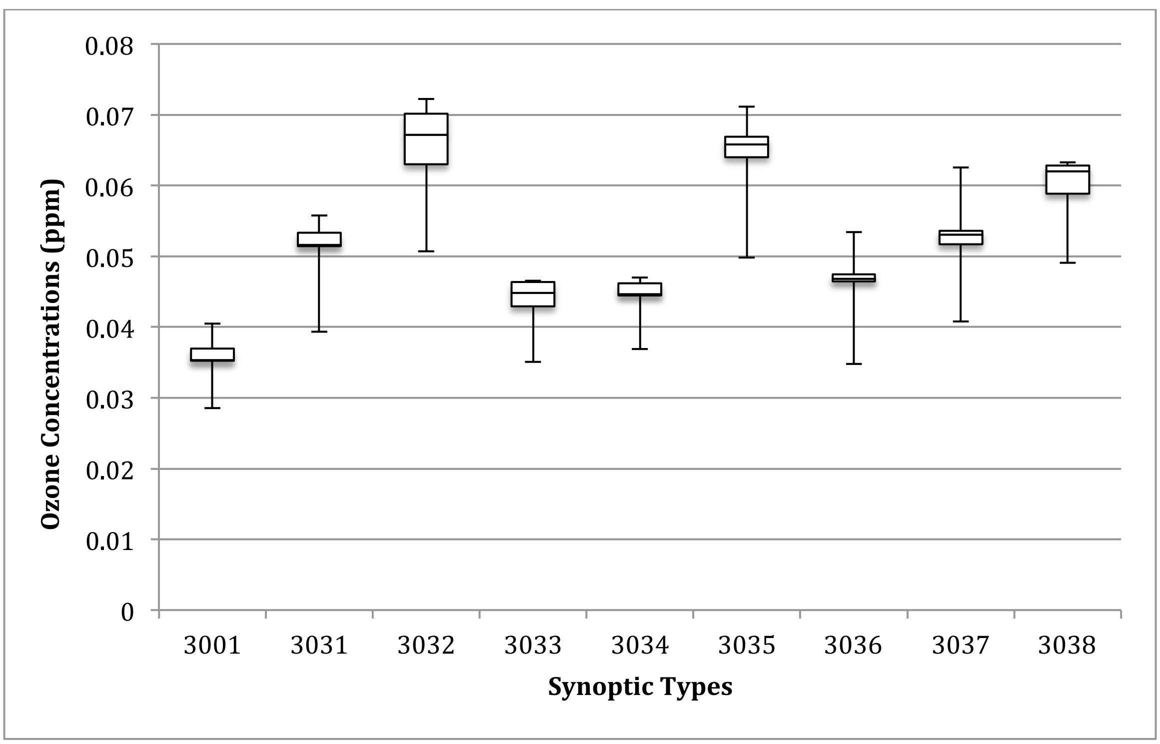


**Figure 4** Boxplots of average ozone concentrations for each synoptic type

While the Southwest Flow 3032 and Hudson's Bay Low 3035 are associated with the highest average ozone concentrations (Figure 4), the New England High 3001 by contrast is associated with low average ozone concentrations. During the New England High 3001 easterly winds are transported to the region. As the PCW region is on the east coast of the United States, easterly winds originate from the Atlantic Ocean where the air is cleaner (Mulcahy et al 2009) than continental air originating from the west of the PCW region. Clean marine air from the east has little interaction with pollution sources, thus resulting in average ozone concentrations that are lower than those associated with other synoptic types, ozone concentrations are firmly within the 'Good' AQI Level. Figure 5 displays the frequencies of occurrence for each synoptic type, with the Weak pattern 3031, Southwest Flow 3032, and Hudson's Bay low 3035 occurring with the greatest frequency during the period. By contrast the New England High 3001 occurred rather infrequently, only 49 times during the 28 year period, generally once or twice a year, though some years it never occurred. The frequency for the other synoptic types, Weak Southwest flow 3033, Off-shore High 3034, New England Low 3036, North-Northwest Flow 3037 and Overhead High 3038 remained consistent (Figure 5) during the study period. Knowing the occurrence for each synoptic type during the study period is an important factor for pollution forecasting, as the New England High and New England Low occur infrequently and are in turn associated with lower ozone concentrations.

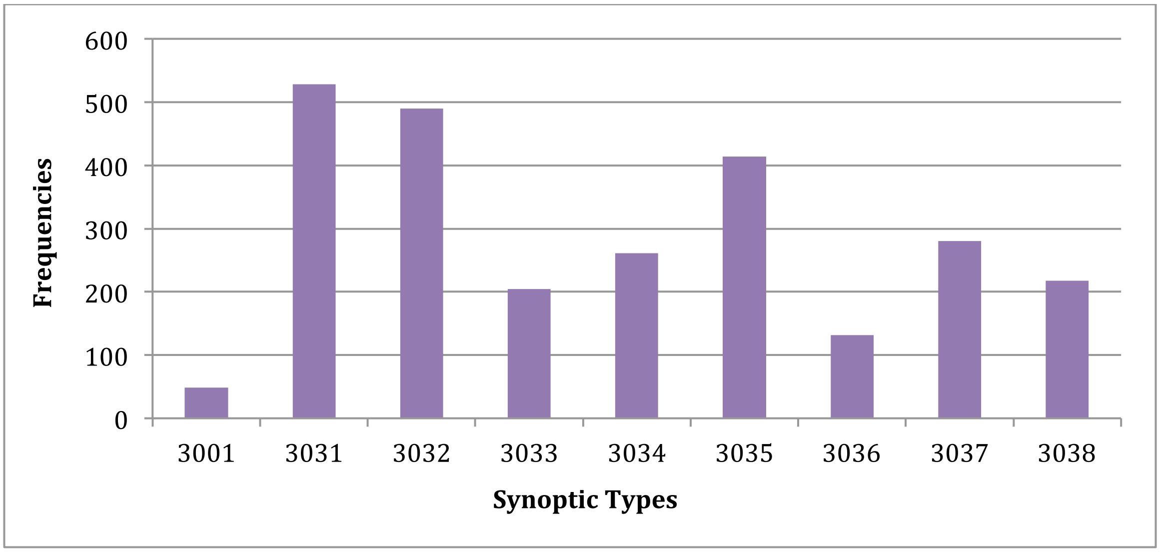


**Figure 5** Number of days when each synoptic type occurred during the period 1990 to 2017.

By understanding the relationship that exists between synoptic climatology and ozone further use can be applied towards forecasting methods for poor air quality days. An ozone concentration of 0.07 ppm or greater is classified as being 'Unhealthy for Sensitive Groups', the dates which had an ozone concentration 0.07 ppm or greater were referred to as a poor air quality day. The frequencies of poor quality days for ozone under each synoptic type are listed in Table 5. Similar to those findings in Figure 4 that show the average ozone concentrations for the Southwest Flow 3032 and Hudson's Bay Low 3035 are the highest, the frequency of poor air quality days in Table 5 are also the highest for those two synoptic types, with the Weak Pattern also responsible for many poor air quality days. It is thereby no coincidence that, seen in Figure 5, the Weak Pattern 3031, Southwest Flow 3032 and Hudson's Bay Low 3035 also occur the most frequently and are associated with the highest number of poor air quality days. While warm air from the south associated with the Southwest Flow type is a requirement for ozone production, the results in Table 5 and Figure 4 do not conclusively state any of the three aforementioned types are prime for high ozone concentrations. One possible explanation for this lies in the frequencies of occurrence for the three synoptic types. The Weak Pattern, Southwest Flow, and Hudson's Bay Low occur with greater frequency during the study period (Figure 5), and in turn are associated with the most poor air quality days (Table 5).

