A CLIMATOLOGY OF AIR POLLUTION IN THE KANSAS CITY METROPOLITAN AREA

by

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Abstract

My thesis characterizes the temporal and spatial behavior of ozone and fine particulate matter in the Kansas City metropolitan area. I also investigate the capability of a synoptic weather typing scheme, the Spatial Synoptic Classification, to characterize and explain the behavior of ozone and fine particulate matter in the Kansas City area.

Daily maximum ozone concentrations from nine active ozone monitoring stations and daily average particulate concentrations six active $PM_{2.5}$ monitoring stations were compared to daily SSC weather type records from 2004-2010. Analysis of Variance (ANOVA) tests were conducted on the ozone and $PM_{2.5}$ data to analyze temporal and spatial behavior. A non-parametric recursive partitioning technique was used to create a conditional inference tree-based regression model to analyze the association between the different SSC weather types and the selected pollutants.

The ANOVA results showed significant seasonal trends with both pollutants. In general, ozone concentrations are typically lower in the spring and autumn months and higher during the summer months. $PM_{2.5}$ concentrations were not as dependent on the season, however, they did tend to be higher in the late summer months and lower in the autumn months.

The results also showed significant differences for both pollutants in average concentration depending on location. The ozone concentrations generally tended to be higher in the areas that are located downwind of Kansas City and lowest at the station located in the middle of the urban area. Fine particulates also seemed to be highest in the downwind portion of the urban area and lowest in the region upwind of the city.

The conditional inference tree showed that higher concentrations of both pollutants are associated with tropical air masses and lower concentrations are associated with polar air masses.

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Acknowledgments

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Chapter 1 - Introduction

Air quality in urban air sheds is affected by complex interactions involving numerous local and regionally-transported atmospheric emissions. The spatial extent and degree of impact that these dynamic variables have on urban air quality is dependent upon many factors including local and regional meteorology. Unique regional processes often affect individual air sheds. One such process that influences the air quality in the Kansas City region is the large-scale seasonal biomass burning that occurs to the west of Kansas City in the Flint Hills of Kansas (KS) and Oklahoma (OK). The smoke from the spring-time burning in the Flint Hills contains atmospheric pollutants that have been shown to have potentially serious effects on human health (Leenhouts 1998). The extent of the health threat posed by the pollution produced from biomass burning is dependent on a number of variables, including meteorological conditions during and after the time of the burning. Problematic levels of air pollution are often associated with weather patterns that reduce pollution dispersion, diffusion, and deposition (Ebi and McGregor 2008). Thus, better understanding of the associations between atmospheric conditions and air pollution patterns is needed so the effects of biomass burning on regional air quality are minimized.

My thesis investigates the spatial, temporal, and meteorological dynamics of ambient air pollution in the Kansas City metropolitan area. Emphasis is placed on determining the capability of a synoptic weather classification scheme, namely the Spatial Synoptic Classification (SSC) system (Sheridan 2002), to explain the dynamics of ozone and fine particulate matter concentrations in and around the Kansas City metro area. This study uses ambient air monitoring records from 15 stations with varying periods of record, ranging from 2004 until 2010 and synoptic meteorological classification records that date from 1970 to 2009. This first chapter provides a history of research related to air pollution climatology, background information on the Flint Hills rangeland burning, and presents the intent of the investigation and its significance.

1.1 Background

1.1.1 Short History of Air Pollution Research

Public dissatisfaction with poor air quality probably dates back to the introduction of coal as a source of heat around the 14^{th} century (Halliday 1961). John Graunt (1662) conducted one of the earliest documented studies that linked poor air quality to poor health. Graunt's work showed that the poor air quality produced by burning coal was a contributing factor to the higher death rates in London.

The Industrial Revolution brought higher levels of air pollution across Europe in the late 1700s (Heidom 1978). Unfortunately, it wasn't until almost a century later that progress in air-quality science began to address the problem Research by Fick (1855) and Reynolds (1883, 1894) in the field of fluid dynamics (fluid meaning any substance that continually flows under an applied stress, which might include liquids, gases, and plasmas) laid the groundwork for studying the behavior of pollutants in the atmosphere. At the end of World War I, an increased interest in atmospheric physics with applications to chemical warfare led to important research in the fields of fluid diffusion and dispersion (Richardson 1920; Taylor 1921; Roberts 1923) contributing greatly to air pollution research.

Industrial urban air quality continued to decline through the mid-1900s, posing a serious health threat to residents of some regions; for example, the episodes of Meuse Valley, Belgium in 1930, Donora, Pennsylvania in 1948, and London in 1952 (Holgate, *et al.* 1999). There were over 4,000 deaths associated with the London air pollution episode alone (Brimblecombe 2001). Primarily because of these types of air quality related events, a large amount of federal and local research specific to atmospheric quality was initiated. Of particular interest was the dispersion and diffusion of combustion pollutants as they related to wind speed and direction, and the deposition of combustion pollutants via precipitation. In 1941 the Trail smelters in the Columbia River Valley of Canada were the first to begin using meteorological variables as part of operational control methods, shutting down the industry whenever the local weather promoted the accumulation of air pollution (Halliday 1961).

Until the 1940s, most urban air pollution could be traced directly to the burning of fossil fuels, and ultimately smoke, soot, and sulfur dioxide. Increased use of automobiles, along with other factors, produced new types of pollution. This new atmospheric pollution was termed “smog” because it was thought to come from industrial smoke and advection fog.

In late July of 1943 a smog episode in Los Angeles, California that lasted several days provided valuable new information to scientists. One of the peculiar characteristics of the Los Angeles smog was its quick onset and cyclic behavior. Lenn (1948) reported that on every morning during this event the air was perfectly clear until about 8:00 AM, having turned hazy and irritating by 8:15 AM. The air quality was usually worse during the morning hours from approximately 8:00 AM to 12:00 PM. Meteorologists noted that strong diurnal temperature inversions (characterized by warmer air at higher altitudes and cooler air near the Earth's surface), combined with low wind speeds and clear skies were associated with the highest concentrations of pollution. The layer of warm air that is situated above the cooler air acts as an insulator, reducing the amount of vertical dispersion that can take place, in effect trapping the air pollution, as shown in figure 1-1(Environment Canada).

Van Haagen-Smit (1953) was the first to recognize that the action of solar radiation on pre-existing petroleum vapors and nitrogen dioxide (NO_2) created smog and damaged vegetation. These results prompted scientists to study the impact of weather not only on the transport and diffusion of primary pollutants, but also on the creation of secondary pollutants. A secondary pollutant is defined as a pollutant not directly emitted into the atmosphere but created through chemical reactions among preexisting pollutants. As the understanding of atmospheric and pollutant interactions grew, it became more apparent that an increase in applied meteorological research was necessary for progress to be made towards improving air quality.

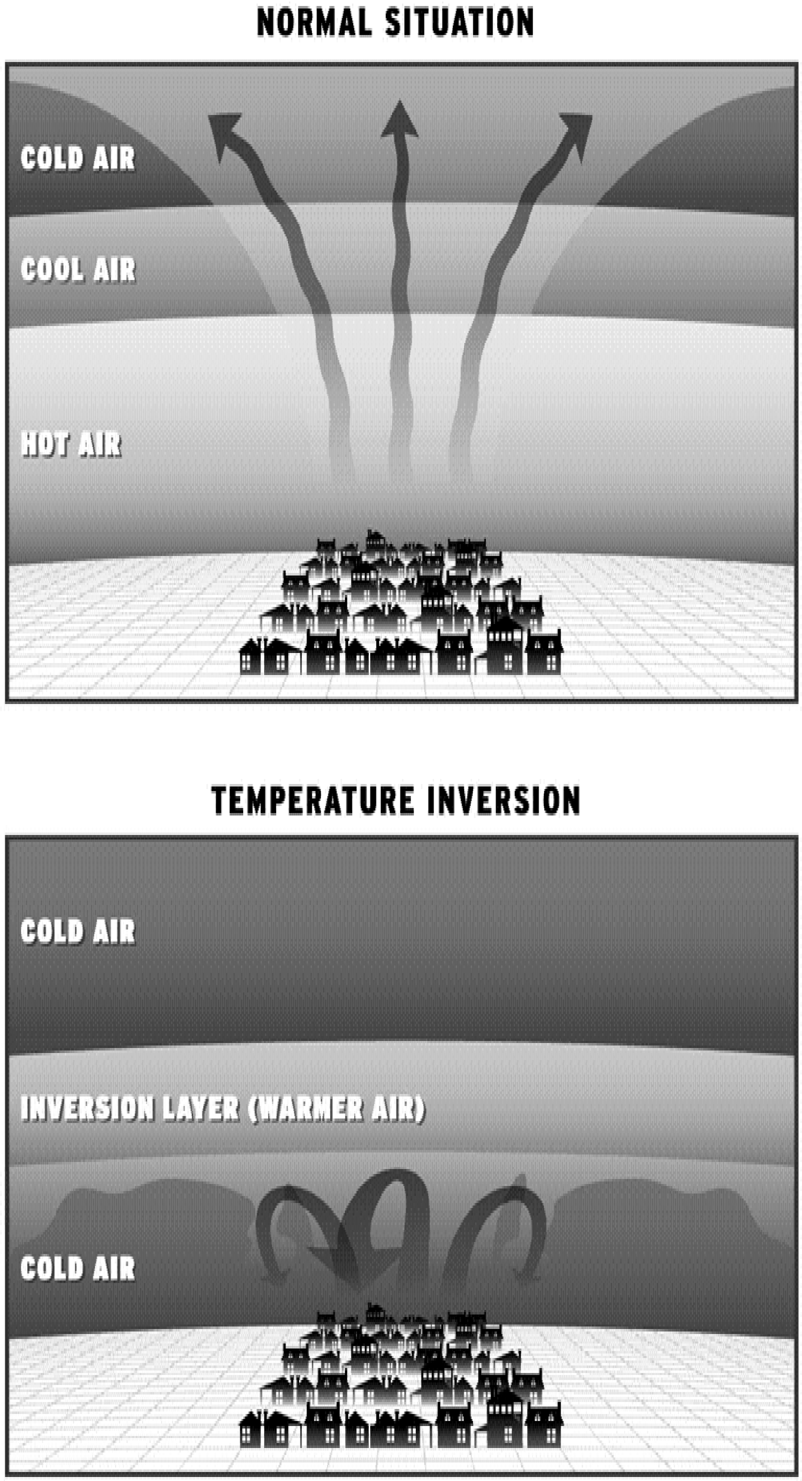


Figure 1.1A comparison of the effects of normal and inverted temperature profiles on atmospheric dispersion

1.1.2 Ozone

Ozone is a trace element in the Earth's atmosphere that is both essential and detrimental to human health. Whether ozone is regarded as "good" or "bad" depends on where it is located in the atmosphere. Earth's atmosphere is approximately 600 km thick and is divided into four layers; 1) the Troposphere (0 km to 15 km), 2) the Stratosphere (15 km to 50 km), 3) the Mesosphere (50 km to 80 km), and 4) the Thermosphere (80 km to 600 km) (Pielke, Sr. 2011). The gaseous composition of the atmosphere consists almost exclusively of nitrogen and oxygen, which account for about 99% of the dry atmosphere (Table 1; from Pidwirny and Budikova 2010).

The Mesosphere and Thermosphere contain a combined total of less than 1% of the total atmospheric gaseous content and have no direct effect on the pollutants analyzed in this study. The majority of the atmospheric ozone content is in the Stratosphere and is collectively called the Stratospheric Ozone Layer (SOL). Ozone comprising the SOL is often referred to as "good ozone" because of its absorption of harmful ultraviolet (UV) solar radiation. Without this atmospheric UV filter, it would not be possible for life to exist on earth.

Though ozone in the Stratosphere is essential to human health, ozone in the Troposphere is one of the primary environmental risk factors of modern times. Generally, stratospheric and tropospheric ozone do not mix. It takes approximately 50 years for ozone created in the Troposphere to migrate to the Stratosphere. Stratospheric ozone only migrates to the Troposphere during extreme atmospheric mixing. Tropospheric ozone is a secondary pollutant, meaning that it is not emitted directly into the atmosphere, but rather created through photochemical processes. Ozone is formed through complex chemical processes that typically involve oxides of nitrogen (NO_x), reactive volatile organic compounds (VOCs), molecular oxygen (O_2), and solar radiation in the wavelength range of .295µm - .43µm (McKee 1994).

While the chemistry of tropospheric ozone is not a focus of my study, a brief section is devoted to it for better understanding of the urban air pollution problem. Detailed presentation of the chemical processes involved in the creation and destruction of ozone is given in Finlayson-Pitts and Pitts (1997). The most common chemical process in urban environments that leads to the creation of ozone begins with the oxidation of NO, which is a major product of combustion (Finlayson-Pitts & Pitts 1997). The NO then interacts with and "scavenges" preexisting O_3, resulting in increased levels of NO_2 and O_2. During conditions when there is a lack of solar radiation (e.g. at night or during cloudy conditions), the process ceases leaving higher concentrations of NO_2 and lower concentrations of O_3. However, if sufficient solar radiation is introduced to the NO_2, photolysis occurs and the NO_2 is broken down into NO and atomic oxygen (O). Under the right conditions, the O is able to then react with O_2 to form O_3 (See Box 1 and Figure 1-2). Because of this strong dependence on the amount of available solar radiation, ozone concentrations consistently follow an annual cycle that peaks during summertime and sinks to the lowest concentrations during the winter months. Due to this pattern, April 1st to October 31st is typically known as the ozone season in the Northern Hemisphere.

Table 1- Average composition of the atmosphere up to an altitude of 25 km.

Gas Name	Chemical Formula	Percent Volume
Nitrogen	N_2	78.08%
Oxygen	O_2	20.95%
*Water	H_2O	0 to 4%
Argon	Ar	0.93%
*Carbon dioxide	CO_2	0.04%
Neon	Ne	0.00%
Helium	He	0.00%
*Methane	CH_4	0.00%
Hydrogen	H_2	0.00%
*Nitrous oxide	N_2O	0.00%
*Ozone	O_3	0.00%
* variable gases		

To summarize this process, the formation of O3 is largely dependent on the preexisting concentration of NO from combustion, as well as the local climatic conditions, particularly the amount of available solar radiation.

Thus, with photochemical pollutants such as ozone, it is particularly important to study meteorological patterns in order to understand not only local transport and diffusion, but also creation and destruction processes.

Chemistry of Tropospheric Ozone Formation

1) $$NO + O_3 \rightarrow NO_2 + O_2$$

2) $$NO_2 + \lambda \rightarrow NO + O$$

3) $$O + O_2 + M \rightarrow O_3 + M$$

Where λ is solar radiation in the wavelength range of .295μm - .43μm and M is a molecule that removes excess energy from the reaction.

Figure 1.2– Chemical processes involved in the photochemical creation of tropospheric ozone.

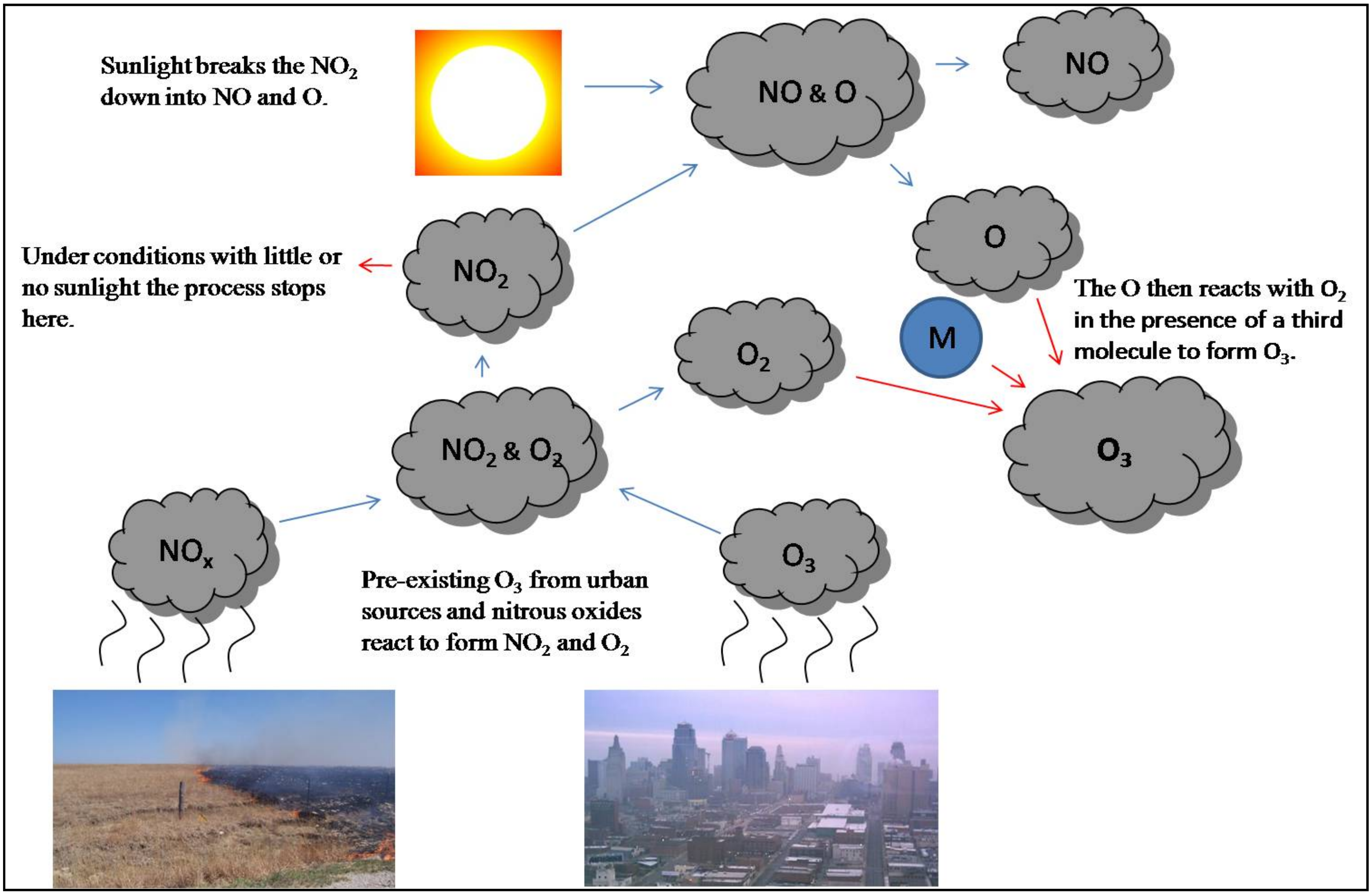


Figure 1.3- Interactions of atmospheric pollutants from urban sources and biomass burning and their role in tropospheric ozone formation.

1.1.3 Particulate Matter

Particulate matter is a term used to define either liquid or solid matter suspended in the atmosphere and is categorized based on the aerodynamic diameter of the particles. The aerodynamic diameter (AD) of a particle refers to the diameter of an idealized particle, or sphere, with unit density that behaves aerodynamically identical to that of the particle in question (Butler 1979). Particles having different dimensions and shapes may still have the same AD. Aerosol particulates are categorized into 5 categories based on size: (1) less than 100 micrometers (PM_{100}) in AD; (2) less than 10 micrometers (PM_{10}) in AD; (3) less than 4 micrometers (PM_4) in AD; (4) less than 2.5 micrometers ($PM_{2.5}$) in AD; and (5) less than 0.1 micrometers ($PM_{0.1}$) in AD (Daly and Zannetti, 2007). $PM_{2.5}$ is the only aerosol pollutant analyzed in this study. The other categories of particulates were excluded for reasons including a lack of available data, posing a relatively low health threat, and because $PM_{2.5}$ is the class that has the highest positive correlation with tropospheric ozone. Since $PM_{2.5}$ is the only category to be analyzed in this study, the other categories are not described in detail.

The composition of $PM_{2.5}$, otherwise known as fine particulates, varies both spatially and temporally. In general, $PM_{2.5}$ in North America is mostly comprised of six major species of particulates (McMurry *et al.* 2004):

- Sulfate
- Nitrate
- Ammonium
- Black Carbon
- Organic Carbon
- Soil

Sulfate is the major contributor to fine particulates in the eastern U.S., while nitrate dominates particulate matter in the western U.S. (Seinfeld and Pandis 2006).

Like ozone, $PM_{2.5}$ is highly affected by local weather conditions. For example, higher humidity levels may allow for enhanced hygroscopic aerosol growth and increased solar radiation can drive photochemical conversions of gases to aerosols (Power *et al.* 2006). Much research has been conducted on the role of climate and meteorology on aerosol behavior (Smirnov *et al.* 1994, 1996, 2000; Yu *et al.* 2000, 2001; Holben *et al.* 2001) and has generally shown that significant fluctuations in aerosol variability can be attributed to insolation, humidity, temperature, wind speed, precipitation, rates of convection, and air mass types.

1.1.4 Rangeland Burning in the Flint Hills

Every spring, from approximately the beginning of March to the end of May, livestock ranchers in the Flint Hills region of KS and OK (see Figure 1-3) burn their pastures. Rangeland burning is an effective ecosystem management technique that has been used since pre-settlement times (Bragg and Hulbert 1976). Unlike other prairie regions, the bluestem prairie of the Flint Hills has escaped cultivation due to the steep terrain and rocky soils, rendering it unsuitable for farming. Consequently, the dense grass that grows throughout the region is used as grazing lands. In order to maintain sufficient forage for the livestock, the rangeland is burned periodically, usually in the spring, to prevent the invasion of woody plant species (Bragg and Hulbert 1976). Land management records suggest that typically about 50-60% (≈1.0-1.2 million hectares) of the Flint Hills prairie is burned on an annual basis, resulting in the combustion of approximately 6.0 Tg of biomass per growing season (Goodin 2008). While it is a necessary and effective method for sustaining quality grazing lands, rangeland burning creates large amounts of air pollution, adding to the complexity of Kansas City air quality issues.

Figure 1.4- Map of the Flint Hills region of Kansas and Oklahoma.

1.1.5 Synoptic Climatology

Although humans studied weather and climates at least as early as the 3rd century B.C. (Chu 1962), and conducted studies and classifications using synoptic climatological analyses, the term synoptic climatology did not appear until 1942 and can be defined as the description and analysis of the totality of weather at a single place, or over a small area, in terms of the properties and motion of the atmosphere over and around the place or area (Jacobs 1946).

Synoptic climatology, as defined by the American Meteorological Society (AMS) Glossary of Meteorology (Glickman 2000), is the study of climate from the perspective of atmospheric circulation, emphasizing the connections between circulation patterns and climatic differences. Synoptic climatology encompasses a wide range of meteorological variables and presents an overall view of the climate system. The goal of synoptic climatology is to study and classify the atmospheric behavior of a region and relate the atmospheric classes to the weather patterns typically associated with them. Barry and Perry (1973) published an exhaustive work on the methods of synoptic climatology in the early 1970s, about the time that synoptic climatology became considered as its own discrete subfield of study.

A major split in types of synoptic climatology methods divides them into manual and automated classification schemes (Yarnal 1993). In the manual classification process, it is the job of the investigator to analyze each set of data and assign it to a previously existing synoptic classification scheme or to create new additional classes. Some examples of the manual classification type are the Muller Classification, the Lamb Catalogue, and Grosswetterlagen (Sheridan 2002). An advantage of the manual system is that it can be customized specifically for the researcher's needs. Disadvantages include that it has a high potential for subjectivity on the part of the researcher and that it is time-consuming.

Automated techniques rely on algorithms to determine the classes based on statistical procedures such as correlation analysis, principle component analysis, and cluster analysis. While being much quicker and often easier to use, Sheridan (2002) identifies the disadvantage of these schemes as the lack of generality among various locations.

A relatively recent effort has been undertaken by various researchers to combine the advantageous aspects of both manual and automated classification systems into hybrid schemes. The Spatial Synoptic Classification (SSC) is a hybrid scheme originally developed by Kalkstein *et al.* (1996). This technique focuses on manually identifying the typical regional winter and summer weather conditions that are associated with six different weather types for each weather station east of the Rocky Mountains. These weather types are: (1) dry polar (DP); (2) dry moderate (DM); (3) dry tropical (DT); (4) moist polar (MP); (5) moist moderate (MM); (6) moist tropical (MT). A detailed description of these weather types given by Sheridan (2002) is presented in appendix A. Once these conditions are identified, the algorithm assigns each day into one of these weather types, or as a transition between two types.

The SSC system was redeveloped by Sheridan (2002) in order to classify not only winter and summer weather patterns, but also fall and spring conditions. Sheridan's redevelopment is based on characterizing typical weather conditions for each weather type for a particular location during each season. This is accomplished by identifying days, known as *seed days*, within four 2-week periods throughout the year that are representative of the typical weather conditions of each weather type at a specific location. The weather parameters used to discriminate among weather types are surface observations recorded at 04, 10, 16, and 22 h EST of the following variables:

- temperature,
- dew point depression (temperature minus dew point),
- mean cloud cover (average of the 4 observations),
- mean sea level pressure (average of the 4 observations),
- diurnal temperature range, and
- diurnal dew point range.

The 2-week periods vary according to location, corresponding with the hottest and coldest two weeks and the midway points between these two periods. This ensures that each weather type is specific to each location and season.

1.1.6 Synoptic Climatology and Air Pollution

There have been many studies that utilize synoptic climatology classifications to analyze the dynamics of air pollution on different spatial and temporal scales throughout the world. A few published examples include studies in: (1) the United States (Kalkstein & Corrigan 1986; Greene, *et al.* 1999; Hu, *et al.* 2010; Davis, *et al.* 2009); (2) Europe (Nilsson, *et al.* 2001; O'Hare &Wilby 1995; Shahgedanova, *et al.* 1998); and (3) Asia (Tanner & Law 2001).

Kalkstein and Corrigan (1986) evaluated sulfur dioxide concentrations in the Wilmington, Delaware area using a synoptic climatology index that they developed. Their synoptic index was based upon seven surface meteorological variables and produced ten clusters, or air mass types, using principle component analysis and clustering techniques. The synoptic approach significantly outperformed multivariate correlation techniques, such as multiple regression. The synoptic index was able to identify air mass types that were associated with consistently high and low sulfur dioxide concentrations. The authors also suggested that a synoptic approach might also have the potential for determining whether long-term trends in air pollution are attributed to changes in emissions or to weather patterns.

Greene *et al.* (1999) used an automated synoptic climatological classification scheme called the Temporal Synoptic Index (TSI) to evaluate the impact of weather on the average ozone and average total suspended particulate (TSP) concentrations. They also analyzed the relationship between the TSI classes and days in the top 5% of ozone and TSP concentrations. Their study area consisted of four U.S. cities: Birmingham, AL, Cleveland, OH, Philadelphia, PA, and Seattle, WA, and the results showed that there are significant differences in the pollution/TSI relationships among the cities. In general, the hottest days were associated with ozone concentrations above the overall mean. However, in Birmingham, one of the hottest and most humid TSI classes was associated with the lowest concentrations of both TSP and ozone, while in Seattle the hottest category was associated with the highest average concentrations of both pollutants. The results of their extreme concentrations analysis showed that the TSI categories with high temperatures and moderate cloud cover were associated with the highest number of days in the 95^{th} percentile for both pollutants.

Hu *et al.* (2010) used the SSC classifications for Atlanta, GA from 2006 to 2009 to forecast air quality based on ozone and $PM_{2.5}$ concentrations. They found that ozone forecasts were more accurately forecast on dry SSC days and less-accurately forecast on moist days. They noted that this is a concern for forecasters since a number of the ozone exceedance days fell on moist SSC days. The $PM_{2.5}$ forecasts, however, performed better on moist SSC days and worse on dry days, particularly dry tropical days. They then integrated a secondary organic aerosol module, which significantly increased the accuracy of the $PM_{2.5}$ forecasts.

Davis *et al.* (2009) compared the advantages and performance of a back trajectory analysis, the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Hess 2004), and air mass approaches to understand short-term variability in surface ozone concentrations. Back trajectory analyses use meteorological parameters such as wind direction and speed, as well as barometric measurements to trace the trajectory of a hypothetical air parcel into the location of interest. Their results showed that the SSC air mass approach generally performed better in discriminating regional ozone levels. However, ozone concentrations were explained with the most accuracy when the SSC was coupled with the back trajectory analysis.

All of the research on synoptic weather classification schemes and pollution concentrations has shown that weather and pollution are highly related. In addition, synoptic classifications have proven as an effective method for explaining the variability in spatial and temporal characteristics of regional and local scale pollution.

1.2 Statement of Problem

The primary objective of my thesis research is to assess the ability of a hybrid climatology classification technique, the SSC, to characterize and model local ozone and fine particulate pollution levels in an urban setting. Another objective is to analyze spatial and temporal variability of pollutant concentrations based on their locations relative to the Kansas City metro area.

The primary hypothesis tested in this research is that there are significant associations among SSC classifications and ozone and $PM_{2.5}$ concentrations, and that the degree of association varies by SSC weather type. This hypothesis is based on previous research showing statistically significant associations between meteorological variables included in the SSC and pollutants. A secondary hypothesis is that pollution concentrations will vary according to their location in respect to Kansas City. Specifically, those stations that are located generally downwind of Kansas City will have higher average concentrations of the studied pollutants. Motivationfor my research comes from the relationship between rangeland burning in the Flint Hills and ozone concentrations in the Kansas City region. The results of the analyses will help to understand why there are high pollution concentrations around Kansas Cityduring some burn periods and low concentrations during others.

1.3 Significance of the Study

Air pollution, as with most environmental issues, is a complex and controversial problem. Local weather and short-term changes in weather conditions are the single largest controlling factor of the concentration and distribution of local atmospheric pollution (Dabberdt, *et al.* 2003). Much research has been conductedon the dynamics of air pollution; however, due to the spatial and temporal variability of the problem, most of the research has focused on national spatial extents, or similarly large-scale dynamics. The urban setting provides a dynamic air pollution environment and it is important to study the climatology of these local fluctuations. Intra-urban air pollution dynamics is an important field of research because of the relatively large number of people that are affected. Many epidemiological studies signify the health issues related to air pollution.

Almost every urban air shed is unique in some way. However, models developed to characterize air pollution climatology in one region may be adaptable to other demographically similar locales. One factor that adds to the complexity of the Kansas City air pollution problem specifically is the annual rangeland burning that occurs just to the west of Kansas City in the Flint Hills of Kansas and Oklahoma. While this method is highly effective for the renewal of nutritious forage for cattle, it also presents a significant source of precursor emissions that can be converted into higher levels of ozone in the downwind Kansas City region. The magnitude of this impact on Kansas City air quality is largely dependent upon the regional weather conditions, reinforcing the importance of studying the weather-pollution relationship in this region. This study provides information on the weather conditions conducive to ozone precursor accumulations, and ultimately ozone formation, in and around Kansas City.

Chapter 2 - Study Area and Methods

2.1 Study Area

2.1.1 Regional Climatology

The region of interest is centered on the Kansas City metro area, located on the state border shared by MO and KS. In the context of the SSC, Kansas City lies within the western True Mid-Latitude climate region, characterized by long summers with significant Moist Tropical (MT) frequency, and relatively limited Moist Polar influence. Figure 2-1 shows the total frequency for each weather type from 1970 to 2010 in the Kansas Cityarea. According to the SSC website, this is the only climate group affected by all weather types year-round (http://sheridan.geog.kent.edu/ssc.html). For a description of the SSC weather type categories, see appendix A.

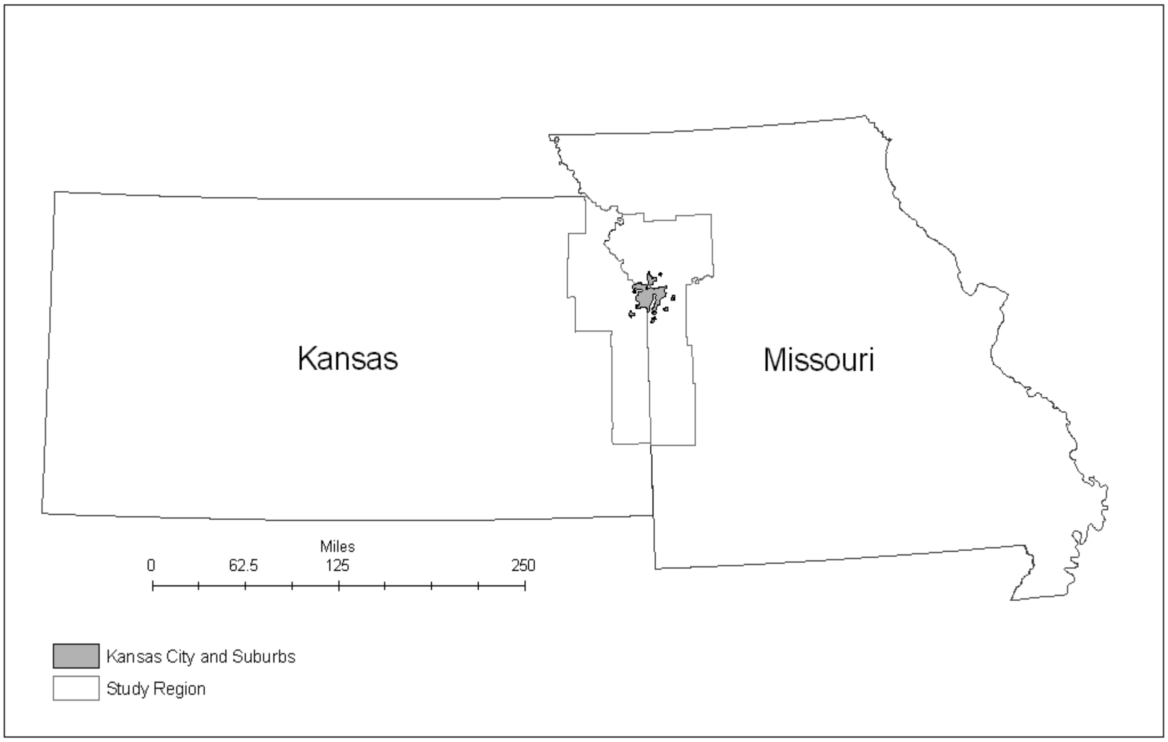


Figure 2.1- Map of the region of interest surrounding the Kansas City metro area and suburbs.

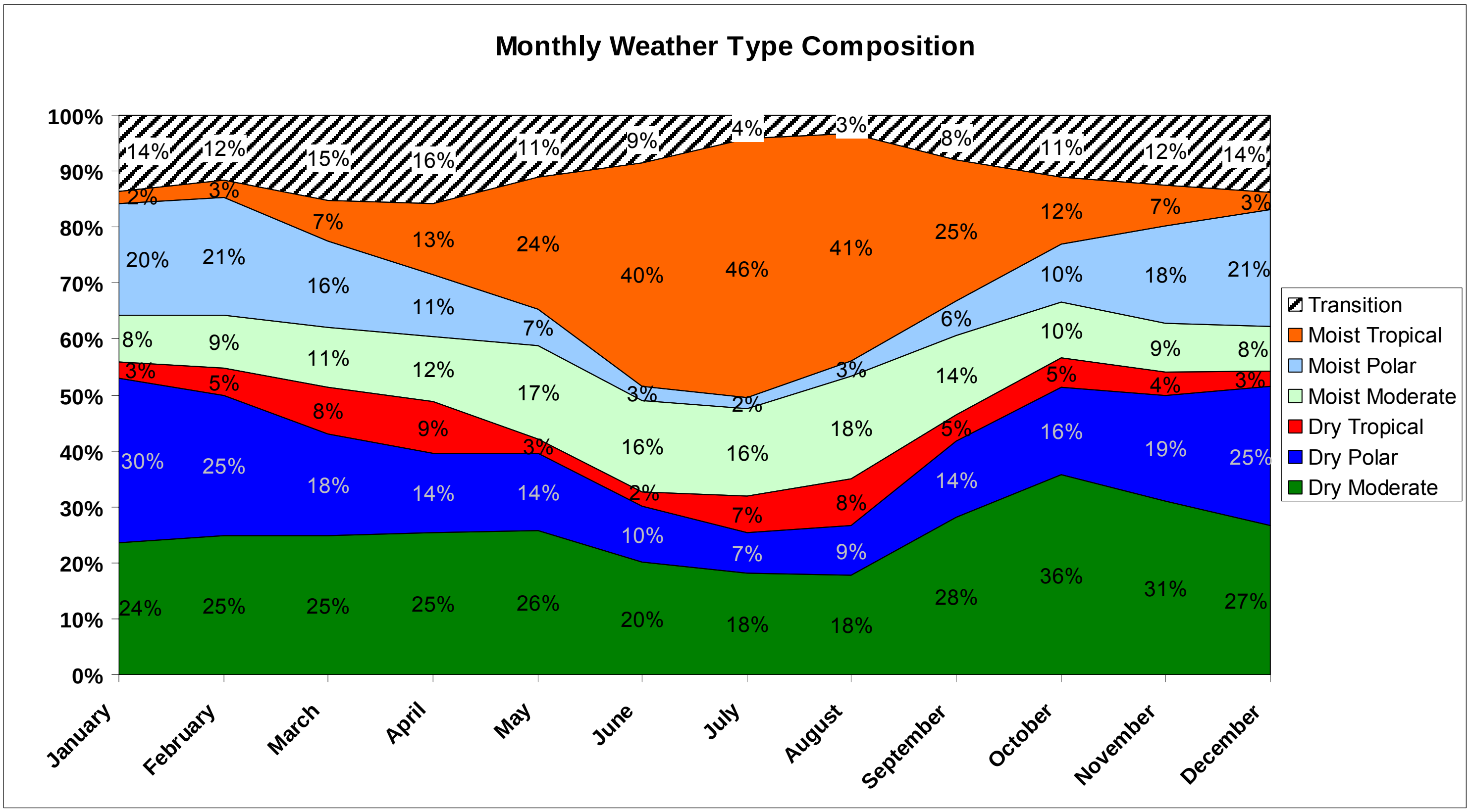


Figure 2.2 Monthly SSC weather type composition

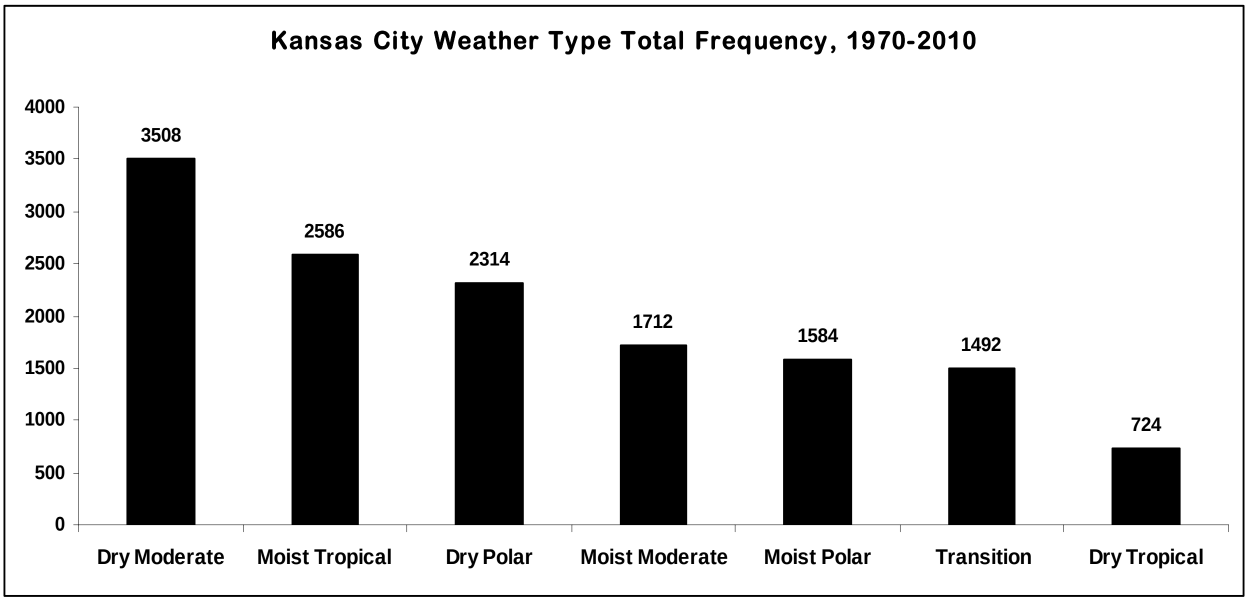


Figure 2.3- Total number of days in Kansas City categorized into the respective SSC weather type.

2.1.2 Regional Circulation Patterns

A relevant aspect of Kansas City's geographic location is that it is generally downwind of the Flint Hills. Wind direction and speed can be a critical factor in pollution dispersion and transportation on local and regional scales. Whether the precursor pollutants from the burning in the Flint Hills are transported to the Kansas City area primarily depends on the regional atmospheric circulation.

Appendices B and C contain wind roses depicting directional wind frequency data collected at the Kansas City regional airport. Appendix B shows the wind roses that are associated with the respective SSC weather types. In general, the DP and MP weather types develop in air masses that originate to the north of Kansas City, either coming from the Arctic region, or advecting from the Great Lakes region. The direction of transport in the polar air masses is typically from North to South. The DT and MT weather types indicate an air mass that has originated to the south or southwest of Kansas City over the hotter regions of the Unites States. Thus, air in the tropical air masses is transported from South/Southwest to North/Northeast. The DM and MM weather types are essentially mild air masses that have been modified by various atmospheric processes.

Considering the regional circulation of the SSC weather types, pollutants created by combustion in the Flint Hills will likely have the highest potential to negatively impact the Kansas City air quality during episodes of DT and MT air. Not only do these weather types provide the Southwest to Northeast transportation, they also provide the necessary photochemical meteorological context needed for ozone formation.

2.1.2 Pollution Monitoring Stations

The monitoring stations were chosen for their coinciding periods of record and also to ensure that a sufficient variety of spatial contexts are represented. It was important that enough stations were chosen for each pollutant type to provide representation of the pollutant type relative to the SSC conditions both upwind and downwind of Kansas City and also sufficient representation of different land use/land cover settings. Tables 2-1 and 2-2 provide information on land use and location setting for each station, as well as the specific monitoring purpose of each station.

Since ozone is capable of being transported for longer distances than the aerosols of concern, stations were used that characterize ozone behavior in a larger spatial context. This was not quite as important with the aerosol stations given that their atmospheric extinction rate is much higher than that of ozone.

Station ID	Pollutant	County	Land Use	Location Setting	Latitude	Longitude	Monitoring Purpose
200910010	Ozone	Johnson	Commercial	Suburban	38.839	-94.746	Exposure
201030003	Ozone	Leavenworth	Residential	Urban	39.327	-94.951	Exposure
201070002	Ozone	Linn	Agriculture	Rural	38.136	-94.732	Regional Transport
202090021	Ozone	Wyandotte	Residential	Urban	39.118	-94.636	Exposure
290370003	Ozone	Belton	Industrial	Rural	38.770	-94.580	Exposure
290470003	Ozone	Clay	Residential	Rural	39.417	-94.283	Unknown
290470005	Ozone	Clay	Agriculture	Rural	39.303	-94.376	Highest Concentration
290470006	Ozone	Clay	Agriculture	Rural	39.332	-94.581	Extreme Downwind
290490001	Ozone	Clinton	Agriculture	Rural	39.531	-94.556	Extreme Downwind

Table 2– Selected metadata pertaining to the ozone monitoring stations.