| **Days greater than .07 ppm** | | |
|---|---|---|
| **Synoptic Type** | **Number of poor air quality days** | **Percent** |
| 3001 New England High | 0 | 0.00 |
| 3031 Weak Pattern | 132 | 14.51 |
| 3032 Southwest Flow | 297 | 32.64 |
| 3033 Weak Southwest Flow | 31 | 3.41 |
| 3034 Offshore High | 29 | 3.19 |
| 3035 Hudson's Bay Low, Frontal | 224 | 24.62 |
| 3036 New England Low | 11 | 1.21 |
| 3037 North-Northwest Flow | 93 | 10.22 |
| 3038 Overhead High | 93 | 10.22 |
| **Total of bad air quality days** | **910** | |

**Table 5** Count of days where the ozone concentration was 0.07 ppm or greater, denoting a bad air quality day for the summer months of June, July, August from 1990 to 2017.

To understand the strength of the relationship between synoptic types and ozone concentrations, correlation tests were run, where correlation coefficients for the number of days when ozone concentrations were 0.07 ppm or greater per year occurred (Table 6). The positive values, such as those for Southwest Flow 3032, Weak Southwest Flow 3033, Hudson's Bay Low 3035, North-Northwest Flow 3037, and Overhead High 3038 are all measures of a positive correlation between the two variables. A positive correlation between synoptic type and ozone concentration suggests that a relationship does indeed exist when the values are positive. Only the Southwest Flow 3032, North-Northwest Flow 3037, and Overhead High 3038 synoptic types have a significant positive relationship with high ozone. With correlation values suggesting that a relationship exists between the Southwest Flow 3032, Weak Southwest Flow 3033, Hudson's Bay Low 3035, North-Northwest Flow 3037, and Overhead High 3038 and high ozone, future statistical tests can more completely explain the effectiveness of a forecasting tool with these five synoptic types in particular. As the other four synoptic types express a negative correlation with high ozone, a forecasting tool would do best to explain the potential for cleaner air in the PCW region during those four types.

| | 3001 | 3031 | 3032 | 3033 | 3034 | 3035 | 3036 | 3037 | 3038 |
|---|---|---|---|---|---|---|---|---|---|
| High $O_3$ | **-0.40** | **-0.69** | **0.64** | 0.23 | -0.22 | 0.08 | -0.22 | **0.43** | **0.50** |

**Table 6** Correlation matrix for the frequencies of synoptic types and the frequencies of high ozone days. The correlation between synoptic types and ozone concentrations is significant at $p = 0.05$, with a critical value of 0.37. Values greater than 0.37 are of significance and displayed in bold.

Negative correlation values exist during the New England High 3001 where the winds are easterly and clean marine air masses. Cleaner marine air masses transport fewer pollutants to the region, providing fewer opportunities for high ozone concentrations and the subsequent poor air quality days to occur. The Weak pattern has a relatively strong negative correlation with high ozone days. This weak pattern occurred 528 times during the study period, of those 528 days, 25%, or 132 days were associated with poor air quality. A negative correlation between synoptic types and frequency of high ozone days follows that as the frequency of the 3031 Weak Pattern increases, the frequency of high ozone days will decrease. Negative correlation between the Offshore High 3034 and high ozone is weak, where high ozone concentrations occurred only 29 times during these conditions. Although pollution concentrations are generally higher during high pressure systems, I posit that the correlation between the Offshore High 3034 and ozone levels is due to the proximity of the high pressure system to the PCW region. An offshore high farther from the east coast may have less of an affect on pollutant concentrations. Low pressure systems such as the New England Low 3036 are associated with precipitation events which will cleanse the air and dilute the pollutants.

Running a regression model between synoptic types and ozone concentrations assesses the potential of a forecasting tool using TSI criteria. Multiple R produces the same output as a correlation coefficient test. The associated correlation coefficients for each synoptic type can be found above, in table 6. The $R^2$ values for every synoptic type are small, ranging from 6.47 e-3 for Hudson's Bay Low 3035 to 0.47 for the Weak Pattern 3031. Small $R^2$ values such as these provide a lack of confidence for the fit of data around a regression line. With small $R^2$ values the likely success for a forecasting tool is questionable. However, the results of significance F prove that half of the synoptic type regression models are statistically significant, with values less than 0.05. The New England High 3001 (0.033), Weak Pattern 3031 (5.53 e-5), Southwest Flow 3032 (2.5 e -4), North-Northwest Flow 3037 (0.0217), and Overhead High 3038 (6.18 e -3) are all statistically significant. The remaining synoptic types have significance F's that are greater than 0.05, where the results are not dependable. Finally, the sum of squares (SS) value is important when the residual SS is smaller than the total SS, as is the case with two of the synoptic types, 3031 and 3032 (Table 7). The residual is the sum of squares error, which is the difference between the observed value and the predicted value; the error here should be small, which would better explain the power of the regression.

| | **3031** | **3032** |
|---|---|---|
| **Sum of Squares Residual** | 678.94 | 278.71 |
| **Sum of Squares Total** | 1283.43 | 471 |
| **$R^2$** | 0.47 | 0.41 |

**Table 7** Regression results for 3031 and 3032

$R^2$ values from the regression model explain a lack of confidence in using synoptic types to predict high ozone events. However, significance F results from a regression model prove that when values are less than 0.05 a relationship between variables is statistically significant, which is the case for the New England High 3001, Weak Pattern 3031, Southwest Flow 3032, North-Northwest Flow 3037, and Overhead High 3038. With statistically significant values for the above synoptic types, the regression model better fits the data. Therefore, a forecasting tool would provide optimal results under the synoptic types New England High 3001, Weak Pattern 3031, Southwest Flow 3032, North-Northwest Flow 3037, and Overhead High 3038.

Ozone concentration amounts were also analyzed by their spatial distribution, and a representation of the ozone concentrations at each monitoring site for the study period is seen in Figure 6, with most locations recording similar amounts. The boxplots show the rather homogenous distribution of ozone concentrations across the region. Concentrations at each location have medians that are in a healthy range, not reaching past 0.06 ppm and potentially into unhealthy air quality when 0.07 ppm is reached.

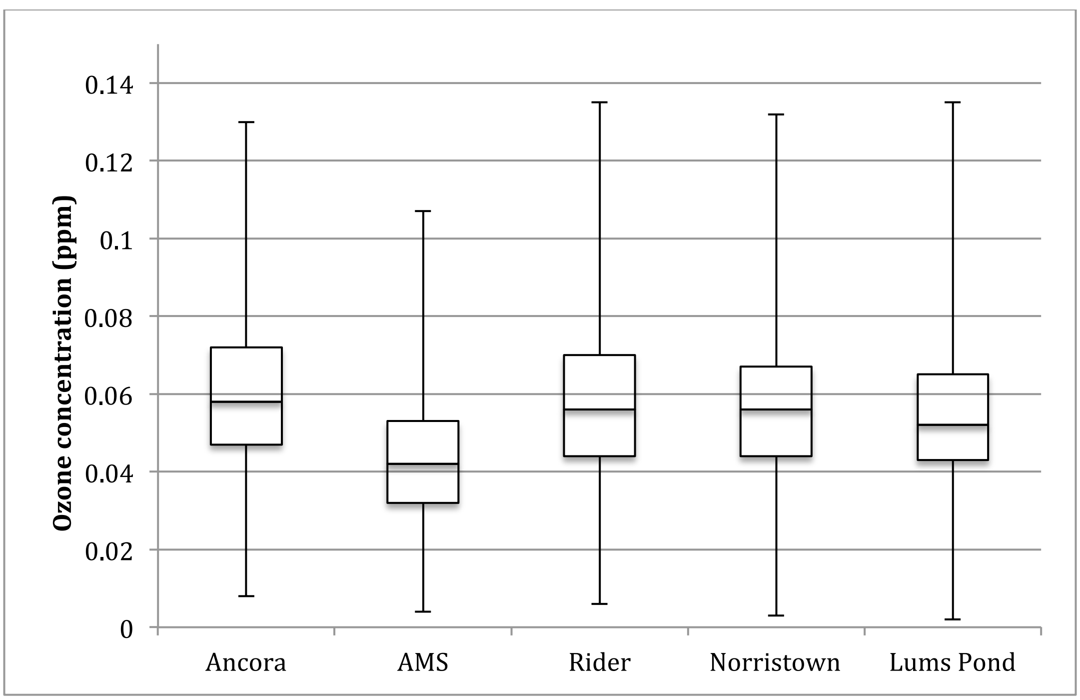

**Figure 6** Boxplots of the ozone concentrations at each of the monitoring sites. AMS is the Air Management Services location in Center City, Philadelphia, Pennsylvania.

It can be noted that the Air Management Services (AMS) location records concentrations that are lower than the other monitoring sites. The AMS monitoring station is in the Juniata section of Philadelphia, to the northeast of Center City Philadelphia. The spatial scale of this monitoring site is 'neighborhood' (City of Philadelphia 2018), where the location is "within some extended area of the city that has relatively uniform land use with dimensions in the 0.5 to 4.0 kilometers range", residential row homes are the common land use type around the monitoring site. As the objective for the AMS monitoring site is to monitor population exposure, the range of the monitor extends 0.5 to 4.0 kilometers. The AMS location likely records lower concentrations than those monitors at the suburban locations because the precursors for ozone formation are more strongly emitted in cities and transported over suburban areas, though not uniformly so, providing the time required to transform into ozone.

The chemical reaction necessary in the production of ozone, between nitric oxide (NO) and sunlight, is the same chemical reaction that scavenges ozone (Wallace and Hobbs 2006, Sharma et al 2016, irCELine 2019); urban locales have greater abundance of nitric oxides, providing more opportunities to produce yet destruct ozone. Provided that nitric oxide concentrations are greatest in urban areas, more frequent ozone scavenging is thought to occur in those locations. Due to the lowered nitric oxide concentrations typically found in rural areas, ozone scavenging by NO is less frequent, leading to greater ozone concentrations in rural areas. Future work is needed here to understand the nitric oxide precursors that exist in and around the AMS location that contribute to lower ozone concentrations.

In Figure 7 the average ozone concentrations at each location are displayed, further categorized into the nine synoptic types. Here, the spatial distribution of ozone can be explained alongside synoptic types. The average ozone concentrations are homogenous, however when synoptic types are introduced, differences in concentrations emerge. The Southwest Flow 3032 relates to higher average ozone concentration amounts, regardless of spatial distribution. The New England High 3001 records lower average ozone concentrations also regardless of geographic location. The noticeable spatial difference is with the Air Management Services Laboratory location, as mentioned above in Figure 6, where concentrations for all synoptic types are less than concentrations for the other locations. When clustered by monitoring site and synoptic type, fewer variations exist based on synoptic type alone, as the same types, Southwest Flow 3032, Hudson's Bay Low 3035 and Overhead High 3038, record the highest average ozone concentrations regardless of location.