Station ID	Pollutant	County	Land Use	Location Setting	Latitude	Longitude	Monitoring Purpose
200910007	$PM_{2.5}$	Johnson	Commercial	Urban	38.974	-94.687	Exposure
200910010	$PM_{2.5}$	Johnson	Commercial	Suburban	38.839	-94.746	Exposure
202090021	$PM_{2.5}$	Wyandotte	Residential	Urban	39.118	-94.636	Exposure
202090022	$PM_{2.5}$	Wyandotte	Residential	Suburban	39.046	-94.694	Exposure
290370003	$PM_{2.5}$	Belton	Industrial	Rural	38.770	-94.580	Exposure
290950034	$PM_{2.5}$	Jackson	Commercial	Urban	39.105	-94.571	Highest Concentration

Table 3– Selected metadata pertaining to the $PM_{2.5}$ monitoring stations.

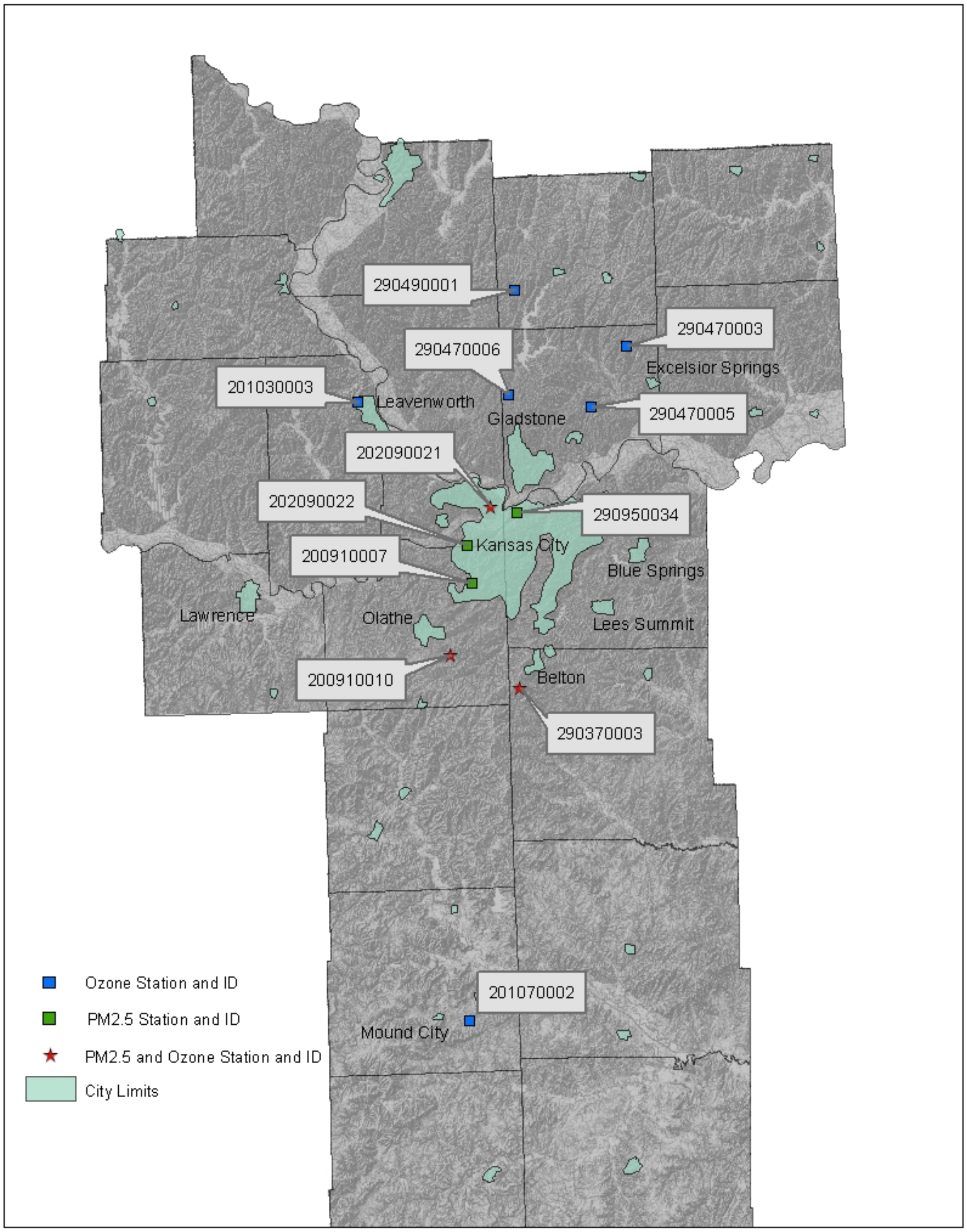


Figure 2.4- Map of the study region showing the locations of the ozone stations (blue squares), the aerosol stations (green squares), and the combined aerosol and ozone stations (red star).

2.2 Data

The ambient air pollution data were retrieved via the Technology Transfer Network (TTN) Air Quality System (AQS) Data Mart (http://www.epa.gov/ttn/airs/airsaqs/), hereafter known as the AQS. The AQS is maintained by the EPA and is a publicly accessible archive of ambient air quality records that have been submitted by tribal, state, and local agencies. Before the submitted data are published in the AQS they undergo quality control and assurance. Once the data are ensured to be of sufficient quality, the data are processed and published on the AQS Data Mart. For the ozone analysis, 1-hour daily maximum values measure in parts per billion (ppb) were obtained. The 1-hour daily maximums were selected based on information from Thompson and others (2001) who noted that these are the values most often used in analyses of tropospheric ozone. Thompson and others (2001) also point out that daily max 1-hour average concentrations are one of the focuses of the National Ambient Air Quality Standards (NAAQS) due to the particularly negative health effects of exceedances of this standard.

To analyze $PM_{2.5}$ behavior, daily averages ($\mu g/m^3$) were extracted from the AQS. These values were selected because they represent the highest temporal resolution available and were also a primary focus of the NAAQS. Also, daily summary values of both ozone and $PM_{2.5}$ are appropriate for this analysis because this is a time frame consistent with the time scales associated with meteorological impacts on pollution concentrations (Thompson, *et al.* 2001).

Sampling frequency was once per hour for ozone and, depending on the station, at 1, 3 or 5 day intervals for $PM_{2.5}$. Although the sampling methods vary among different monitoring stations, these differences do not create a bias in the data, and therefore did not need to be adjusted (Diver 2010). The periods of record vary among stations, ranging from 1980-2010 for ozone stations, and from 1999-2010 for $PM_{2.5}$ stations. To maintain temporally consistent data, only records from active monitors were used.

For the meteorological data, daily SSC weather type classifications for the Kansas City region were acquired from the SSC database (http://sheridan.geog.kent.edu/ssc.html). Daily air mass type observations and wind data recorded for Kansas City, MO, (station ID: MCI) were obtained for the period of 1972-2010. The observation records were then categorized by month and also by year. The SSC was chosen as the meteorological input for the analyses due to the relationship among the variables used in the SSC classifications and pollution concentrations. The weather variables that the SSC is designed to use in differentiating weather types are surface-based observations made 4 times per day of 1) temperature, 2) dew point, 3) wind, 4) air pressure, and cloud cover. Another advantage of the SSC is that the classification algorithm accounts for seasonal cycles in weather patterns. For example, the conditions required for a day to be classified as MT in July will be different than in January. If this were not the case, there would obviously be disproportionate frequencies of polar days in the winter and tropical days in the summer. Despite this temporal adaptation, the SSC still typically shows a higher frequency of tropical days in the summer and polar days in the winter which is a naturally occurring characteristic of the Mid-Latitude climate region, and not a result of a statistical bias in the classification of SSC weather types (See appendix A).

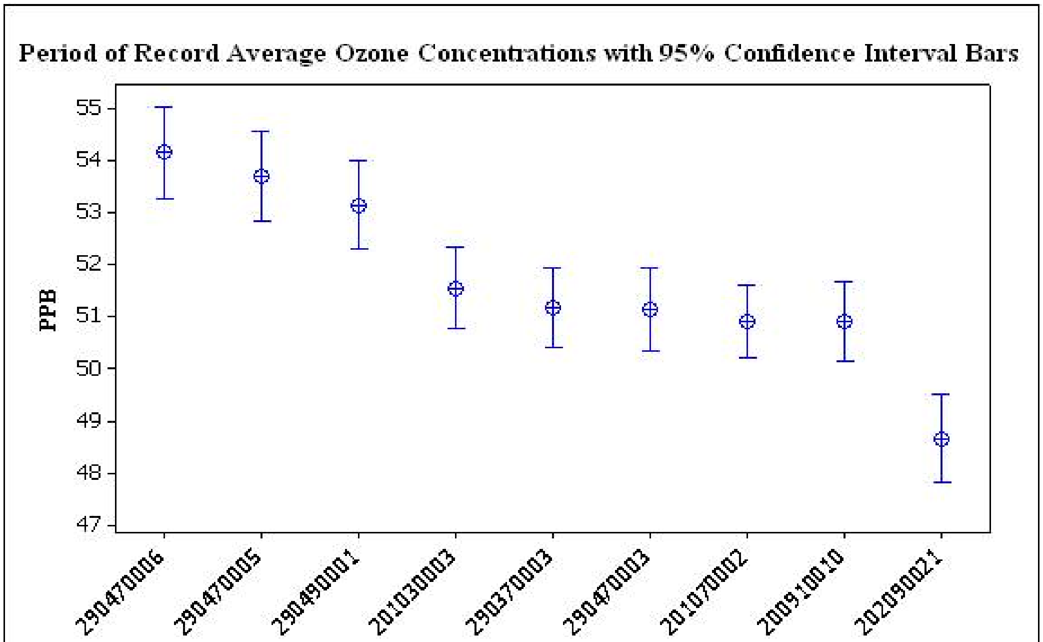
Chapter 3 - Analysis and Results

3.1 Statistical Analysis

Pollution data from each station/variable were first screened for quality separately. Outliers were visually identified using histograms. All of the outliers analyzed appeared to be technical errors and were deleted. Univariate normality was assessed based on a qualitative visual analysis of the Q-Q plots. The data from the ozone monitoring stations were all found to be normally or near-normally distributed. The $PM_{2.5}$ datasets were found to be distributed lognormally and were natural-log transformed prior to subsequent analysis. The SSC data were scrutinized for missing records or possible abnormalities. Missing records were noted to prevent inaccurately matching the dates of pollution data to SSC data.

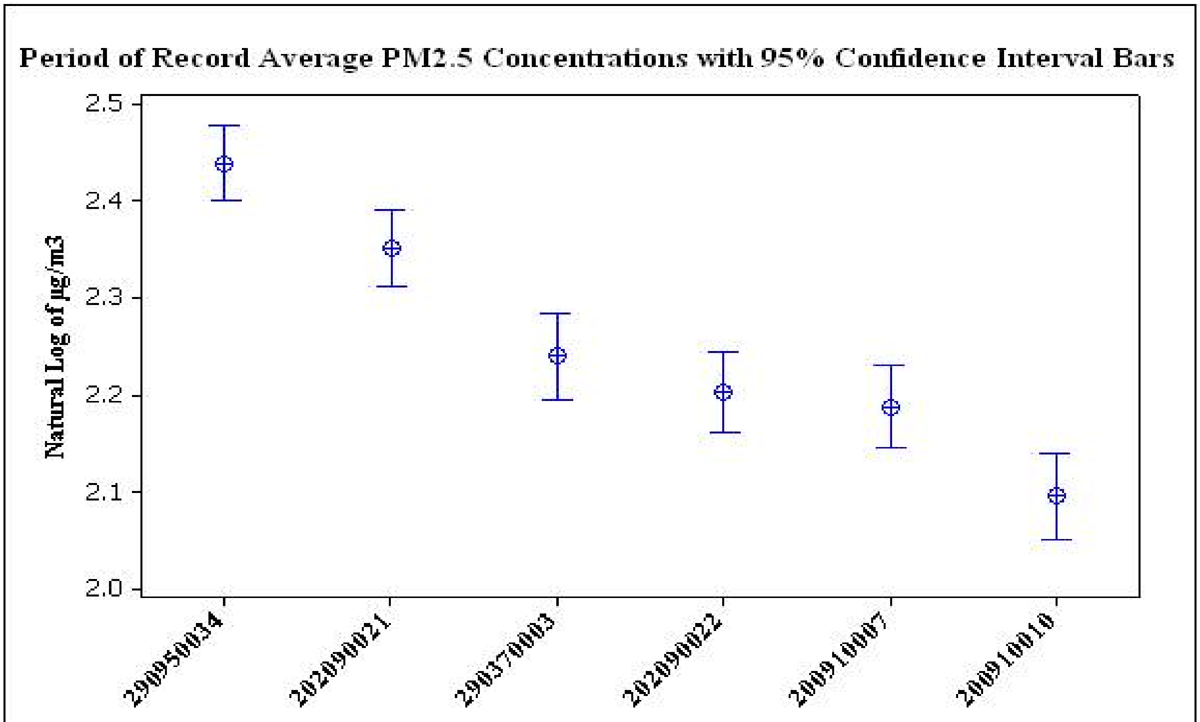
Data-collection objectives varied among stations, which presented large systematic gaps in the data. For example, if a monitoring station was initiated with the objective of recording the highest annual ozone concentrations, data-collection activities were discontinued during the winter months when ozone typically is at its lowest levels. As a result, three ozone monitoring stations only were operated during non-winter periods and only have sufficient records from April through October of each year in operation. To reduce the amount of seasonal bias, only days on which all ozone monitoring stations have recorded values were used in the analyses. After the missing data were deleted, there were 1242 ozone observations dating from 2004-2010. Likewise, the periods of record and temporal resolution varied among the $PM_{2.5}$ stations and only days on which all aerosol monitoring stations have recorded values were kept, leaving 559 records dating from 2004-2010.

After the data were screened and compiled, summary statistics for the entire period of record were calculated from the pollution records at each station. The pollution data were then stratified by month to characterize the seasonal behavior of the pollutants at each monitoring site. To determine the effect of seasonality on ozone and $PM_{2.5}$ concentrations, analysis of variance (ANOVA) tests were conducted on the monthly average pollution concentration at each station. One-way normal Analysis of Means (ANOM) tests (Ott1967), which are essentially a graphic version of the ANOVA, were also conducted to provide a satisfactory graphic description of the ANOVA results (see figure 3-3 through 3-11 (ozone) and 3-12 through 3-17 ($PM_{2.5}$)). Spatial variability of the pollutants was analyzed by conducting ANOVA tests to compare the overall average pollution concentrations of each station. ANOM tests were conducted on the station averages to provide a graphical summary of the ANOVA results (See figures 3-18 (ozone) and 3-19 ($PM_{2.5}$)).



Ozone Descriptive Statistics	N	Mean	StDev	Minimum	Q1	Median	Q3	Maximum	Skewness	Kurtosis
200910010	1242	50.91	13.66	6	42	51	59	112	0.14	0.47
201030003	1242	51.55	14.29	11	42	51	60	111	0.3	0.43
201070002	1242	50.91	12.66	14	43	51	60	87	0.02	-0.17
202090021	1242	48.65	15.16	6	39	48	58	130	0.34	0.96
290370003	1242	51.17	13.60	8	43	51	60	108	0.16	0.53
290490001	1242	53.15	15.35	12	43	52	62	109	0.48	0.41
290470003	1242	51.15	14.31	11	41	50	60	104	0.4	0.38
290470006	1242	54.15	15.74	11	44	53	63	113	0.47	0.39
290470005	1242	53.69	15.57	11	43	52	62	111	0.53	0.63

Figure 3.1- Average ozone concentrations in parts per billion at all ozone monitoring stations with 95% confidence interval bars. Table includes the associated descriptive statistics.



Natural Log of PM2.5 Descriptive Statistics	N	Mean	StDev	Minimum	Q1	Median	Q3	Maximum	Skewness	Kurtosis
290950034	558	2.44	0.46	1.16	2.13	2.44	2.75	3.95	0.03	-0.18
202090021	558	2.35	0.48	0.69	2.01	2.38	2.66	3.65	-0.13	0.05
290370003	558	2.24	0.54	0.59	1.87	2.28	2.63	3.87	-0.17	-0.25
202090022	558	2.20	0.51	0.83	1.87	2.21	2.55	3.91	-0.05	-0.08
200910007	558	2.19	0.51	0.88	1.84	2.21	2.53	3.48	-0.02	-0.4
200910010	558	2.10	0.54	0.74	1.74	2.10	2.47	3.41	-0.12	-0.38

Figure 3.2- Average $PM_{2.5}$ concentration at all particulate monitoring stations with 95% confidence interval bars. Table includes the associated descriptive statistics.

3.2 Temporal Variability

3.1.1 Ozone

The results of the analyses conducted on the monthly averages of the ozone stations comprising cluster 1 (graphs outlined in red) indicated a significant seasonal dependence. Typically, the average concentrations of cluster 1 for April, May, and September were not significantly high or low. The exceptions to this pattern are stations:

- 290470003, High: April; Low: September, $p<0.001$, $F = 45.18$
- 201030003, High: April, May, $p<0.001$, $F = 44.69$
- 202090021, Low: September, $p<0.001$, $F = 59.49$

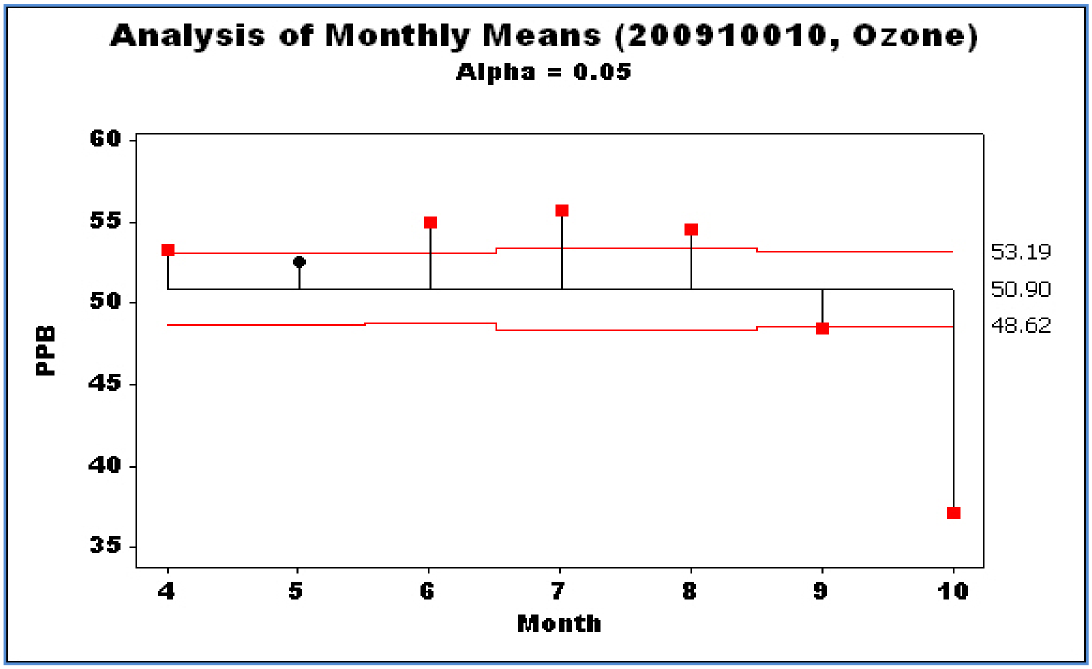
June, July, and August were associated with the highest average ozone concentrations for all of cluster 1. The higher average concentrations during the summer months are primarily because of the increase in incident solar radiation, resulting in more energy used to convert more precursor pollutants into ozone.