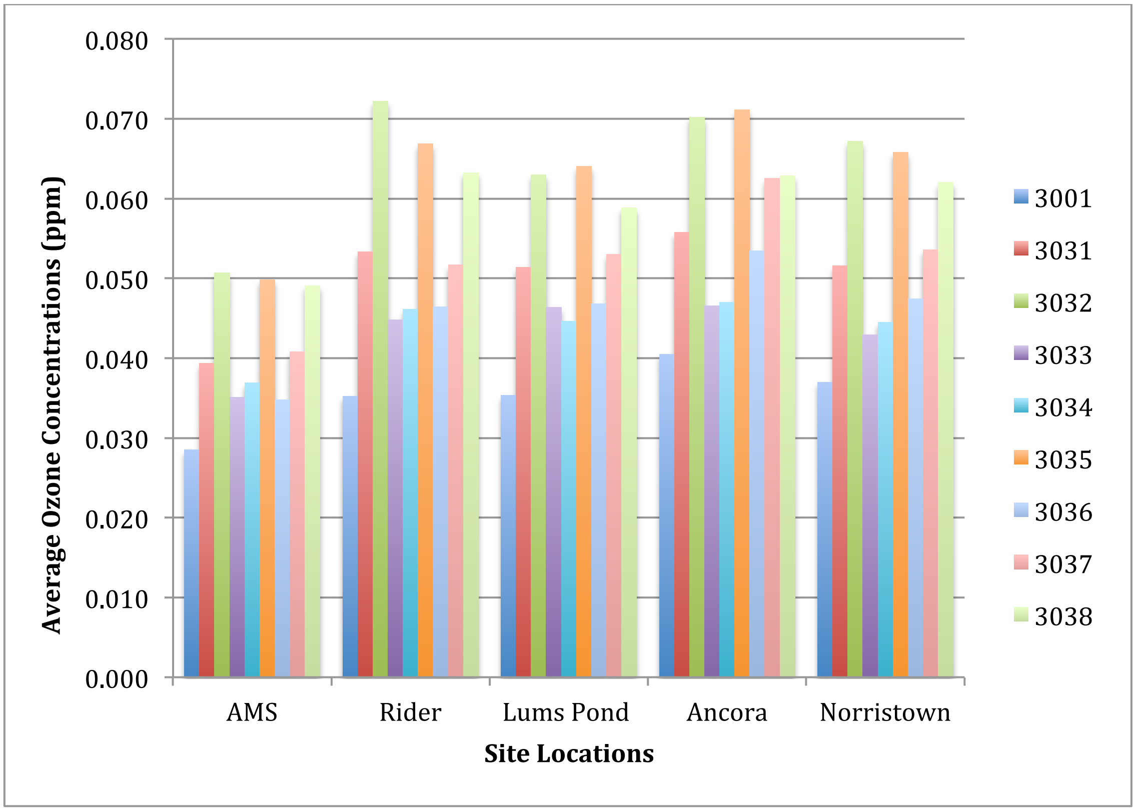


**Figure 7** Average ozone concentrations at each monitoring site, grouped by synoptic type

The variance of the ozone concentrations at each location (Figure 8) appears similar to the ozone concentrations, where Rider and Ancora both experienced high concentrations during the Southwest Flow 3032 synoptic type. As the variance explains how spread the data sets are, greater variability exists at Ancora and Rider and for Southwest Flow 3032 and Hudson's Bay Low 3035. Both synoptic types are associated with warm air advecting into the region, which supports the production of high ozone concentrations. As noted earlier during the discussion of correlation and regression between synoptic types and ozone, the strength of the relationship is positive but at times weak. It is only during the Southwest Flow 3032 that the relationship between synoptic climatology and air pollution is moderately strong, at 0.64, as values closer to +1 are considered strongly positively correlated. It is during the Southwest Flow that a greater chance exists of high ozone and poor air quality. While it is probable that poor air quality will occur during the Southwest Flow 3032 and Hudson's Bay Low 3035, this study cannot say with absolute certainty that under every Southwest Flow 3032 or Hudson's Bay Low 3035 condition a poor air quality day will be experienced.

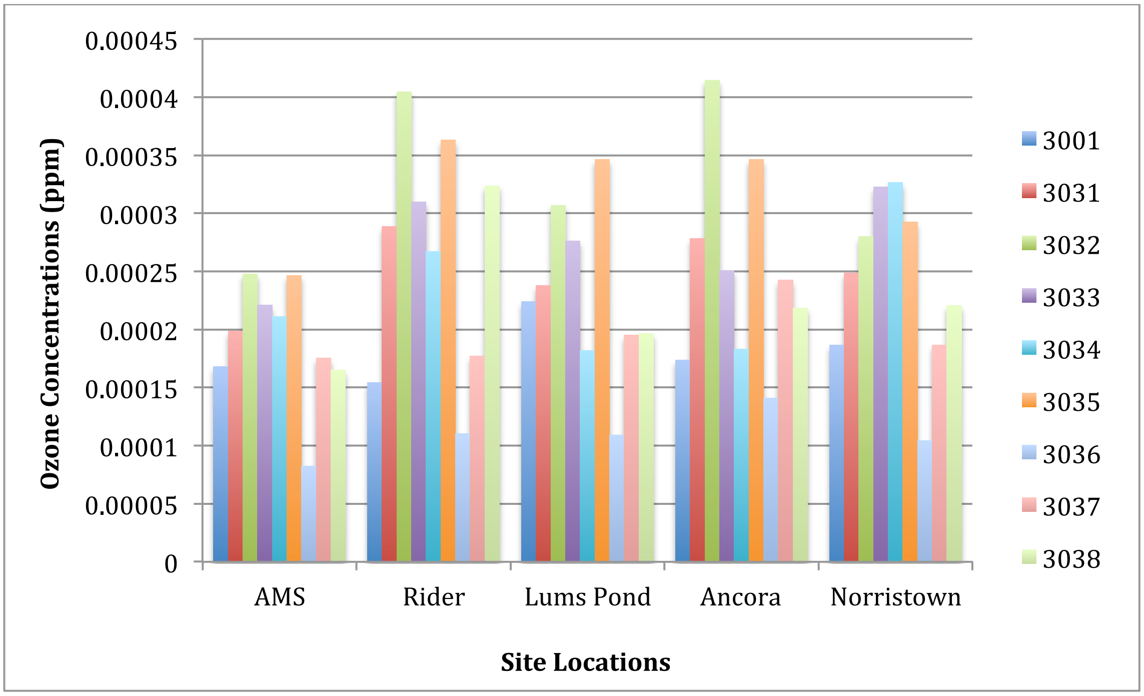


**Figure 8** Variance of ozone concentrations at each monitoring site, grouped by synoptic type

To better understand this relationship, a multi-day analysis during poor air quality events should be done to assess the strength of correlation and ability of forecasting. Knowledge of the synoptic typing prior to a high ozone episode would greatly assist the air quality managers and forecasters in predicting the next several days' air quality.

### 4.2 PM 2.5 and synoptic climatology

Average PM 2.5 concentrations were evaluated for all nine synoptic types (Figure 9). The Southwest Flow 3032 and Hudson's Bay Low 3035 synoptic types show the greatest average PM 2.5 concentrations, with the Weak Pattern also corresponding to higher average PM 2.5 concentrations. During the Southwest Flow 3032 type, warm air advects into the area, providing the heat necessary to transform primary pollutants into PM 2.5. With the Hudson's Bay Low 3035 a low pressure system resides over the Hudson Bay. Low pressure systems have lower atmospheric pressure at the center, with rising air and water vapor that condenses to form clouds, which in turn precipitate out. Prior to the passage of a cold front the winds are from the south-southwest, providing warm air, cloud cover builds as the front moves into the region. With the Weak Pattern air mass thunderstorms are likely, this is a common summer time pattern. In contrast, the New England High and New England Low are associated with the lowest average PM 2.5 concentrations. During either of these types winds are from the north.

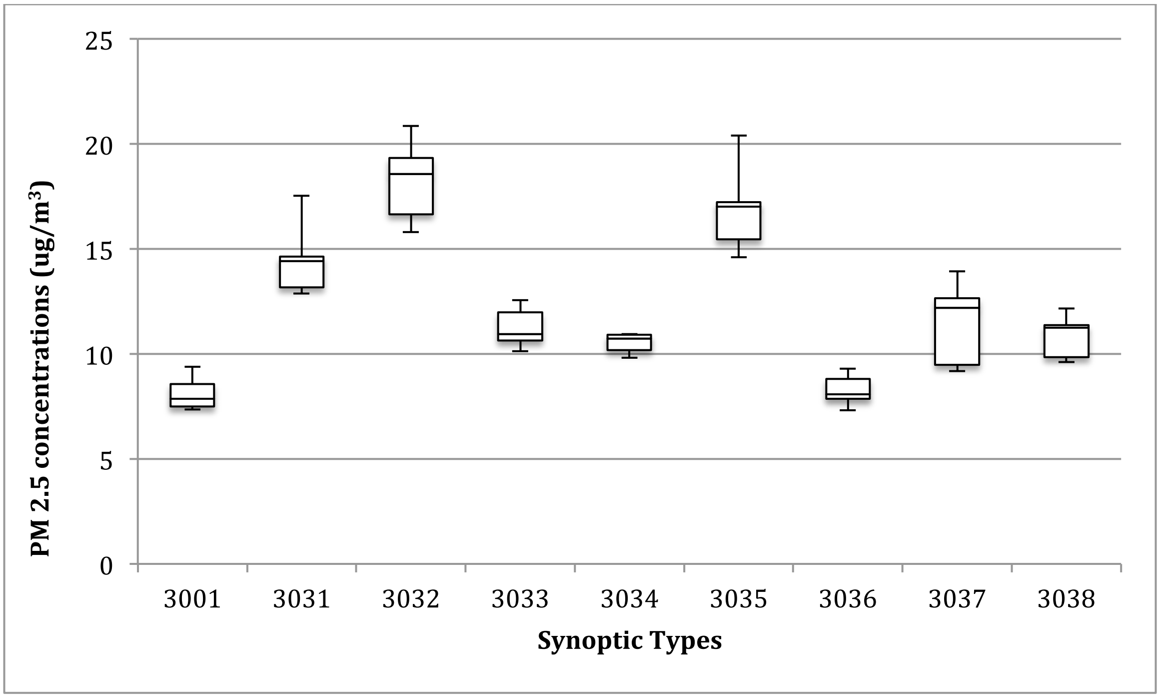


**Figure 9** Boxplots of average PM 2.5 concentrations for each synoptic type

A PM 2.5 concentration of 35.4 ug/m$^3$ or greater is classified as being 'Unhealthy for Sensitive Groups', the dates which had PM 2.5 concentrations of 35.4 ug/m$^3$ or greater are referred to as a poor air quality day. The frequencies of poor quality days for PM 2.5 during each synoptic type are listed in Table 7. Similar to those findings in Figure 9 that show the average PM 2.5 concentrations for the Southwest Flow 3032 and Hudson's Bay Low 3035 are the highest, the frequency of poor air quality days in Table 7 are also the highest for those two synoptic types, with the Weak Pattern also responsible for many poor air quality days. Frequencies of occurrence for the three synoptic types might explain the frequencies with which the Weak Pattern, Southwest Flow, and Hudson's Bay Low occur under poor air quality days. Lower average PM 2.5 concentrations, as seen in the New England High 3001 and New England Low 3036, may also be attributed to less frequency of occurrence overall during the study period. The conditions during the

Southwest Flow 3032, with associated warm temperatures, and the Hudson's Bay Low 3035, with warm air prior to the frontal passage, are prime for high PM 2.5 concentrations and a greater amount of poor air quality days. A correlation analysis and regression were performed to ascertain a relationship between synoptic types and air quality.

| **Days greater than 35.4 ug/m$^3$** | | |
|---|---|---|
| **Synoptic Type** | **Number of poor air quality days** | **Percent** |
| 3001 New England High | 1 | 1.25 |
| 3031 Weak Pattern | 22 | 27.5 |
| 3032 Southwest Flow | 20 | 25 |
| 3033 Weak Southwest Flow | 2 | 2.5 |
| 3034 Offshore High | 3 | 3.75 |
| 3035 Hudson's Bay Low, Frontal | 25 | 31.25 |
| 3036 New England Low | 3 | 3.75 |
| 3037 North-Northwest Flow | 3 | 3.75 |
| 3038 Overhead High | 1 | 1.25 |
| **Total of bad air quality days** | **80** | |

**Table 8** Count of days where the PM 2.5 concentration was 35.4 ug/m$^3$ or greater, denoting a bad air quality day for the summer months of June, July, August from 1990 to 2017.

To understand the strength of the relationship between synoptic types and PM 2.5 concentrations correlation tests were run, with correlation coefficients for the number of days when PM 2.5 concentrations were 35.4 ug/$m^3$ or greater per year generated (Table 8). Only with Southwest Flow 3032 does a relationship with PM 2.5 exist (Table 8), with a positive correlation value of 0.66. A positive correlation between synoptic type and PM 2.5 concentration suggests that a relationship does indeed exist when the values are positive. With a correlation value suggesting that a relationship exists between the Southwest Flow 3032 and high PM 2.5 concentrations, future statistical tests can more completely explain the effectiveness of a forecasting tool with this one synoptic type. As the other synoptic types express a negative correlation with high PM 2.5 concentrations, a forecasting tool would do best to explain the potential for cleaner air in the PCW region during those four types.

| | 3001 | 3031 | 3032 | 3033 | 3034 | 3035 | 3036 | 3037 | 3038 |
|---|---|---|---|---|---|---|---|---|---|
| High PM 2.5 | -0.29 | -0.47 | **0.66** | 0.10 | 0.11 | -0.25 | 0.07 | 0.21 | 0.30 |

**Table 9** Correlation matrix for the frequencies of synoptic types and the frequencies of high PM 2.5 days. The correlation between synoptic types and PM 2.5 concentrations is significant at $p = 0.05$, with a critical value of 0.48. Values of significance are displayed in bold.

Running a regression model between synoptic types and PM 2.5 concentrations will assess the potential of a forecasting tool. Multiple R produces the same output as a correlation coefficient test. The associated correlation coefficients for each synoptic type can be found above, in table 8. The $R^2$ values are very small. The range of $R^2$ values is such: New England Low 3036 has an associated $R^2$ value of 0.005, Southwest Flow has an $R^2$ value of 0.44. All values within this range provide no confidence that the data fits the regression line, providing no goodness of fit. With small $R^2$ values the likely success for a forecasting tool is questionable. With significance F, the value for only one synoptic type – Southwest Flow 3032, is statistically significant, at 0.0037. The remaining synoptic types have significance F's that are greater than 0.05, where the results are not dependable. Due to the lack of statistical significance for the regression analysis with synoptic types and PM 2.5, I postulate that different variables would be better suited to explain the complex relationship between climatology and air quality. Perhaps individual meteorological variables such as air temperature or wind speed and wind direction would better represent the relationship, with larger agreement between the variables. Finally, the sum of squares value is important when the residual SS is smaller than the total SS, as is the case with two of the synoptic types, 3031 and 3032 (Table 9). The residual is the sum of squares error, which is the difference between the observed value and the predicted value; the error here should be small, which would better explain the power of the regression.

| | **3031** | **3032** |
|---|---|---|
| **Sum of Squares Residual** | 551.55 | 137.51 |
| **Sum of Squares Total** | 706.47 | 245.53 |
| **$R^2$** | 0.22 | 0.44 |

**Table 10** Sum of square values for 3031 and 3032

PM 2.5 concentration amounts were also analyzed by spatial distribution, a representation of the PM 2.5 concentrations at each monitoring site for the study period is seen in Figure 10. A lack of spatial difference is identified, as all of the locations record similar amounts. Each boxplot shows a large distribution in the upper whiskers, extending from a healthy range to a largely unhealthy concentration range. The highest observed values for each location are excessive, with Lums Pond having a higher concentration than at the other sites. Lums Pond may record the highest PM 2.5 concentrations from single events where greater amounts of PM 2.5 are released. The Lums Pond location being the most southern location in this study records PM 2.5 transport from the Baltimore and Washington, D.C. region, with its high rates of vehicle traffic influencing PM 2.5 concentrations. Outside of the highest value, little variability between the locations is seen, as the average concentrations for each location are fairly consistent. It is when the concentrations are further distinguished between synoptic types where differences are seen, where the average PM 2.5 concentrations are highest under Southwest Flow 3032 and Hudson's Bay Low 3035 (Figure 11). When clustered by monitoring site and synoptic type, fewer variations exist based on synoptic type alone, as the same types, Southwest Flow 3032 and Hudson's Bay Low 3035 record the highest average ozone concentrations regardless of location, the average concentrations are also high under the Weak Pattern.