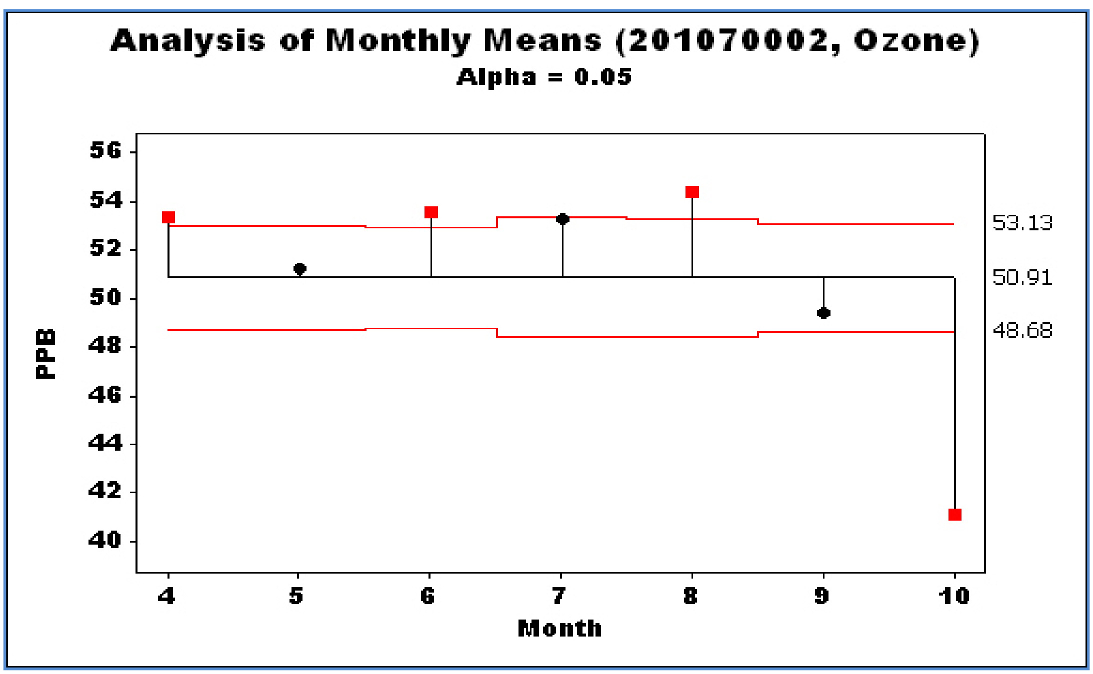
The results of the analysis conducted on the stations comprising cluster 2 (graphs outlined in blue) also show a significant seasonal dependence. Unlike most of the cluster 1 stations, all of the cluster 2 stations have significantly high average concentrations for April. One hypothesis that would explain this pattern is that seasonal dependence is caused by higher amounts of combustion pollutants cluster 2 stations receive in April from being in closer proximity to the rangeland burning occurring during this time in the

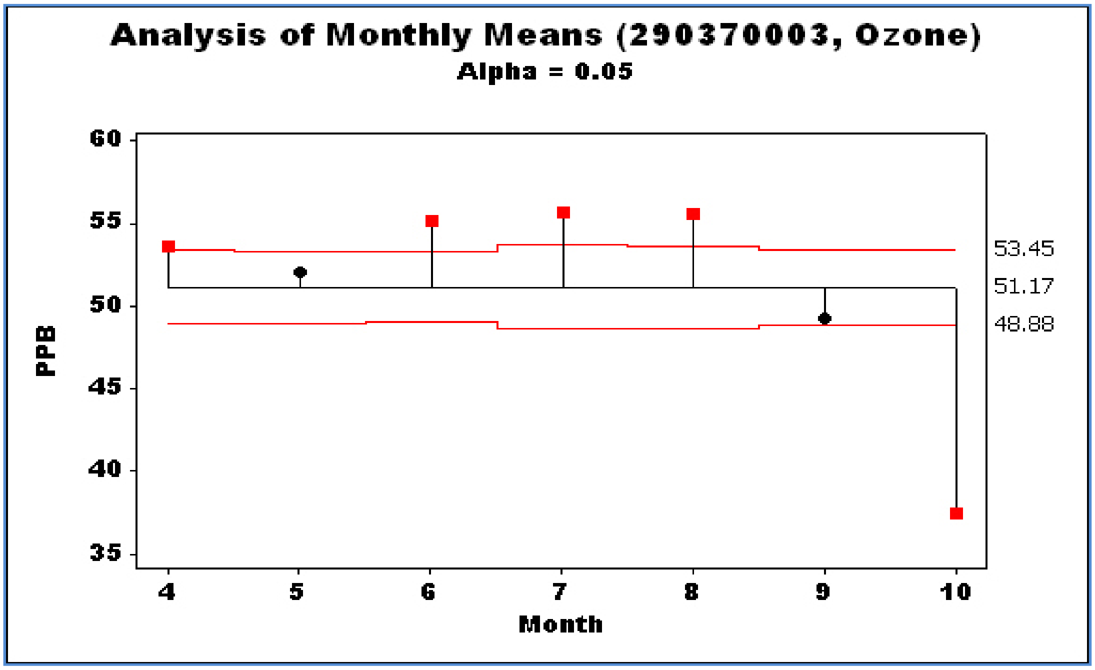
Flint Hills, as well as other burning practices that occur to the south of Kansas City. This hypothesis is supported by the fact that the prominent wind direction during April in the Kansas City region is from the south, southwest (see appendix C)

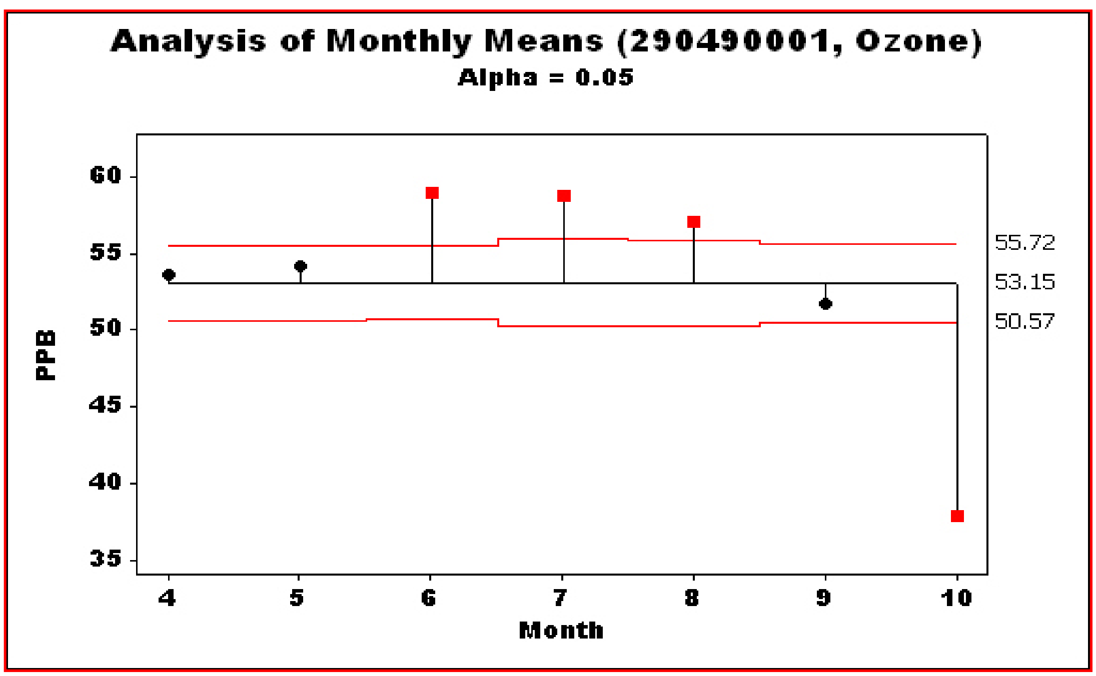
All stations in both of the clusters have similarly very significantly low averages for October. While a decrease in ozone is to be expected because of the decrease in available solar radiation, it is not clear why such a decrease in ozone levels should be so drastic and sudden. If the solar flux was the sole cause of this phenomenon, a similarly drastic and sudden *increase* would be expected in monthly average ozone concentrations between May and June. The increase in average ozone from May to June is approximately 3.8 ppb and 2.6 ppb for cluster 1 and cluster 2, respectively. Also note the degree of increase in ozone varies among stations. However, the decrease from September to October is a difference of approximately 12.9 ppb and 10.5 ppb for cluster 1 and cluster 2, respectively, and there is much less variation among the stations within each cluster. While there is noticeable decrease in the average frequency of MT from September to October, along with increases in the average frequencies of DP and MP, these changes in weather type frequencies do not seem large enough to account for the drop in ozone concentrations. This is particularly true considering that there are decreases in the average frequencies of DP and MP from April to May, and an increase in the average frequency of MT from April to May that are of similar magnitude as the autumn changes in frequencies that do not result in similarly increased ozone concentrations.

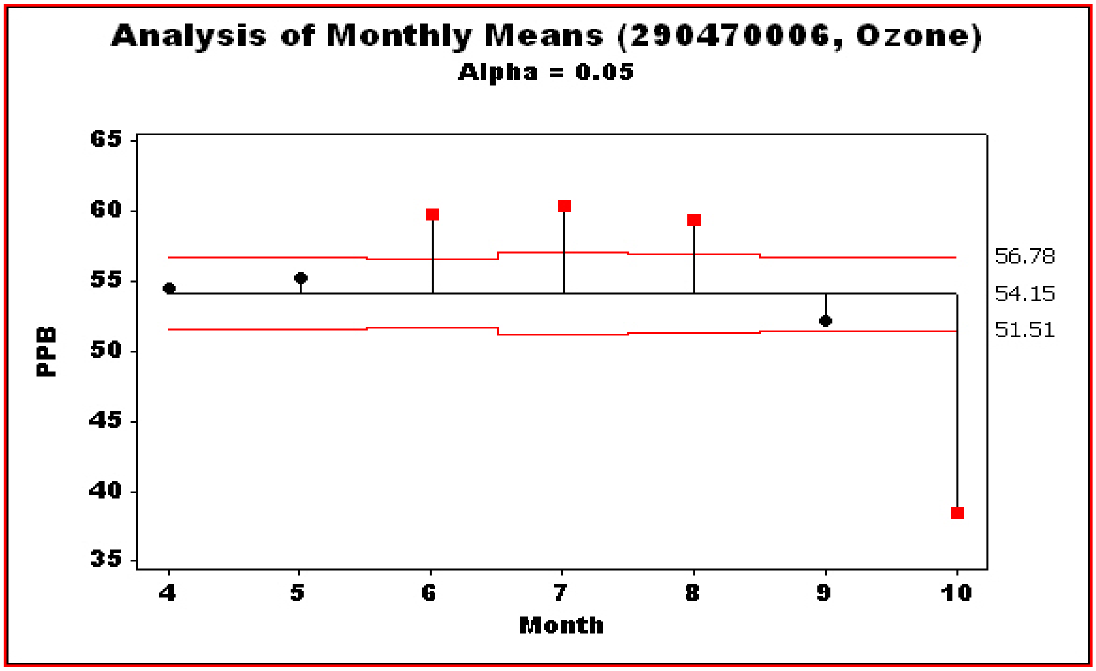
Figure 3.3- Graphical summaries of analysis of mean monthly ozone concentrations for selected climatic stations. Red and blue graph borders imply station membership to cluster 2 and cluster 1 respectively. Red box point symbols imply two-tailed significance.

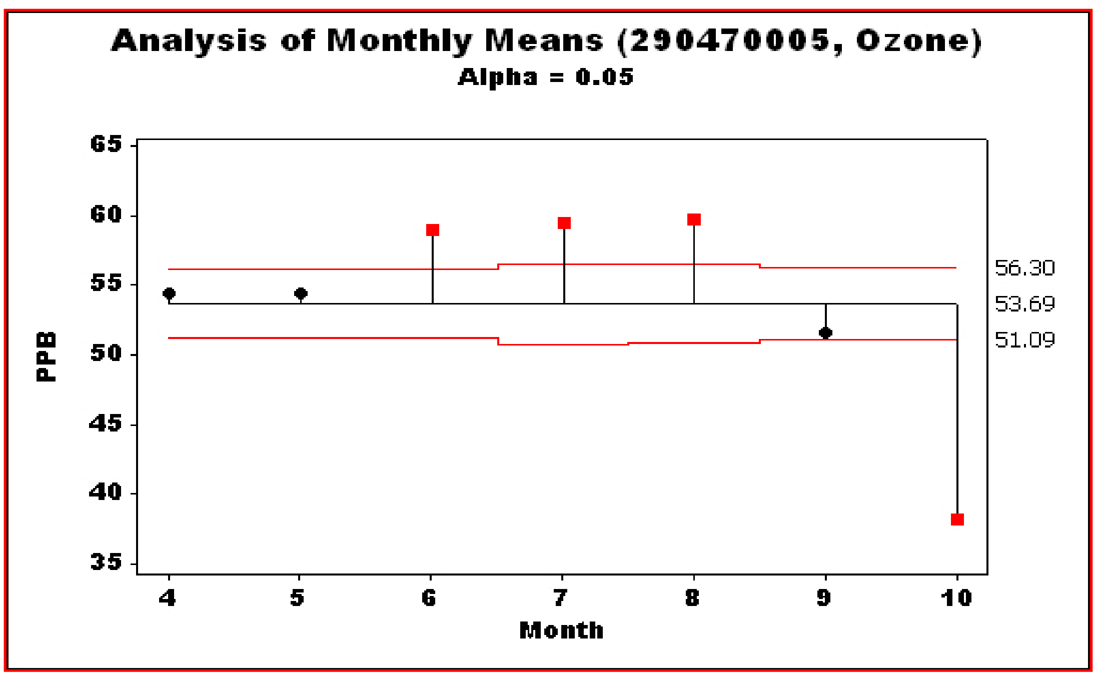


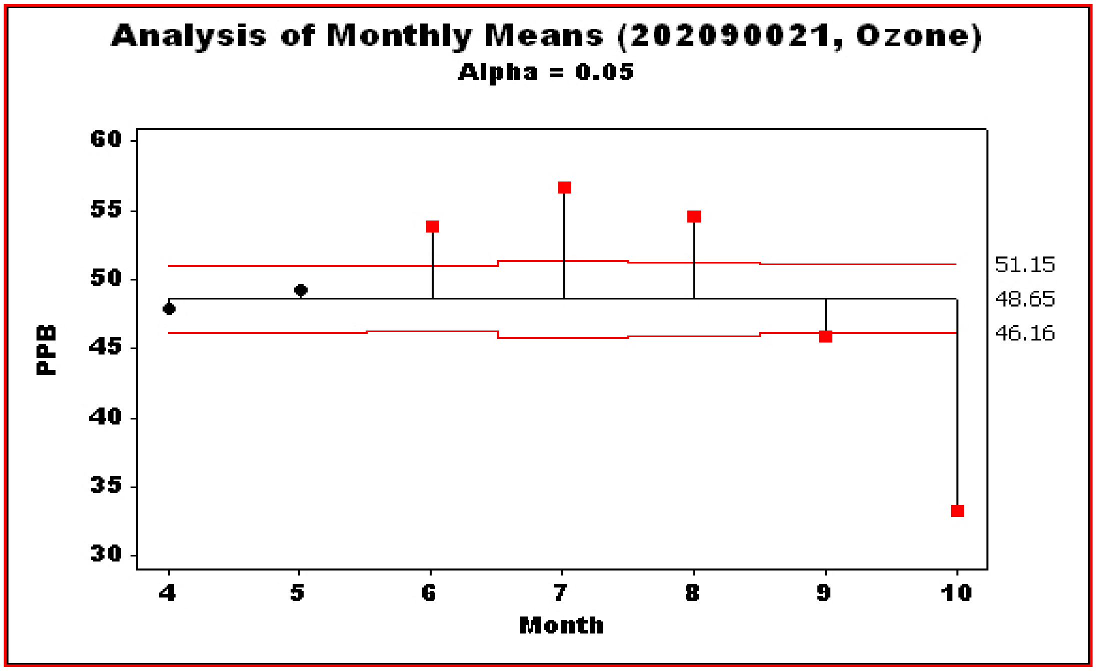


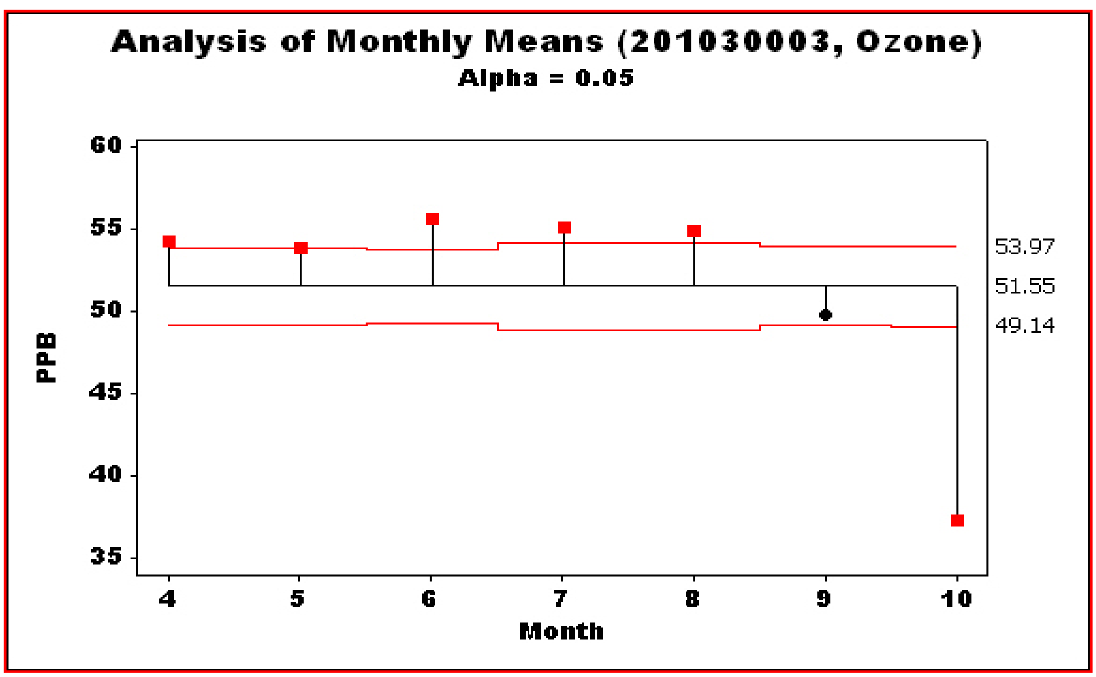

Analysis of Monthly Means (290370003, Ozone)
Alpha = 0.05
PPB
60
55
50
45
40
35
4
5
6
7
8
9
10
Month
53.45
51.17
48.88

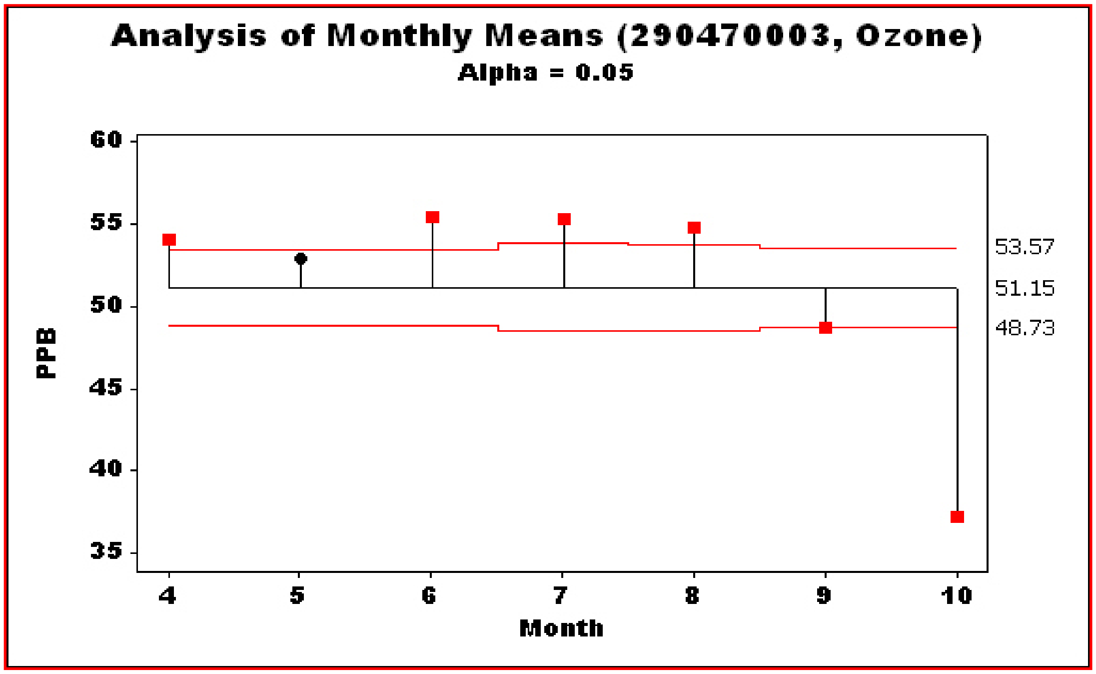

Analysis of Monthly Means (290490001, Ozone)
Alpha = 0.05
PPB
60
55
50
45
40
35
4
5
6
7
8
9
10
Month
55.72
53.15
50.57


Analysis of Monthly Means (290470006, Ozone)
Alpha = 0.05
65
60
55
50
45
40
35
PPB
4
5
6
7
8
9
10
Month
56.78
54.15
51.51


Analysis of Monthly Means (290470005, Ozone)
Alpha = 0.05
65
60
55
50
45
40
35
PPB
4
5
6
7
8
9
10
Month
56.30
53.69
51.09


Analysis of Monthly Means (202090021, Ozone)
Alpha = 0.05
60
55
50
45
40
35
30
PPB
4
5
6
7
8
9
10
Month
51.15
48.65
46.16


Analysis of Monthly Means (201030003, Ozone)
Alpha = 0.05
60
55
50
45
40
35
PPB
4
5
6
7
8
9
10
Month
53.97
51.55
49.14



Analysis of Monthly Means (290470003, Ozone)
Alpha = 0.05
60
55
50
45
40
35
PPB
4
5
6
7
8
9
10
Month
53.57
51.15
48.73

3.1.2 $PM_{2.5}$

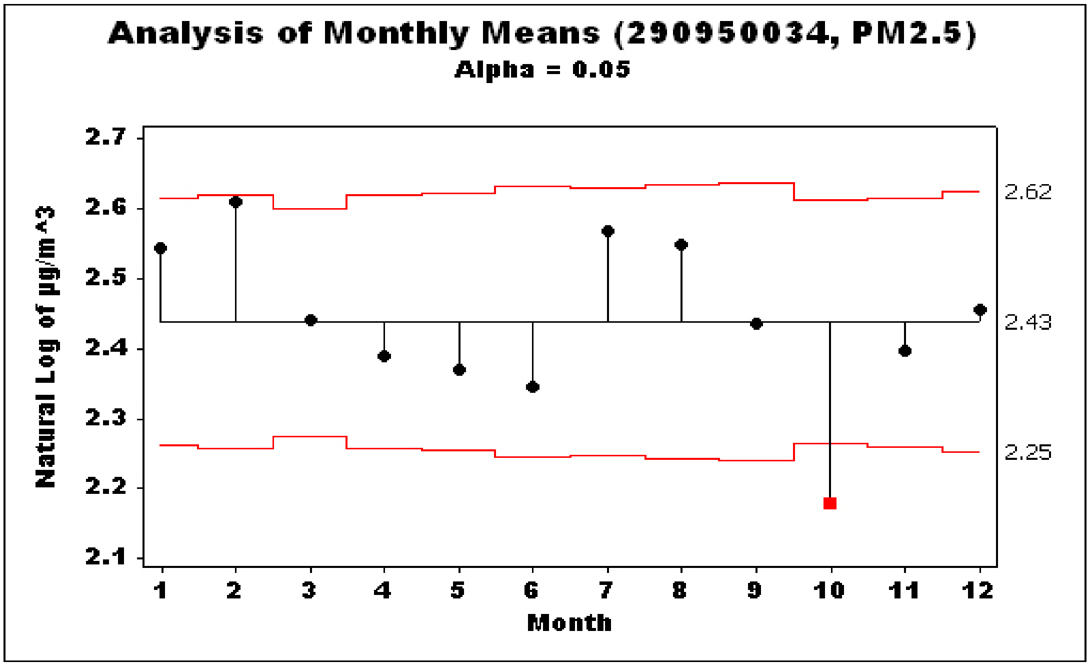
The results of the ANOVA tests conducted on the monthly average $PM_{2.5}$concentrations at the particulate monitoring stations showed that fine particulates in this region have less substantial seasonal variation than ozone. There were no stations that showed significant deviation from the mean for the months of November through June, and September. There were five stations that showed significantly high $PM_{2.5}$ concentrations for July and/or August. Those stations were:

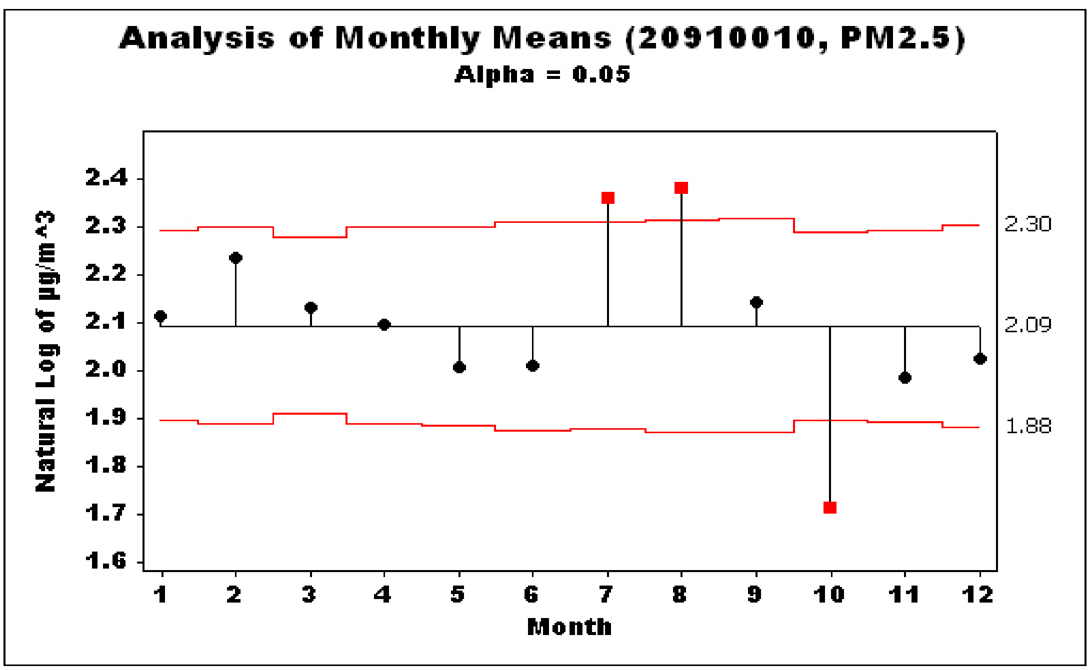
- 202090022, High: July, $p<0.001$, $F = 4.21$
- 202090021, High: July, $p<0.001$, $F = 4.15$
- 200910010, High: July and August, $p<0.001$, $F = 5.28$
- 290370003, High: July and August, $p<0.001$, $F = 5.68$
- 200910007, High: August, $p<0.001$, $F = 5.1$

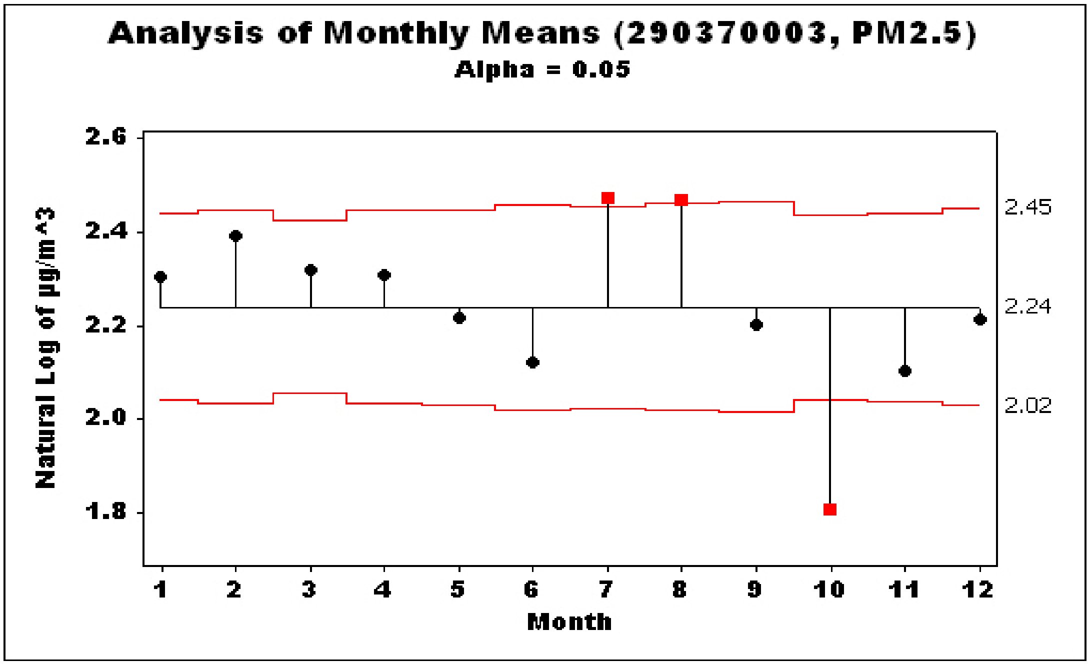
As with the analysis of ozone, all of the stations showed significantly low average concentrations for October.

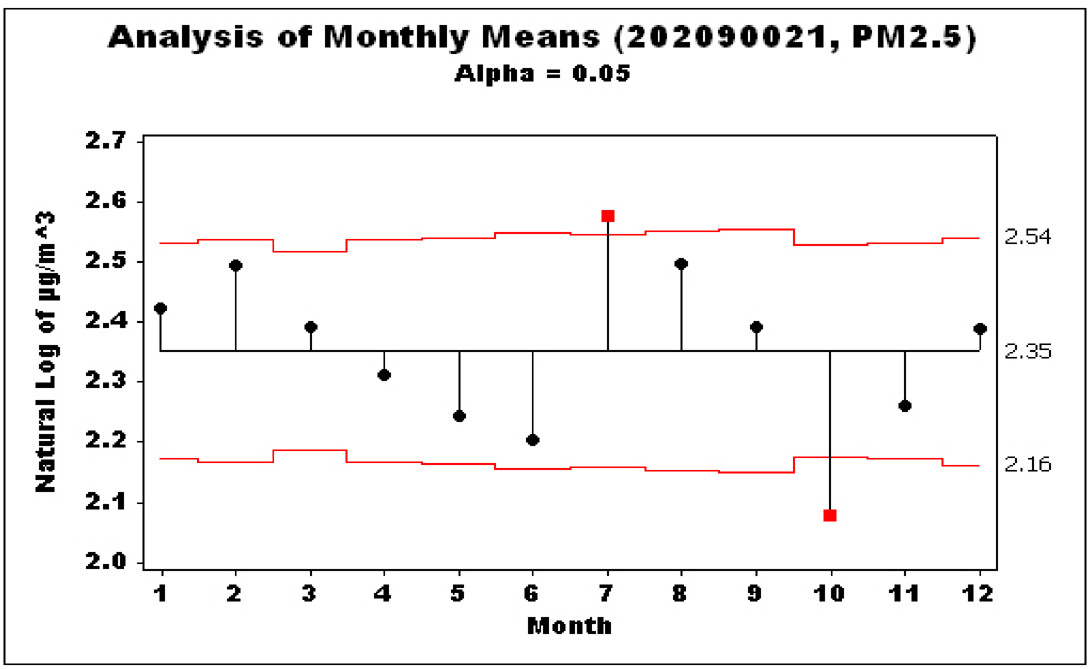
One explanation for the consistently high average concentrations in July and August is the higher levels of humidity and incident solar radiation. The humidity can allow for enhanced hygroscopic growth, and both higher radiation and humidity enhance reactions that produce secondary SO_4 particles (Blanchard 2004). Photochemical reactions that produce organic carbon particulates may also proceed at faster rates during summer months, allowing for higher concentrations of organic carbon particulates in the Kansas City air shed.

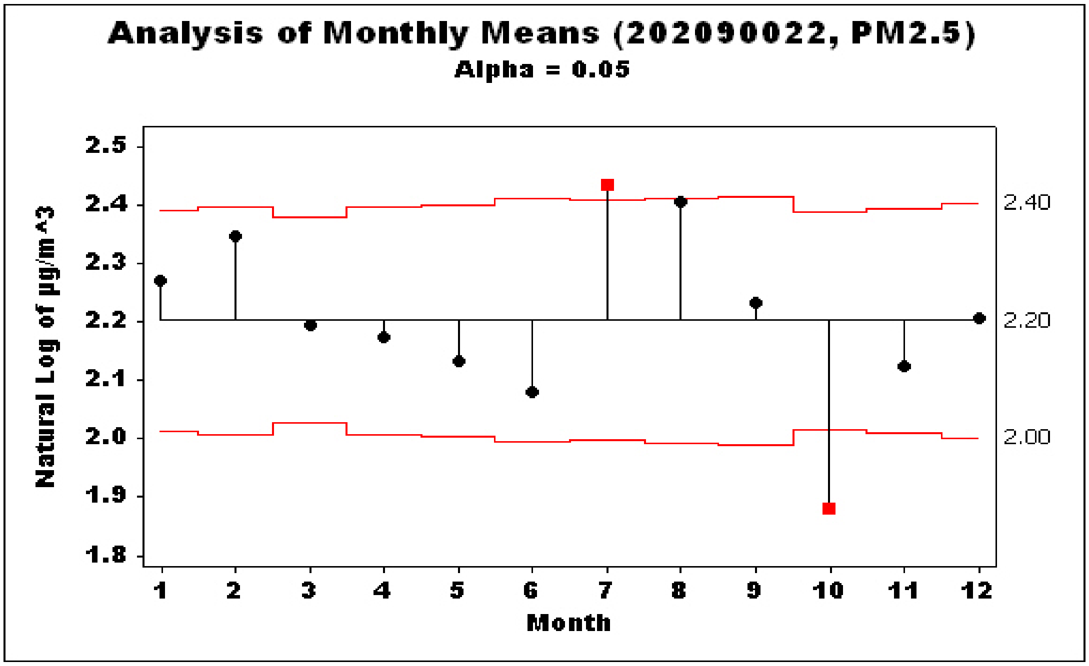
Figure 3.4- Graphical summaries of analysis of mean monthly $PM_{2.5}$ concentrations for selected climatic stations. Red box point symbols imply two-tailed significance.

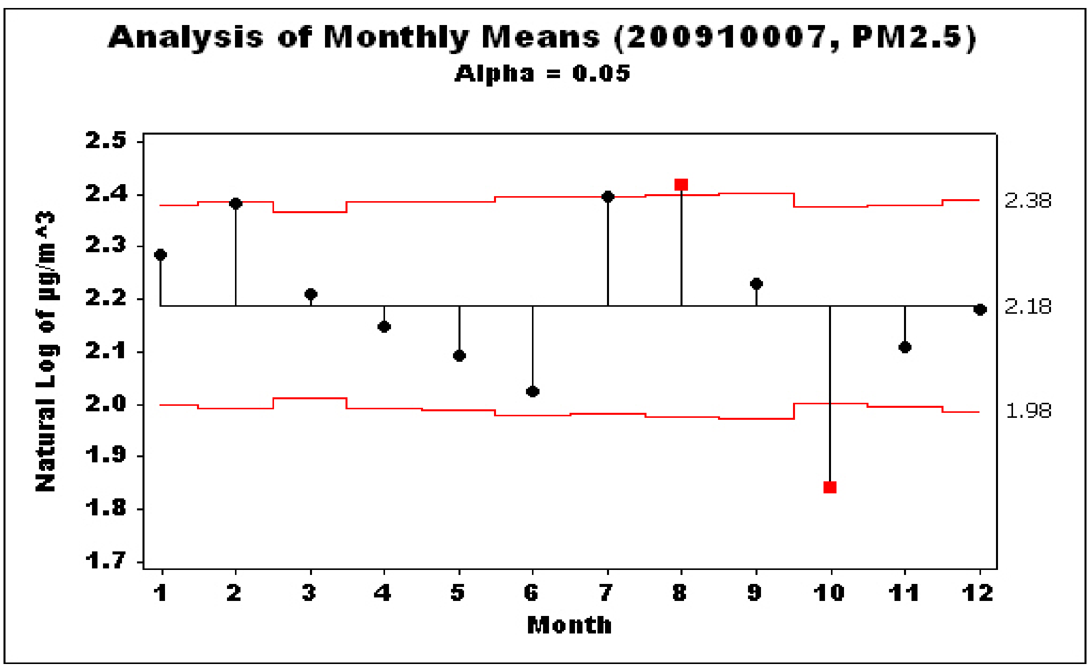





Analysis of Monthly Means (290370003, PM2.5)
Alpha = 0.05
Natural Log of µg/m^3
2.6
2.4
2.2
2.0
1.8
2.45
2.24
2.02
1 2 3 4 5 6 7 8 9 10 11 12
Month


Analysis of Monthly Means (202090021, PM2.5)
Alpha = 0.05
Natural Log of µg/m^3
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2.0
2.54
2.35
2.16
1 2 3 4 5 6 7 8 9 10 11 12
Month

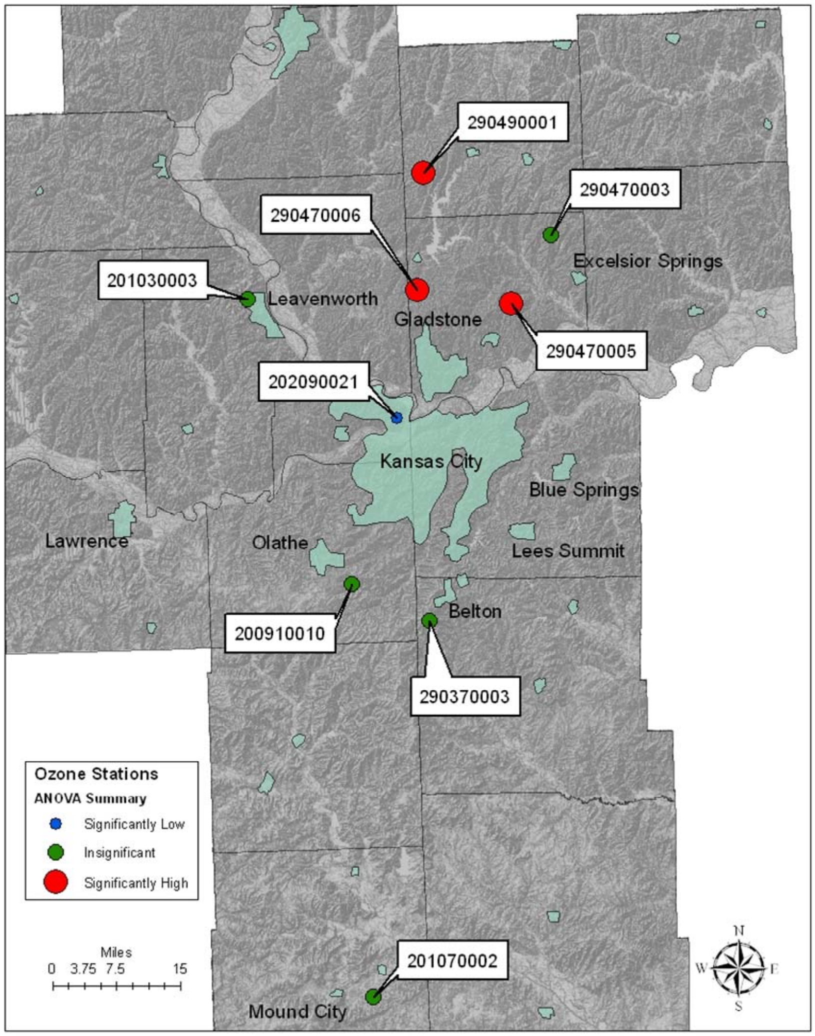

Analysis of Monthly Means (202090022, PM2.5)
Alpha = 0.05
Natural Log of µg/m^3
2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
2.40
2.20
2.00
1 2 3 4 5 6 7 8 9 10 11 12
Month


Analysis of Monthly Means (200910007, PM2.5)
Alpha = 0.05
Natural Log of µg/m^3
2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
2.38
2.18
1.98
1 2 3 4 5 6 7 8 9 10 11 12
Month

3.2 Spatial Variability

3.2.1 Ozone

The results of the ANOVA (see figure 12) conducted on the overall average ozone concentrations for each station showed significant differences in ozone levels depending on location ($p<0.001$, $F = 16.76$). Three stations had significantly high ozone averages (290470006, 290470005, and 290490001), five stations had insignificant ozone averages, and one station had a significantly low ozone average (202090021). All of the stations with significantly high ozone averages are located downwind of Kansas City, and in a rural agricultural setting. While station 290470003 is also located downwind of Kansas City its insignificant average may be explained by the fact that it is located in a rural residential, rather than agricultural, setting. The only station that had significantly low results is also the only station used in the analysis that is located within the Kansas City limits.



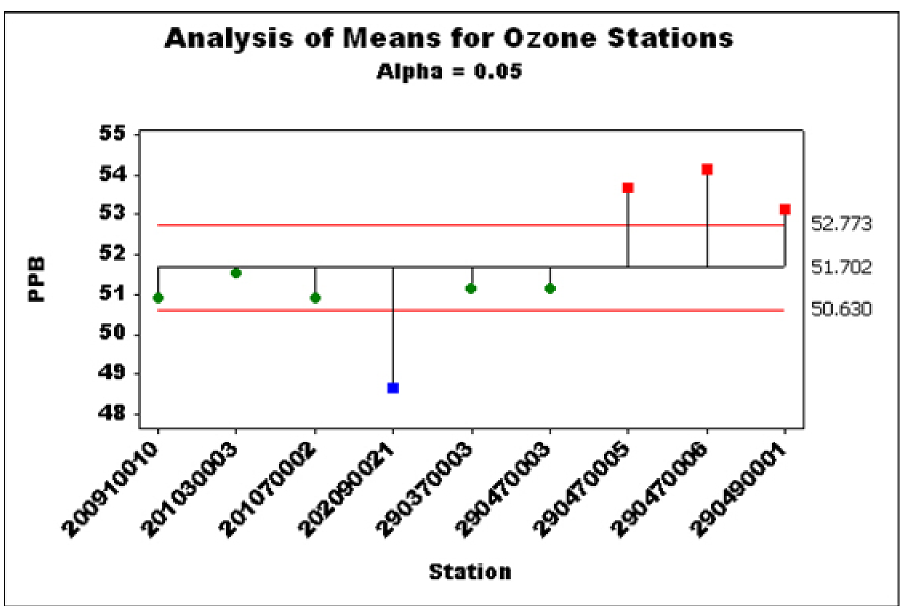
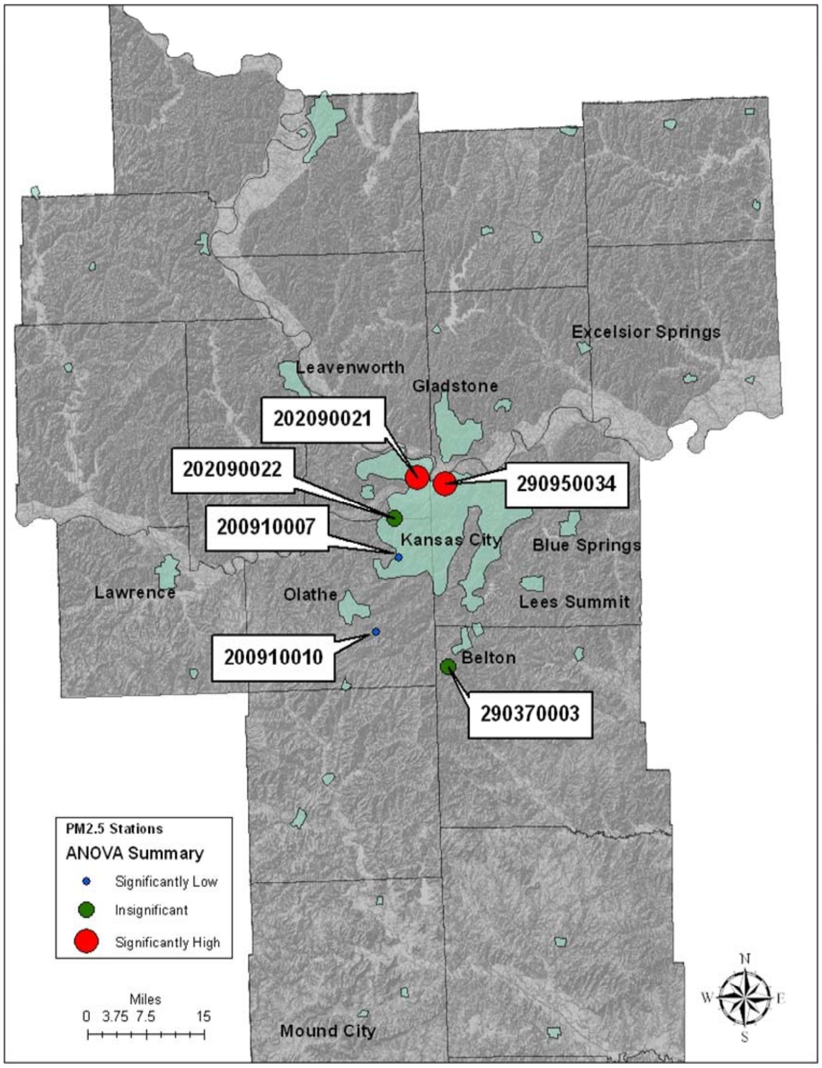


Figure 3.5- Map of the results from the ozone station ANOVA and graphic analysis of means summary.