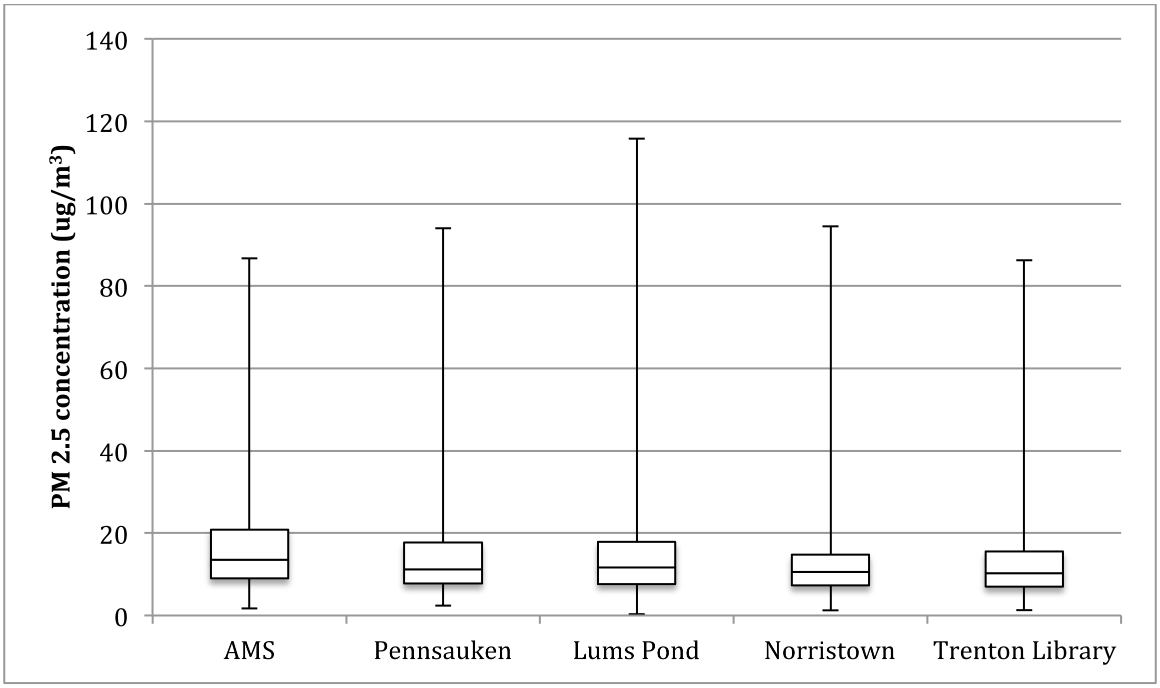


**Figure 10** Boxplots of the PM 2.5 concentrations at each of the monitoring sites


**Figure 11** Average PM 2.5 concentrations at each monitoring site, grouped by synoptic type

The variance of the PM 2.5 concentrations at each location (Figure 12) appears similar to the PM 2.5 concentrations, where Lums Pond experiences high concentrations during the North-Northwest Flow 3037, with concentrations also attributed by the transport of local pollutants from the Baltimore-Washington, D.C and PCW region; Pennsauken also experiences greater variance in concentrations under the North-Northwest Flow 3037 pattern. Here, the variance can be understood as how spread the data sets are, where greater variability exists at the locations that records higher concentrations. The North-Northwest Flow is weak flow with a less intense pressure gradient presiding over the region. This weak flow might aid in the retention of pollutants over the region, dampening the dispersion potential of PM 2.5. Larger variance explains a greater spread in pollutant concentrations, as seen earlier in Figure 10 where the highest PM 2.5 concentration was recorded in Lums Pond.

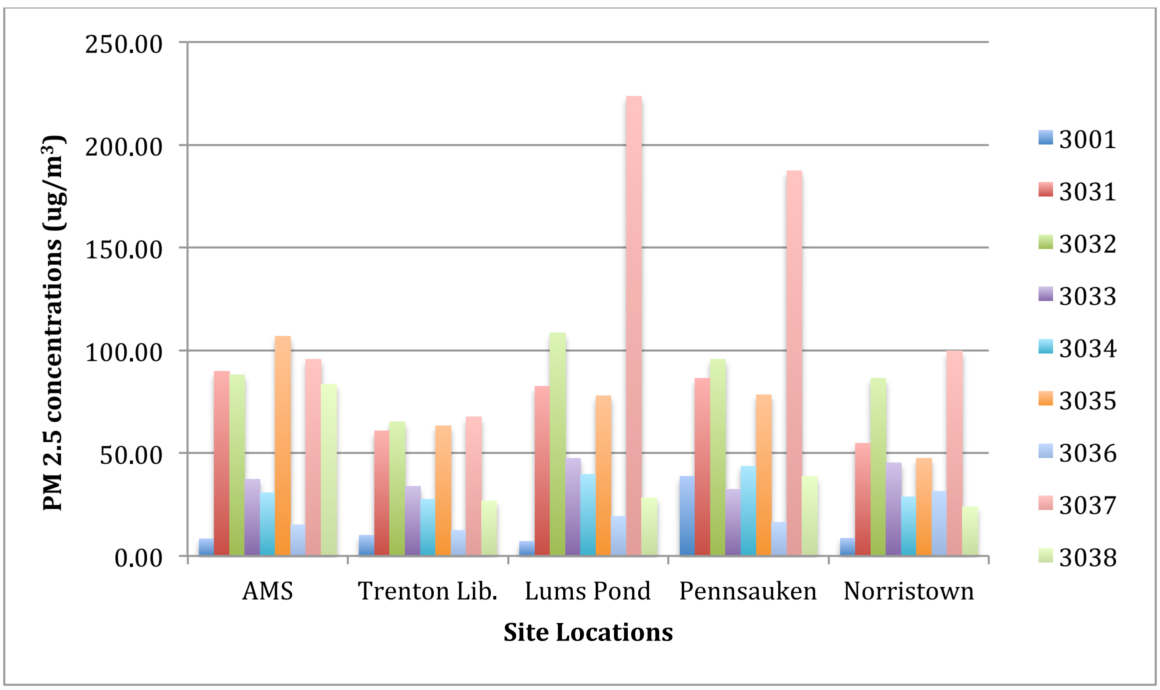

**Figure 12** Variance of PM 2.5 concentrations at each monitoring site, grouped by synoptic type

As noted earlier during the discussion of correlation and regression between synoptic types and PM 2.5, the strength of the relationship is positive but at times weak. It is only during the Southwest Flow 3032 that the relationship between synoptic climatology and air pollution is moderately strong, at 0.66. It is during the Southwest Flow that a greater chance exists of high PM 2.5 and poor air quality. While it is probable that poor air quality will occur during the Southwest Flow 3032, this study cannot say with absolute certainty that under every Southwest Flow 3032 condition a poor air quality day will be experienced.