3.2.2 $PM_{2.5}$

The results of the PM2.5 ANOVA show that the average concentrations differ significantly among stations ($p<0.001$, $F = 32.54$). Two stations (200910010 and 200910007) had significantly low averages, two stations (202090022 and 290370003) had averages that were neither significantly high nor low, and two stations (202090021 and 290950034) had significantly high averages.

As figure 3.6 shows, the stations with significantly low averages are both located either on the fringe of the Kansas City limits or completely outside of the metro area, and generally upwind of Kansas City. Similarly, the insignificant stations are located either outside or on the fringe of Kansas City limits. However, both of the significantly high stations are located more towards the center of Kansas City and farther downwind of the majority of the metropolitan area.



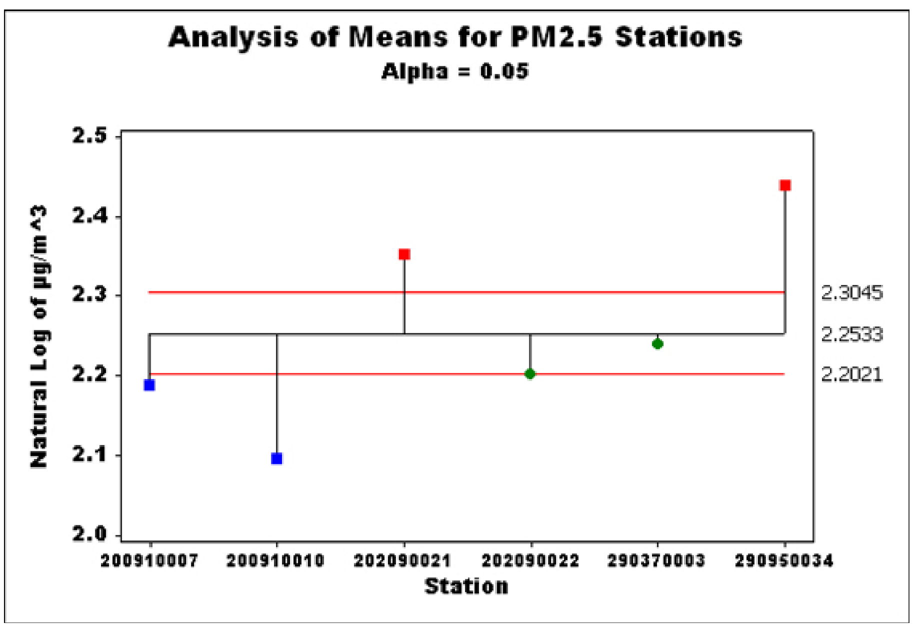


Figure 3.6- Map of the results from the PM2.5 station ANOVA and graphic analysis of means summary.

Chapter 4 - Synoptic Climatology of Pollution

Before comparing the pollution data with the SSC data, the pollution monitoring stations for each pollutant were clustered using a hierarchical average linkage clustering technique. This was done to reduce the data, as well as eliminate collinearity among stations. The $PM_{2.5}$ correlation coefficients all showed similarity around or above $r^2 = 0.92$ (See figure 4.1). Since the $PM_{2.5}$ stations showed no distinct clusters and all of the stations had high similarity levels, an average value was calculated from all of the stations for each day. The cluster analysis of the ozone stations revealed a potential separation into two clusters (cluster 1 stations: 290470006, 290490001, 290470005, 290470003, 201030003, and 202090021; cluster 2 stations: 290370003, 200910010, and 201070002) (See figure 14). The respective stations were averaged together within each potential cluster and compared using an F-test for equal variance as well as a paired T-test for difference of means. Both of the statistical tests showed significant differences between the two clusters at the 95% confidence level (p-values < 0.000). As a result, the clusters remained separate variables. The clusters from both pollutants were then combined with the daily SSC classes. Summary statistics were calculated for the pollutants based on the respective SSC classes (Figures 4.2 and 4.3).

To test the association between the SSC and pollution levels tree-based classification models were built using a non-parametric recursive partitioning technique. It was decided that non-parametric statistical analyses should be conducted because of the unequal frequencies of weather type occurrences. The computation for these models was done using the R statistical analysis environment (http://www.r-project.org).

Most recursive partitioning algorithms are based on a two-stage process: First the observations are grouped based on similarity; second, a constant model in each cell of the resulting partition. One of the most widely-used algorithms of this class is 'CART' (Breiman *et al.* 1984). Traditional partitioning techniques such as CART provide no concept of statistical significance and cannot distinguish between significant and insignificant improvements in the information measure (Mingers 1987). The partitioning methods used to distinguish the effects of synoptic weather types provide p-values at each split, as well as the probability of classification into the respective weather type category.

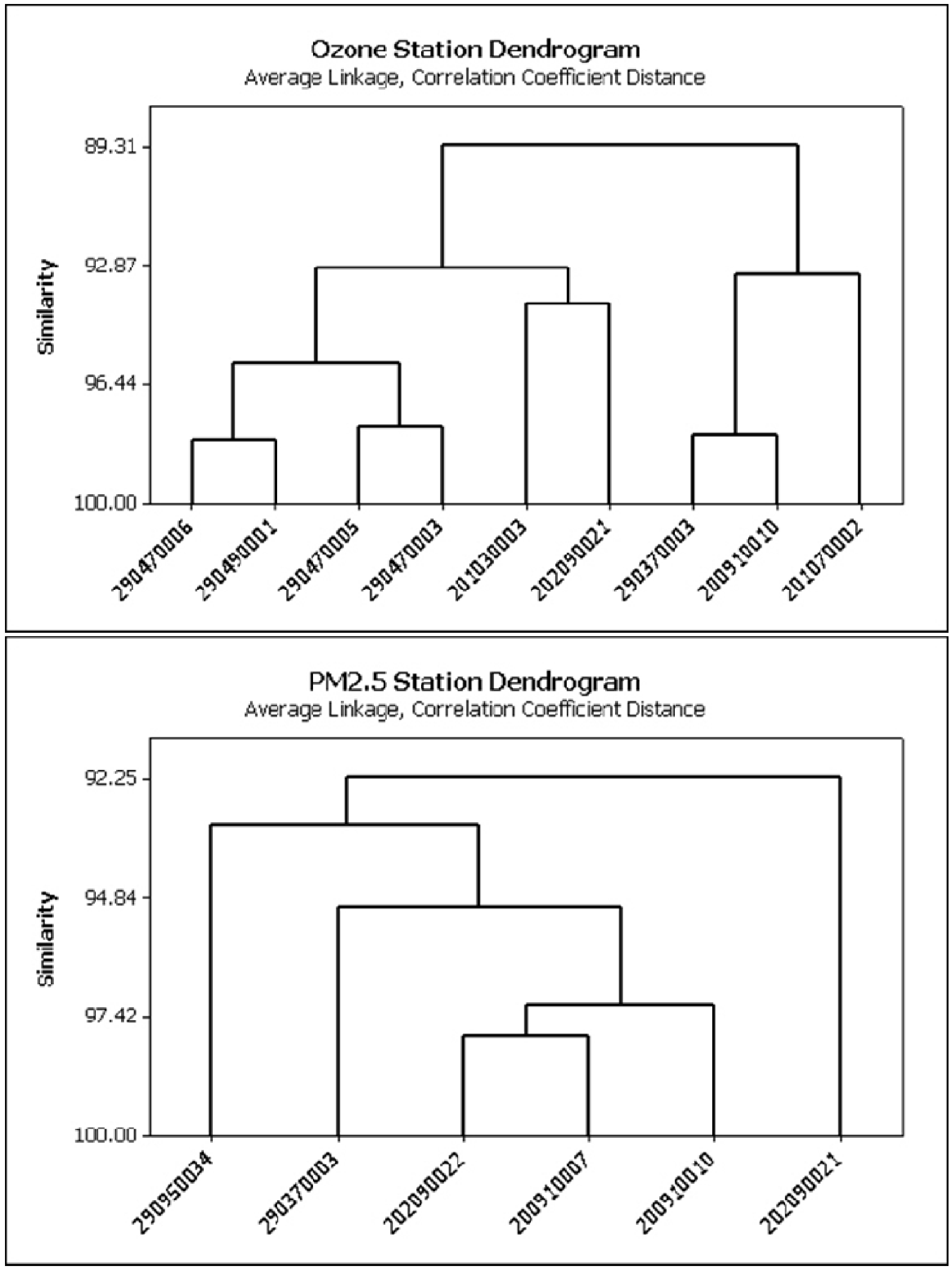
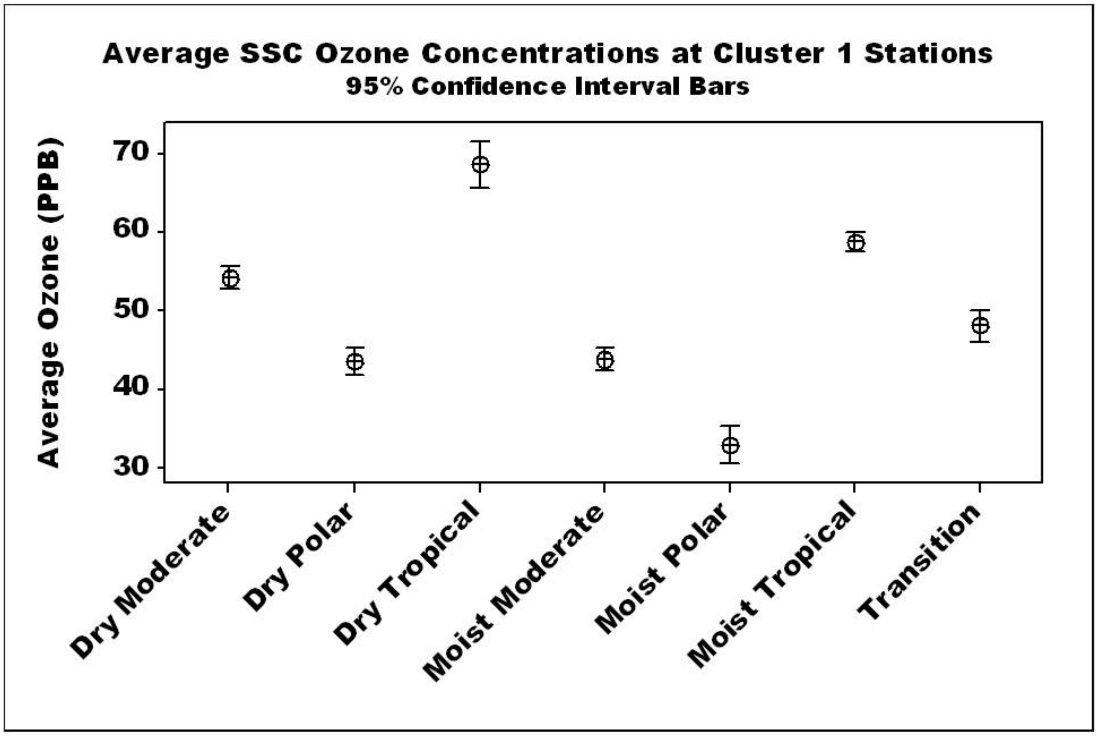


Figure 4.1- Dendrograms of the hierarchical cluster analysis for the ozone and PM2.5 stations.

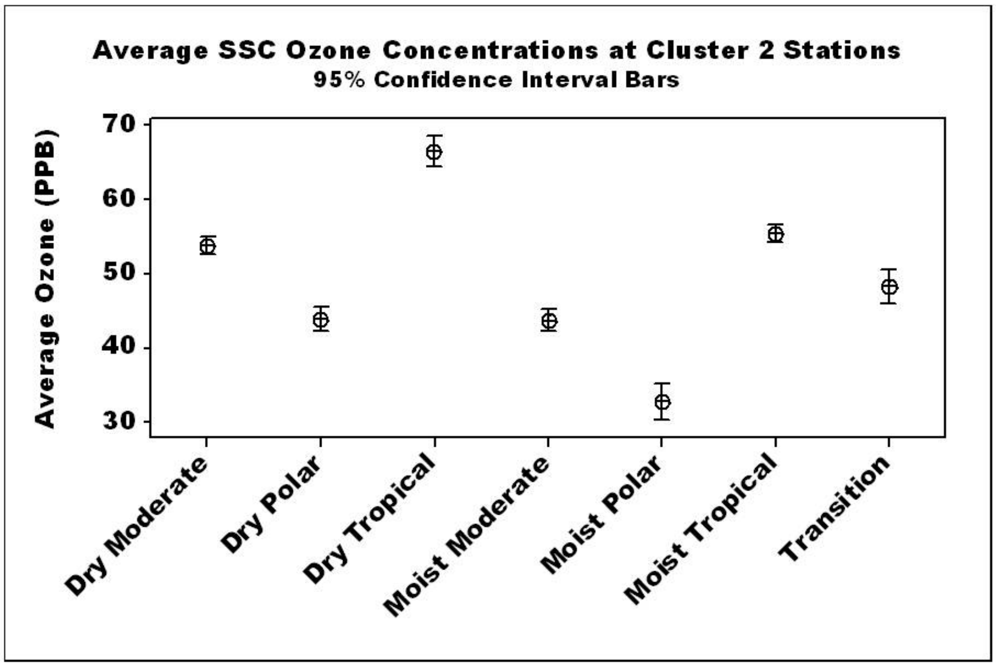
4.1 Ozone

The summary statistics shown in figures 3-21 and 3-22 depict the general effect of each SSC weather type on regional ozone concentrations. The highest ozone concentrations are associated with the hottest, driest weather conditions. These weather types include DT, followed by DM and MT. The MP weather type has, by far, the lowest associated average ozone concentration, followed by DP and MM.



Cluster1	N	Mean	StDev	Minimum	Q1	Median	Q3	Maximum	Skewness	Kurtosis
DM	330	54.11	13.14	26.50	45.38	53.67	61.54	91.33	0.36	-0.10
DP	124	43.50	9.55	20.50	36.21	44.67	50.29	66.50	-0.03	-0.50
DT	61	68.53	11.51	42.50	60.42	68.33	75.33	93.67	0.25	-0.31
MM	174	43.73	10.17	12.83	37.63	44.75	49.67	68.33	-0.33	0.25
MP	68	32.84	9.86	11.33	25.71	32.92	40.54	51.33	-0.02	-0.94
MT	372	58.69	12.64	19.50	49.50	57.25	67.50	96.83	0.22	0.09
TR	98	47.99	10.58	25.50	40.67	48.33	54.96	77.00	0.17	-0.06

Figure 4.2- Summary statistics and graphical representation of mean cluster 1 ozone concentrations for the SSC weather types.



Cluster2	N	Mean	StDev	Minimum	Q1	Median	Q3	Maximum	Skewness	Kurtosis
DM	330	53.87	10.64	25.33	46.58	54.33	61.08	89.00	0.01	0.00
DP	124	43.86	9.54	21.33	36.67	45.33	51.58	62.67	-0.34	-0.55
DT	61	66.68	8.07	45.00	60.83	67.33	72.00	89.00	0.06	0.70
MM	174	43.71	10.18	15.67	38.58	43.67	50.08	75.67	0.06	0.59
MP	68	32.69	10.27	13.00	25.17	32.67	41.33	54.67	-0.01	-0.92
MT	372	55.58	11.33	23.67	47.33	55.00	62.67	91.00	0.27	0.14
TR	98	48.31	11.44	25.33	40.67	47.83	54.17	99.67	1.01	3.34

Figure 4.3- Summary statistics and graphical representation of mean cluster 1

The conditional inference tree-based classification analysis of the ozone and SSC records resulted in six terminal nodes stemming from five binary splits that were significant, with p-values less than 0.001. A terminal node constitutes the point at which dividing the data further does not result in a significant gain in information. Essentially, there are no significant patterns left in the respective group of data. The air mass frequencies within each of terminal nodes are then graphed on a column chart. The terminal nodes (TN) are labeled TN 1 through TN 6 in general order of lowest to highest ozone concentrations.

The first significant split divides observations into groups based on an ozone threshold value of 26 PPB at the cluster 1 stations. There were 39 daily records that were classified into TN 1 (overall node 2), having ozone concentrations ≤ 26 PPB. Of the 39 observations in TN 1, 32 were associated with SSC classifications of either MM or MP. The remaining days were fairly similar frequencies of DP, MT, and TR weather types. There were no occurrences of either the DM or DT weather types in this node. This observation is consistent with previous research that shows that cloud and cold days are not conducive to ozone formation due to the lack of solar radiation.

TN 2 (overall node 5) is comprised of days with maximum ozone concentrations that average between 26 and 43 PPB at the cluster 1 stations. This node had a total of 269 observations and did not have a clearly dominant SSC weather type. The three most frequent weather types in this node occur approximately 20-25% of the time and are DM, MM, and DP. The other three SSC weather types that occur in this node all occur about 10% of the time and are MP, TR, and MT. Again, there are no days with DT weather conditions.

TN 3 (overall node 7) contains 192 records with cluster 1 values ranging between 42 and 49 PPB. The biggest change in SSC frequency that occurs in the transition from TN 2 to TN 3 is an increase from 8% to 26% of node observations that are MT weather types. There is a decrease in MP frequency from 12% to 5%, as well as DP frequency from 20% to 14%.

TN 4 (overall node 8) shows a clear distinction in the SSC vs. pollution association with a significant decrease in MM frequency relative to TN 3, along with significant increases in DM and MT frequencies. Out of the 336 cluster 1 observations with ozone records between 48 and 58 PPB, 109 were on DM days and 113 were on MT days. Together, DM and MT weather patterns occur on 66% of the days in TN 4.

In TN 5 (overall node 10), the MT weather type accounts for the weather conditions on 103 of the 196 days with ozone concentrations between 58 and 63 PPB. The MT weather type is most prominent in this terminal node group because the majority of MT days experience relatively high amounts of solar radiation according to Sheridan's description of the SSC classes. However, these also are a high-humidity and cloud-cover days when at least part of the solar radiation is blocked, which limits the amount of precursor gases that can be converted to ozone.

TN 6 is characterized by a large rise in proportional DT frequency, which makes up 44 of the 195 TN 6 observations. This fact is important considering the DT weather type only occurs a total of 61 times throughout the period of record for this analysis. This means that about72% of days with DT weather conditions were associated with average daily maximum ozone concentrations above 57 PPB across the cluster 1 stations and above 62 PPB across the cluster 2 ozone stations. There were no DP or MP days, and only 3 MM days.

Figure 4.4 - Conditional inference tree from recursive partitioning of cluster 1 and cluster 2 ozone concentrations. Terminal node bar graphs represent the portion of each terminal node comprised of each SSC.

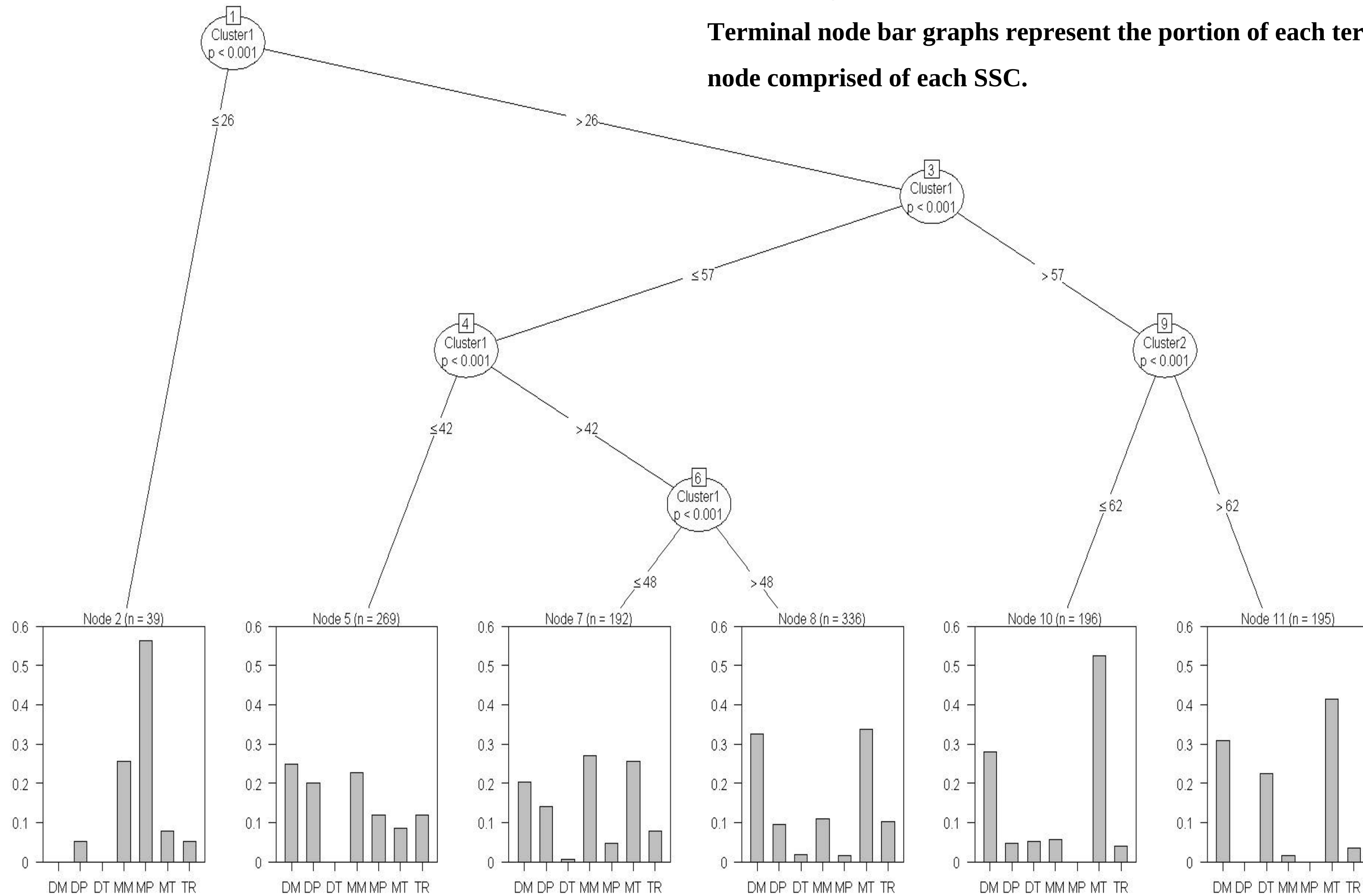


Figure 4.4 – Ozone and SSC conditional inference tree.