**4.3 Comparing ozone and PM 2.5**

Throughout the 28-year study period the frequencies of every synoptic type has varied (Figure 13). The New England High 3001 did not occur at times, though the frequency was consistent throughout, only occurring once or twice a year. In contrast, the Weak Pattern 3031, Southwest Flow 3032, and Hudson's Bay Low 3035 occurred with the most frequency during the 28-year period. In Figure 13 the frequency for Weak Pattern 3031 increases during the study period, Southwest Flow 3032 frequency stays rather high throughout, and Hudson's Bay Low has the greatest frequency during 2008. Changes in frequency might have an effect on the frequencies of high pollution episodes, especially for the Southwest Flow 3032, as a greater correlation exists for that synoptic type and for each pollutant.

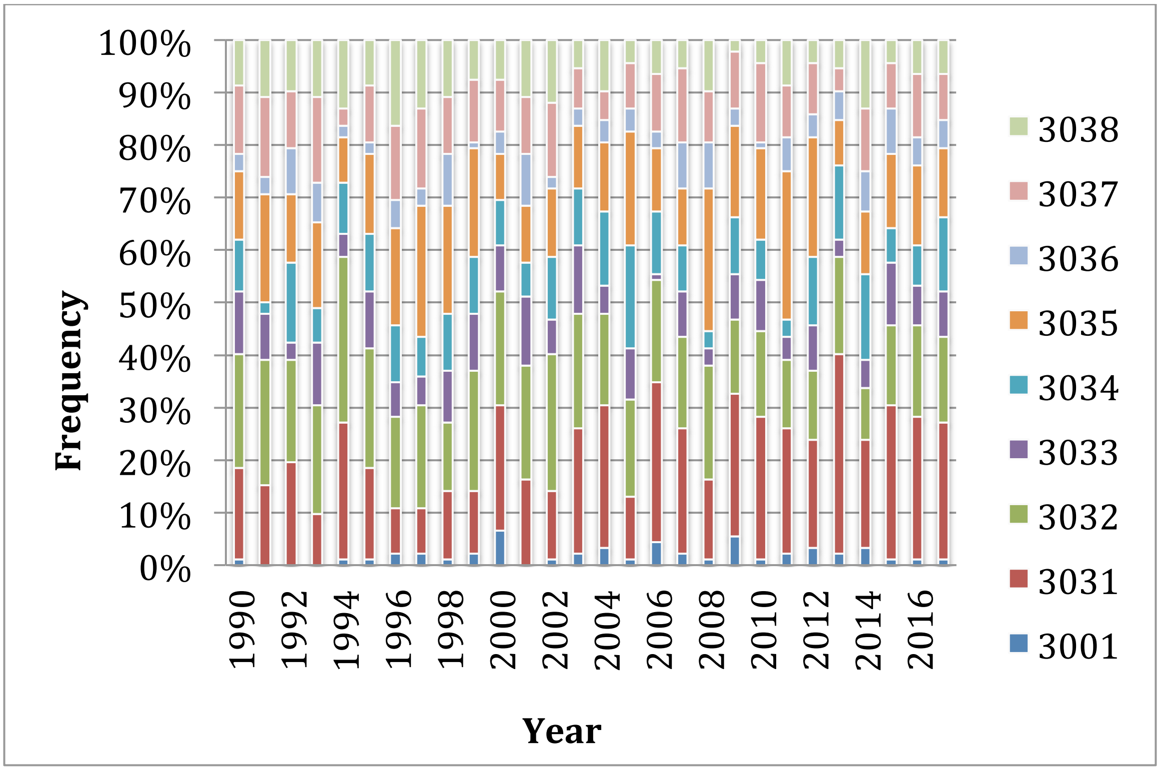


**Figure 13** Percentages of occurrence for each synoptic type during the study period 1990 to 2017.

For both pollutants, the highest concentrations are found with the Southwest Flow 3032 and Hudson's Bay Low 3035 TSIs. The number of poor air quality days differed between the two types, where ozone experienced more poor air quality days during June July and August from 1990 to 2017. Differences in the frequency of poor air quality days could be attributed to the lack of seasonality that exists with PM 2.5, and with ozone concentrations being greatest during the summer months. Consistency of the synoptic types that were present during the poor air quality days for each pollutant was evident, with the Weak Pattern 3031, Southwest Flow 3032, and Hudson's Bay Low 3035 recording the highest frequency of poor air quality days. In contrast, for both ozone and PM 2.5 the New England High 3001 is associated with low average concentrations.

Positive correlations between synoptic types and pollutants are similar under the Southwest Flow 3032, Weak Southwest Flow 3033, North-Northwest Flow 3037, and Overhead High 3038. Unlike with ozone where the synoptic types New England High 3001, Weak Pattern 3031, Southwest Flow 3032, North-Northwest Flow 3037 and Overhead High 3038 are significantly correlated, only Southwest Flow 3032 is significantly correlated with PM 2.5.

The correlation coefficient that explains the relationship between ozone and PM 2.5 is 0.73, this positive value measures a strong positive correlation between ozone and PM 2.5. A strong positive correlation value between ozone and PM 2.5 signifies a strong relationship between the two pollutants, wherein as one pollutant increases the other would expect to increase as well. Due to their strong positive relationship and the significant correlation that both pollutants have to the Southwest Flow 3032 pattern, it could be forecasted that ozone and PM 2.5 will both have high concentrations during Southwest Flow 3032. Since a positive correlation value exists for Southwest Flow 3032, Weak Southwest Flow 3033, North-Northwest Flow 3037 and Overhead High 3038 and both ozone and PM 2.5, forecasting based on these synoptic types could also be done, although low regression scores create concern regarding the usefulness of statistical forecasting methods.

Figure 14 shows that poor air quality days of ozone and PM 2.5 decrease in frequency around 2008. Following 2008, PM 2.5 no longer achieves elevated concentrations, and the frequency for ozone decreases, though the latter rises again in 2010. Following the

2012 season rates of poor air quality significantly drop off. In 1997, 2008 and 2015 the National Ambient Air Quality Standards (NAAQS) for ozone were made more stringent; NAAQS for PM 2.5 were made more stringent in 1997, 2006, and then 2012. While changes to legislation were not taken into consideration in this study and all years were assessed using the current standards, it is possible that the decrease in the frequency of poor air quality days is associated with states' efforts to comply with federally mandated standards. Federally mandated standards for pollutants are strengthened upon further scientific evidence of effects on human and environmental health. As standards are strengthened, the aim is to improve the quality of the air, and when comparing the study period to the tight current standards, a decrease in number of poor air quality days is seen.

Poor air quality days may vary throughout the study period because of larger meteorological and climatological patterns. Introducing atmospheric teleconnection data, as teleconnections influence temperature and rainfall, could aid in the discussion for fluctuations in pollutant concentrations during the study period. As teleconnections are large scale atmospheric events, and air quality to the PCW region is dependent on the transport of pollutants from the Ohio Valley and southern regions, climate variability that impacts regions outside of this study region could in turn impact the atmospheric conditions that are brought to this study site and the associated air quality. Atmospheric teleconnections such as the Atlantic Oscillation, North Atlantic Oscillation, Madden Julian Oscillation, and El Nino and La Nina (ENSO) have the greatest potential to influence the Mid-Atlantic and PCW region.

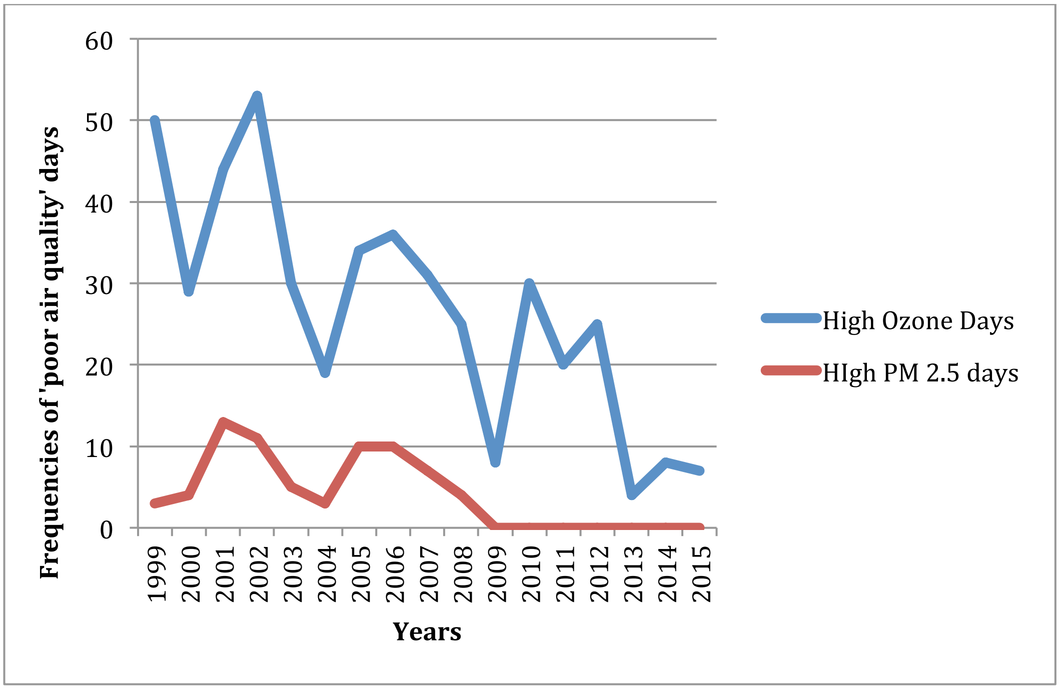


**Figure 14** Frequencies of poor air quality days for both pollutants from 1999-2015.

The frequency for the Southwest Flow 3032 pattern (Figure 13) is evident in the frequencies for ozone and PM 2.5 (Figure 14). The peaks for Southwest Flow 3032 during 1999 to 2015 occur in 2002, 2008 and 2013. The peak in 2002 matches peaks found in ozone and PM 2.5 during that year. The lower frequencies for Southwest Flow 3032 are 2009 and 2014, these match the low frequencies found in both ozone and PM 2.5 for those years. As the Southwest Flow 3032 pattern occurs less frequently in 2009 and 2014, it would be expected that the frequency of poor air quality days for ozone and PM 2.5 also occur less frequently. Additional reasons for the decrease in frequencies of poor air quality days could also be from tighter legislative restrictions on United States emissions or a more efficient use of energy.

**5. Conclusions**

Three synoptic types: 1) Weak flow 3031 pattern, which is associated with air mass thunderstorms that are generally weak, 2) Southwest Flow 3032, a classic Bermuda High, with winds from the southwest, warm and sunny skies and the potential for thunderstorms, and 3) Hudson's Bay Low 3035 with a cold front passage that brings cooler air to the region, with rain likely, are associated with the highest average ozone and PM 2.5 concentrations. These types are associated with the highest average ozone and PM 2.5 concentrations because of the warm air, sunny skies, and weak wind flow patterns that promote the creation of ozone. Related to the Hudson's Bay Low 3035, prior to the passage of the cold front, the winds are from the south-southwest, providing warm air, cloud cover builds as the front moves into the region. The synoptic types associated with the highest average pollution concentration amounts are also the synoptic types with the highest average temperatures.

While warm air from the south associated with the Southwest Flow type is a requirement for ozone production, results do not conclusively state any of the three aforementioned types are prime for high ozone concentrations. The Weak Pattern, Southwest Flow, and Hudson's Bay Low occur with greater frequency during the study period and in turn are associated with the most poor air quality days. While high average ozone and PM 2.5 conditions occur during these types, the three aforementioned types also occur 21%, 19%, and 16% respectively.

The use of a temporal synoptic index to examine air quality during the summer months may not be the best methodology. The relationship between synoptic climatology and pollutants was not robust, with moderate correlation amounts and low regression analysis results for each pollutant. Fewer distinctions between the summer synoptic types were discovered in a meteorological data table. Few differences between the meteorological characteristics of the synoptic types beget difficulties when comparing air quality to synoptic climatology, as little variability exists between types.

With the goal of applying this understanding of a relationship between synoptic climatology and air pollutants towards forecasting air quality, fewer distinctions between synoptic types causes less confidence in the outputs of a forecasting method. The definition of the synoptic types is too broad for forecasting applications. A pattern was clearly discernable with the three synoptic types, however more work is needed to precisely assess the relationships.

To understand the bigger picture of air pollution, future studies could examine the precursors of ozone, such as nitric oxide. When understanding ozone and the photochemical reactions required to transform primary pollutants, knowing the emission sources would assist legislation in controlling future air pollution emissions. As the Mid-Atlantic states experience frequent episodes of high pollution due to transport of pollutants from west to east, back trajectories such as the HYSPLIT model would provide a larger spatial distribution of emissions and assist in the identification of emission sources.

Expanding the meaning of an air quality episode to include the days prior to the onset would better address the strength of the relationship between synoptic climatology and air pollution. Future studies would look at the day or days leading up to an air quality episode to improve forecasting capabilities. Future work would also investigate small scale, short-term pollution events, such as summer barbeques and holiday fireworks displays to gain insight into the human health impacts and various environmental impacts. By dividing the study period based on legislative standards, a more complex understanding of how air quality has changed through time can be gleaned. It is assumed that more strict air quality standards would lead to cleaner air, with fewer direct emissions. Although the relationship that air quality has to the climate will need to be reassessed with a changing climate system.

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