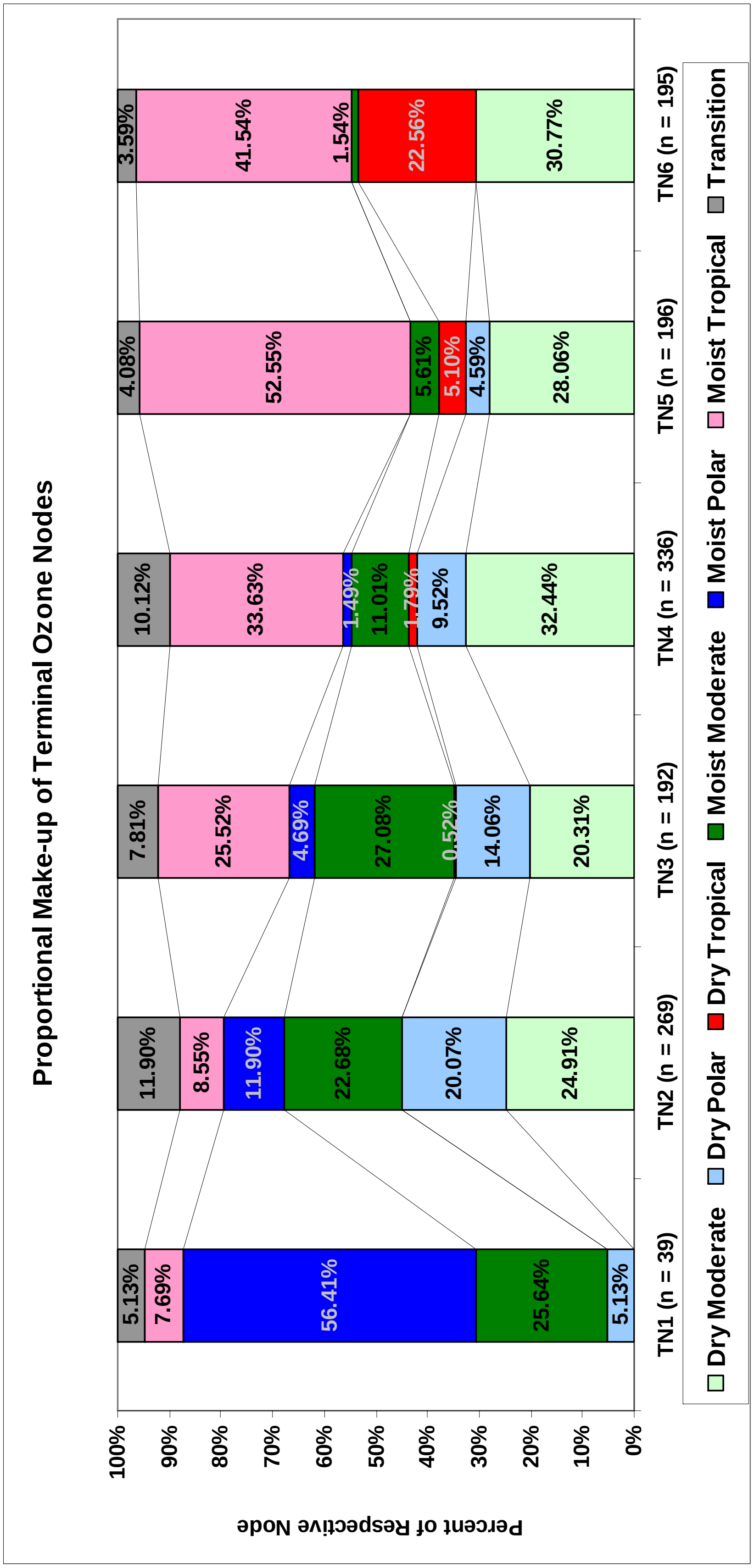


Figure 4.5 - Percent of each terminal node from the ozone recursive partitioning that is made up of each distinct SSC weather type.

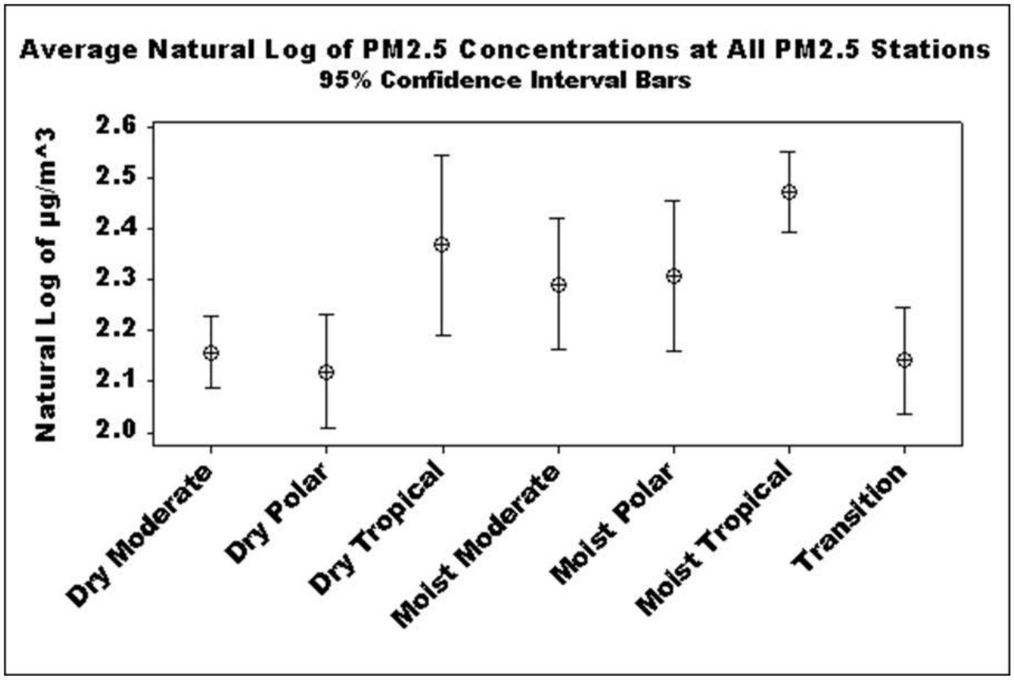
Figure 4.5 – Ozone and SSC conditional inference tree terminal nodes.

4.2 PM2.5

The summary statistics shown in figure 3-25 depict the general effect of each SSC weather type on regional $PM_{2.5}$ concentrations. There is less association among the different SSC weather types and relative concentrations of fine particulates than among the different SSC weather types and relative concentrations of ozone. There is still a pattern of higher concentrations associated with the moist weather types, with the MT weather type having the highest average concentration of $PM_{2.5}$. The DP, DM, and TR weather types are associated with the lowest average $PM_{2.5}$ concentrations.

The recursive partitioning of the fine particulate concentrations resulted in only one significant split of SSC weather types, giving two terminal nodes (See figure 3-26). There are two primary differences between TN 1 and TN 2. The first is the change from a comparatively high occurrence of DM days in TN 1 (approximately 34% of TN 1) to a lower percentage in TN 2 (approximately 20%). The second difference is the change from the MT weather type making up about 10% of TN 1 to about 30% of TN 2.

This analysis of the $PM_{2.5}$ concentrations for each SSC weather type show that there is a significantly higher number of days with MT conditions that are associated with higher concentrations of fine particulates. This conclusion agrees with the theory that higher humidity and solar radiation are more conducive to $PM_{2.5}$ creation through hygroscopic growth and/or chemical reactions.



	N	Mean	StDev	Minimum	Q1	Median	Q3	Maximum	Skewness	Kurtosis
DM	148	2.16	0.44	1.31	1.83	2.12	2.44	3.24	0.36	-0.22
DP	82	2.12	0.51	0.97	1.76	2.00	2.52	3.49	0.35	-0.15
DT	27	2.37	0.45	1.33	2.03	2.44	2.70	3.08	-0.45	-0.28
MM	62	2.29	0.51	1.02	1.93	2.34	2.64	3.27	-0.36	-0.13
MP	55	2.31	0.55	1.07	2.01	2.30	2.71	3.62	-0.27	-0.02
MT	107	2.47	0.42	1.41	2.18	2.46	2.71	3.50	0.08	-0.04
TR	64	2.14	0.42	1.11	1.84	2.15	2.47	2.85	-0.32	-0.37

Figure 4.6- Summary statistics and graphical representation of mean PM2.5 concentrations for the SSC weather types.

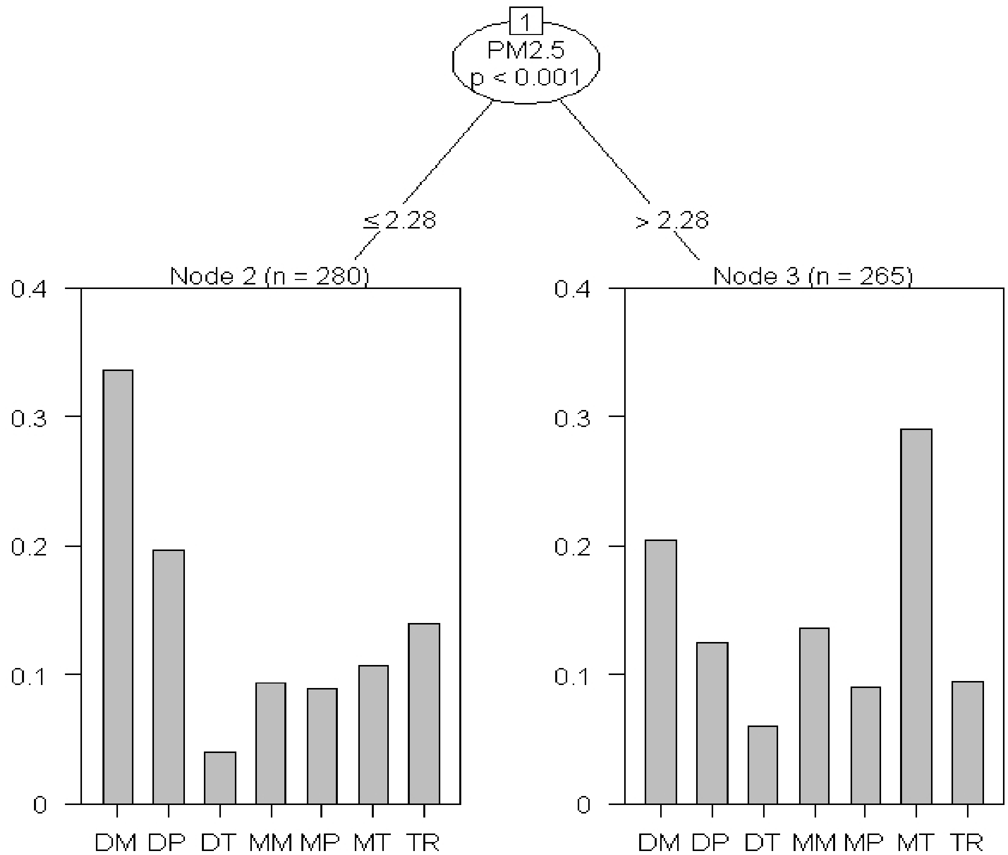


Figure 4.7- Conditional inference tree from recursive partitioning of PM2.5 concentrations. Terminal node bar graphs represent the portion of each terminal node comprised of each SSC.

4.3 Combined Pollutants

There were three monitoring stations that had coinciding $PM_{2.5}$ and ozone periods of record (see figure 2.4). Since it is difficult to determine the relationship between the SSC weather types and the particular effect of rangeland burning emissions on Kansas City air quality by analyzing the individual pollutant concentrations, a similar tree-based analysis was conducted using observations of both $PM_{2.5}$ and ozone.

Figure 4.8 shows the results of the combined tree-based analysis. When analyzed together, the differences in pollution concentrations result in four terminal nodes (TN 1 – TN 4) depicting statistically significant associations with differentiated SSC air mass groups. The frequencies of the SSC weather types within each of the terminal nodes are shown in figure 4.9.

The 13 observations in TN 1 are comprised of occurrences of DP (23%), MM (23%), MP (46%), and TR (8%), and have ozone levels lower than or equal to 25 ppb.

TN 2 is comprised of 88 observations with ozone concentrations between 26 and 61 ppb and $PM_{2.5}$ concentrations less than or equal to 7.93 $\mu g/m^3$. Again, there are no days with DT weather conditions. However, there is an increase in proportional DM occurrences, which account for about 47% of TN 2 observations. The rest of the TN 2 observations are fairly evenly distributed among the other 5 weather types.

TN 3 has a total of 95 observations, and represents days with ozone concentrations between 26 and 61 ppb and $PM_{2.5}$ concentrations greater than 7.93 $\mu g/m^3$. This group is dominated by MT, DM, and MM weather types, which account for about 42%, 23%, and 16% of TN 3 observations, respectively.

TN 4 contains 64 observations that have ozone concentrations greater than 61 ppb and $PM_{2.5}$ concentrations greater than 7.93 µg/m^3. There are no occurrences of MM or MP in this group. MT accounts for about 45% of TN 4 observations. DM and DT account for about 31% and 16%, respectively.

The combined analysis showed similar results to those of the individual analyses, that is, hotter and drier weather conditions are more conducive to higher ozone levels, while hotter and moister weather conditions are more conducive to higher particulate levels. It also revealed that MP weather conditions are rarely associated with high concentrations of both pollutants, while it is relatively more common to have high concentrations of both pollutants with the MT and DT weather types.

Figure 4.8 - Conditional inference tree from recursive partitioning of combined ozone and $PM_{2.5}$ concentrations. Terminal node bar graphs represent the portion of each terminal node comprised of each SSC.

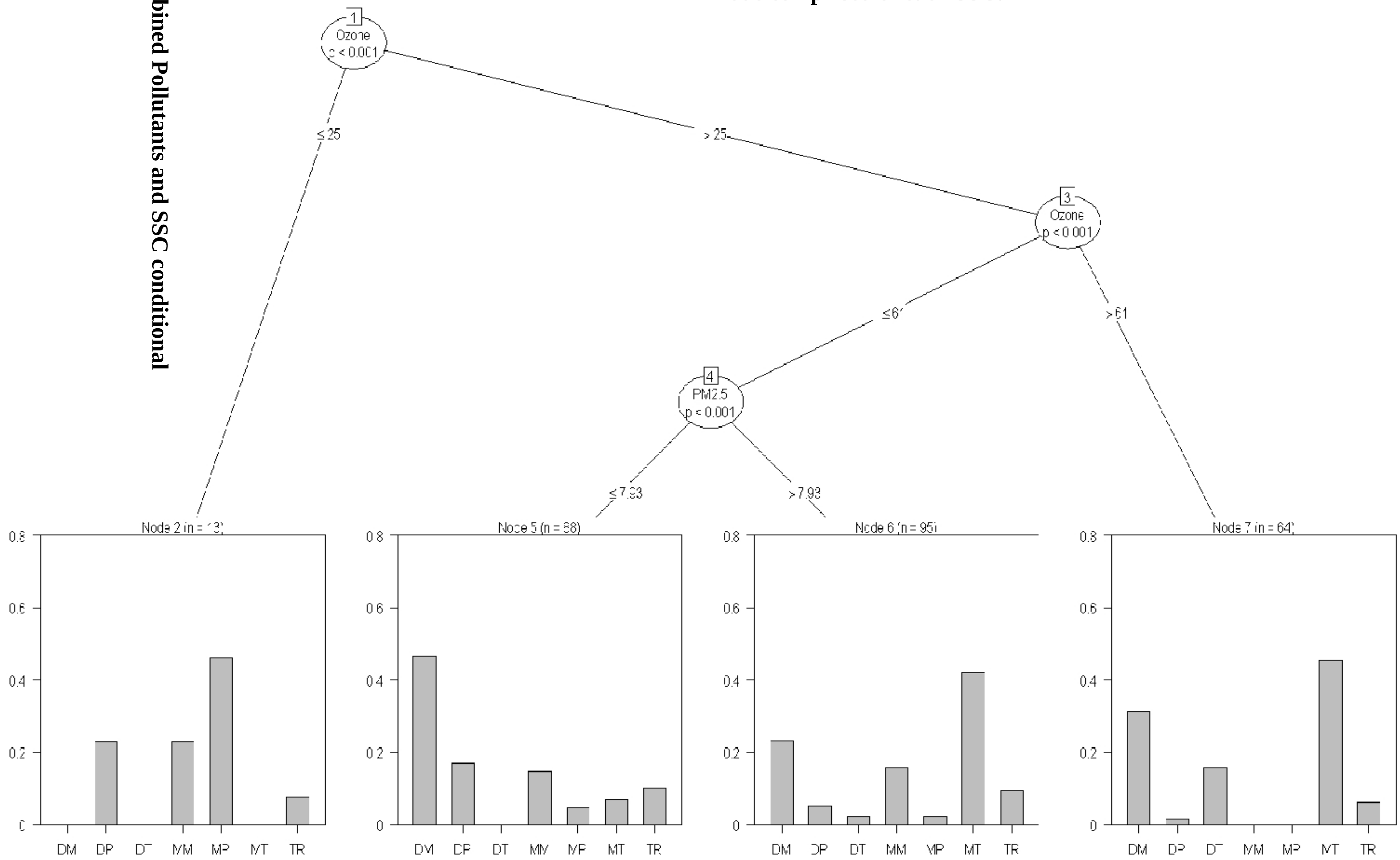


Figure 4.8 Combined Pollutants and SSC conditional inference tree.

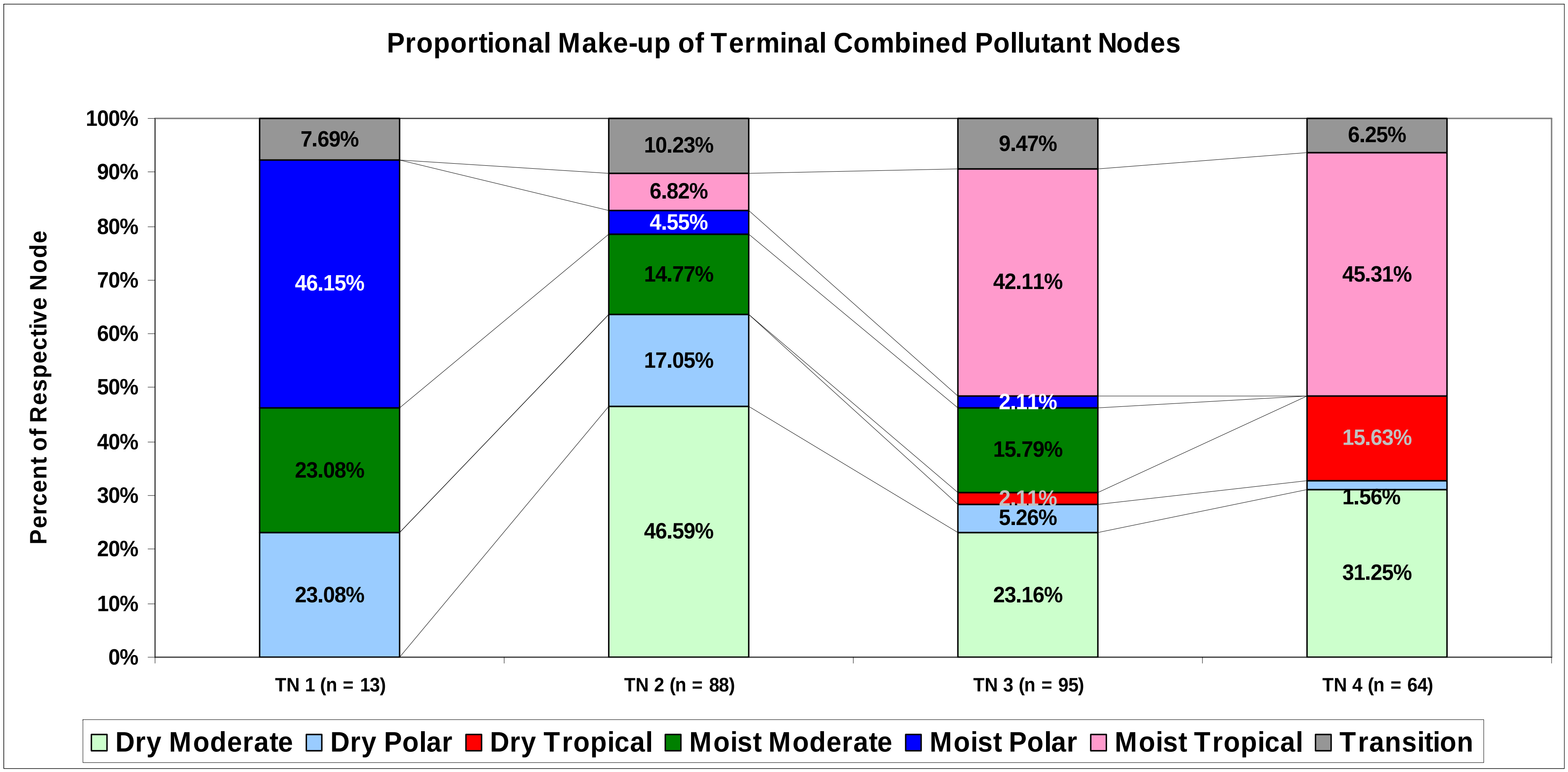


Figure 4.9 - Percent of each terminal node from the combined pollutants recursive partitioning that is made up of each distinct SSC weather type.

Figure 4.9 Combined pollutants and SSC conditional inference tree terminal nodes

Chapter 5 - Conclusions

Urban air quality is closely linked to local and regional meteorological conditions. Synoptic climatology provides an efficient way to compare the effects of multiple weather parameters on atmospheric pollution behavior simultaneously. Since the relationship between climatic conditions and air quality is extremely complex, it is important to study these effects at local and regional spatial scales. My thesis examined the impact of synoptic weather conditions parameterized by a hybrid synoptic climatological scheme known as the Spatial Synoptic Classification (SSC) on ozone and PM2.5 concentrations in the Kansas City metropolitan area. The analyses used pollution records from nine ozone monitoring stations and six $PM_{2.5}$ monitoring stations located in and around Kansas City and the surrounding suburbs.

The degree of the impact that the atmospheric emissions from rangeland burning in the Flint Hills can have on Kansas City air quality varies and can be a potential health threat to residents living in and around the Kansas City metro area. Because this burning is such an important part of sustaining a healthy nutrition source for cattle, ceasing to burn is not an option. Thus, efforts to minimize the impact of the pollution introduced from the burning must be taken. By understanding the role that meteorology plays on the interactions of the air pollution from the Flint Hills biomass burning and the urban air-shed, efforts to minimize the negative impact of the burning on downwind air quality will be much more effective.

Statistical analysis of the spatial and temporal variations in Kansas City ozone and fine particulate concentrations showed that there is significant spatial and temporal variability. Specifically, ozone concentrations are consistently highest in the areas that are downwind of the Kansas City metro area, and lowest in the center of Kansas City's urban area. Also, $PM_{2.5}$ concentrations are highest in the heart of the urban area, and lowest in the areas that are upwind of Kansas City. Ozone concentrations have a high seasonal component, with higher concentrations during the summer months and lower concentrations during the spring and fall months. $PM_{2.5}$ concentrations were generally highest during July and August and lowest during October.

Analysis of the ability of the SSC to characterize ozone and $PM_{2.5}$ behavior showed that both ozone and $PM_{2.5}$ are significantly impacted by different SSC weather types. The weather types representing the driest and hottest meteorological conditions were consistently associated with the highest ozone concentrations. The SSC weather types with the coldest conditions were associated with the lowest ozone concentrations. The highest $PM_{2.5}$were associated with the MT weather type, which is the hottest and most humid of the SSC weather types. The driest and coldest weather conditions were associated with the lowest $PM_{2.5}$ concentrations. The SSC weather types that had a common significant effect on both ozone and $PM_{2.5}$ were the MT weather type, which was associated with high concentrations of both pollutants, and the DP weather type, which was associated with low concentrations of both pollutants.

5.1 Limitations and Future Work

There were large amounts of missing data and only data from April through October for a seven-year period could be used in the analyses. With air pollution, it is important to study long-term trends as well as short-term interactions. Results of similar future studies might be improved by synchronizing regional air pollution monitoring stations to provide more accurate data on the regional pollution behavior. Better temporal signatures could also constructed by extending the annual monitoring into March on all regional monitors. This could also potentially provide more insight into the drastic October decrease in both ozone and $PM_{2.5}$.

This study also showed that using synoptic climatological classification schemes such as the SSC can be useful and efficient in characterizing atmospheric pollution behavior. Since the SSC is relatively new, it may be useful to expand the analysis into other urban and non-urban areas to get a better idea of the air shed dynamics and the role that weather plays in the local and regional air quality.

One weakness of the size-based aerosol classification system is that there can be different species of aerosols with different emission sources that have the same size, and subsequently be classified into the same category. It might be useful to conduct a speciation analysis on $PM_{2.5}$ concentrations and relate various species' behavior to different synoptic weather conditions. This could potentially provide useful information regarding the effect of weather on particulates that can be directly linked to the biomass burning in the Flint Hills.

A good next step in understanding the direct impact on Kansas City air quality from the Flint Hills burning would be to compare historical pollution records with historical burn records and analyze the potential correlations against specific SSC weather types, or other parameters of interest.

Appendices

Appendix A.

SSC Weather types

DP (dry polar) is synonymous with the traditional cP air mass classification. This air mass is generally advected from Polar Regions around a cold-core anticyclone, and is usually associated with the lowest temperatures observed in a region for a particular time of year, as well as clear, dry conditions.

DM (dry moderate) air is mild and dry. It has no traditional analog, but is often found with zonal flow in the middle latitudes, especially in the lee of mountain ranges. It also arises when a traditional air mass such as cP or mT has been advected far from its source region and has thus modified considerably.

DT (dry tropical) air is similar to the cT air mass; it represents the hottest and driest conditions found at any location. There are two primary sources of DT: either it is advected from the desert regions, such as the Sonora or Sahara Desert, or it is produced by rapidly descending air, whether via orography (such as the Chinook) or strong subsidence.

MP (moist polar) air is a large subset of the mP air mass; weather conditions are typically cloudy, humid, and cool. MP air appears either by inland transport from a cool ocean, or as a result of frontal overrunning well to the south of the region. In can also arise in situ as a modified cP air mass, especially downwind of the Great Lakes.

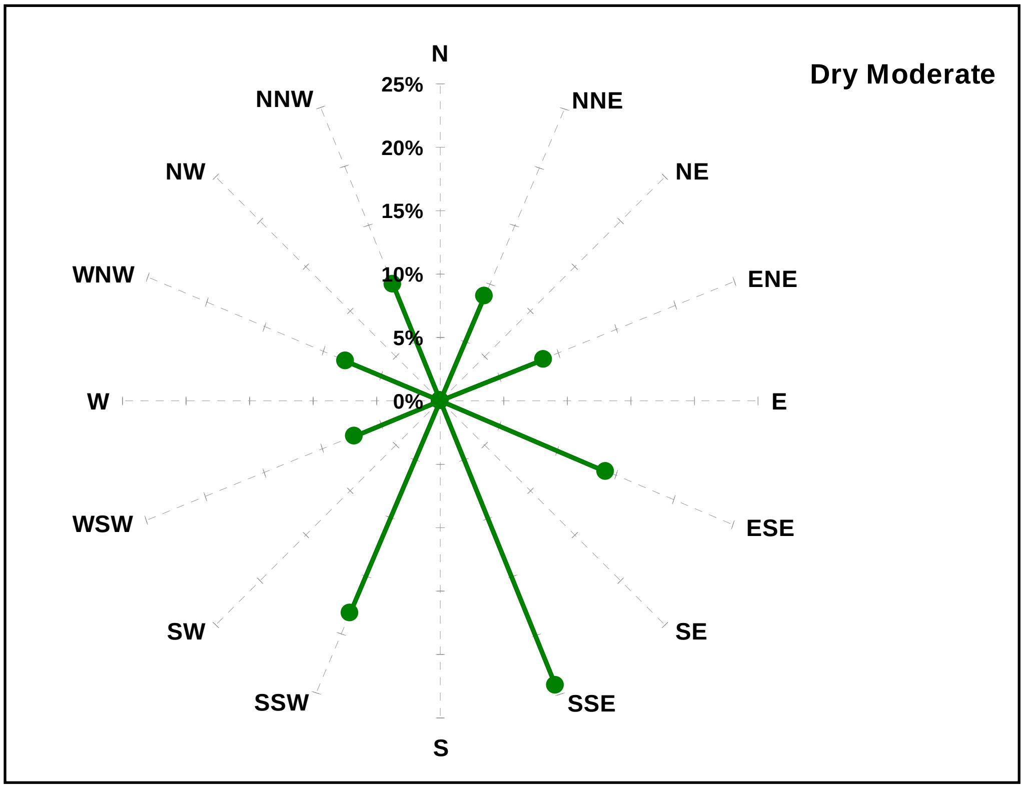
MM (moist moderate) is considerably warmer and more humid than MP. The MM air mass typically appears in a zone south of MP air, still in an area of overrunning but with the responsible front much nearer. It can also arise within an mT air mass on days when high cloud cover suppresses the temperature.

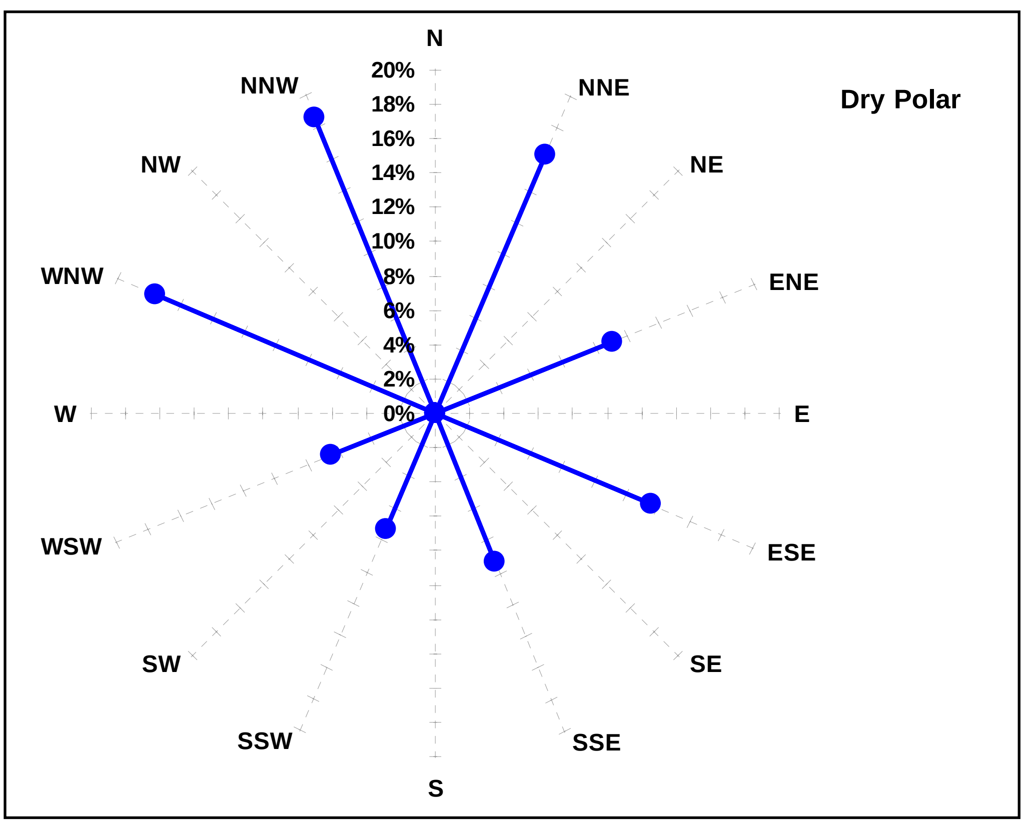
MT (moist tropical), analogous to the traditional mT air mass, is warm and very humid. It is typically found in warm sectors of mid-latitude cyclones or in a return flow on the western side of an anticyclone; as one approaches the tropics this weather type dominates.

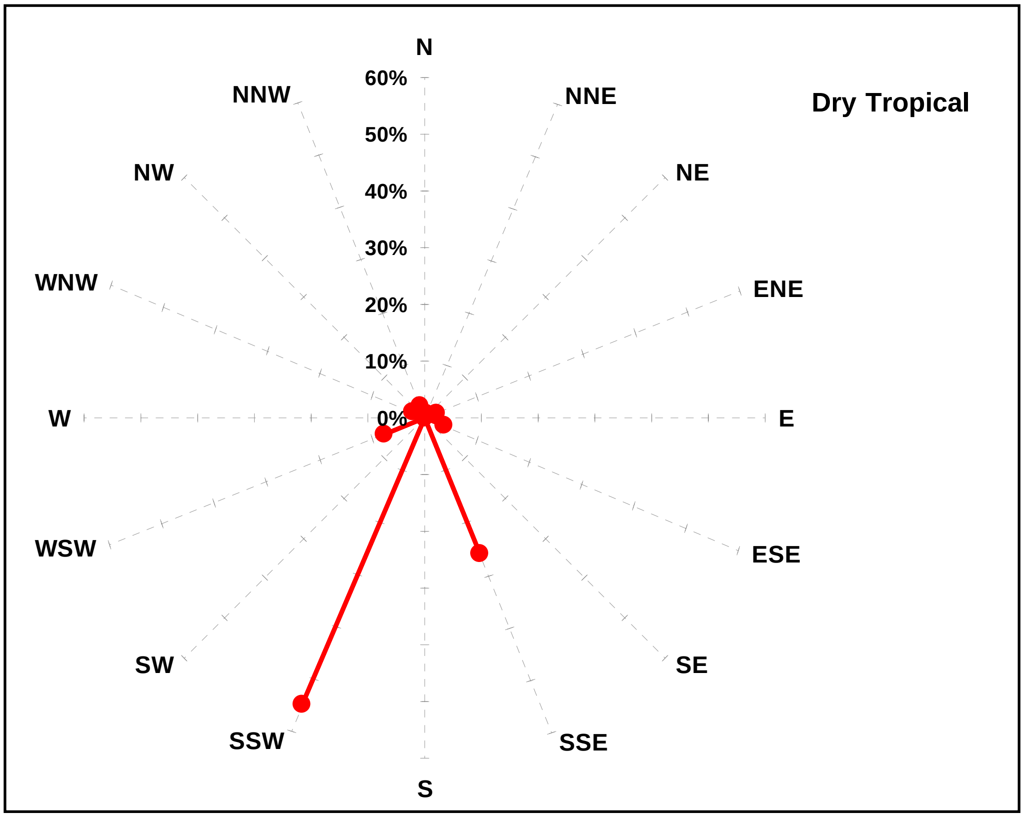
TR (transitional) days are defined as days in which one weather type yields to another, based on large shifts in pressure, dew point, and wind over the course of the day.

Appendix B.

Wind Roses for SSC Weather Types



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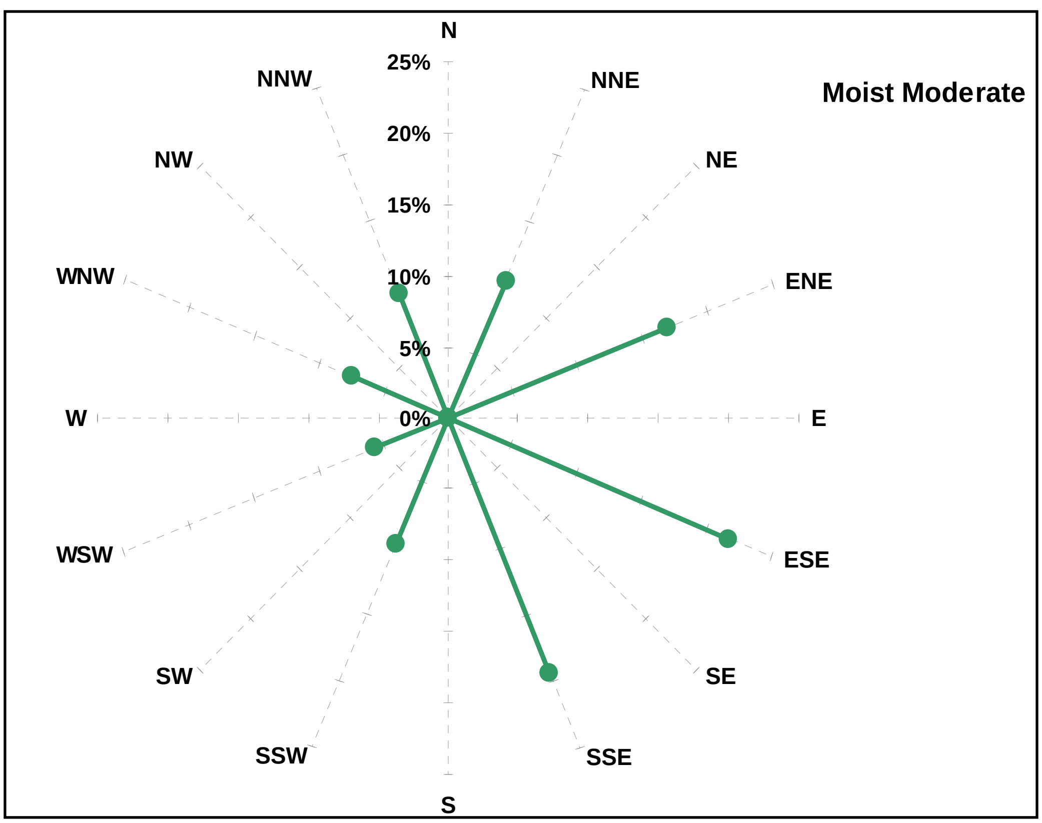
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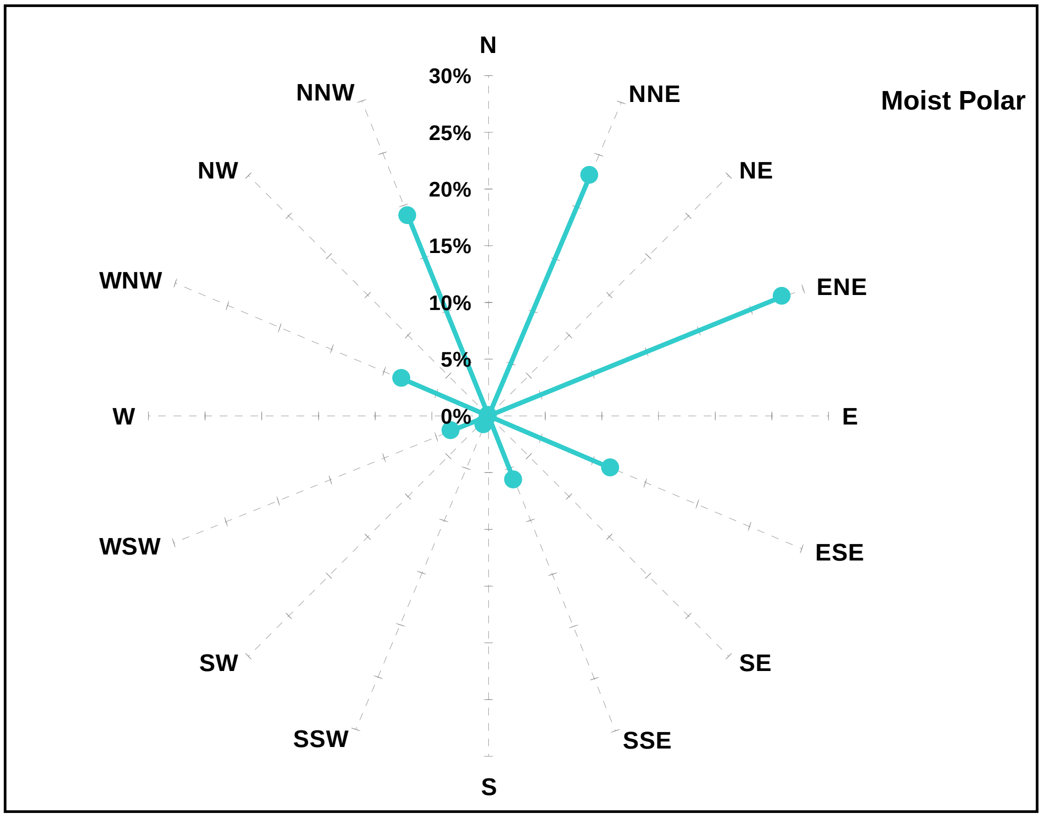
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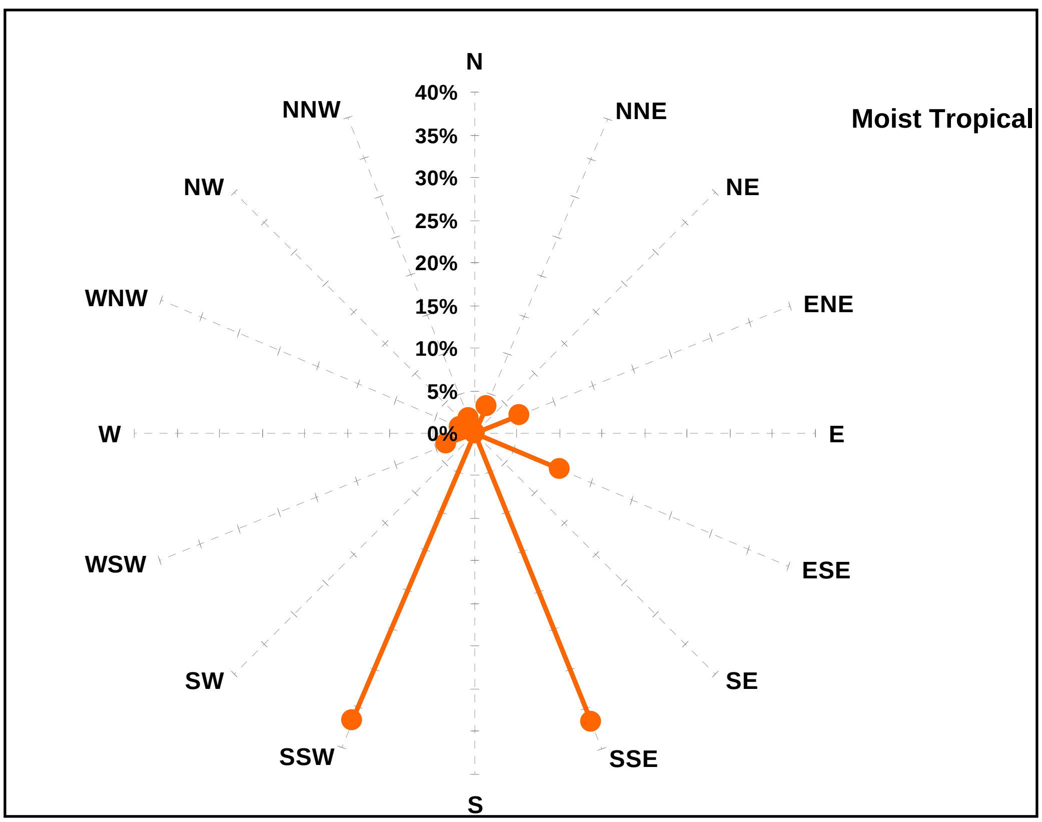
Moist Tropical
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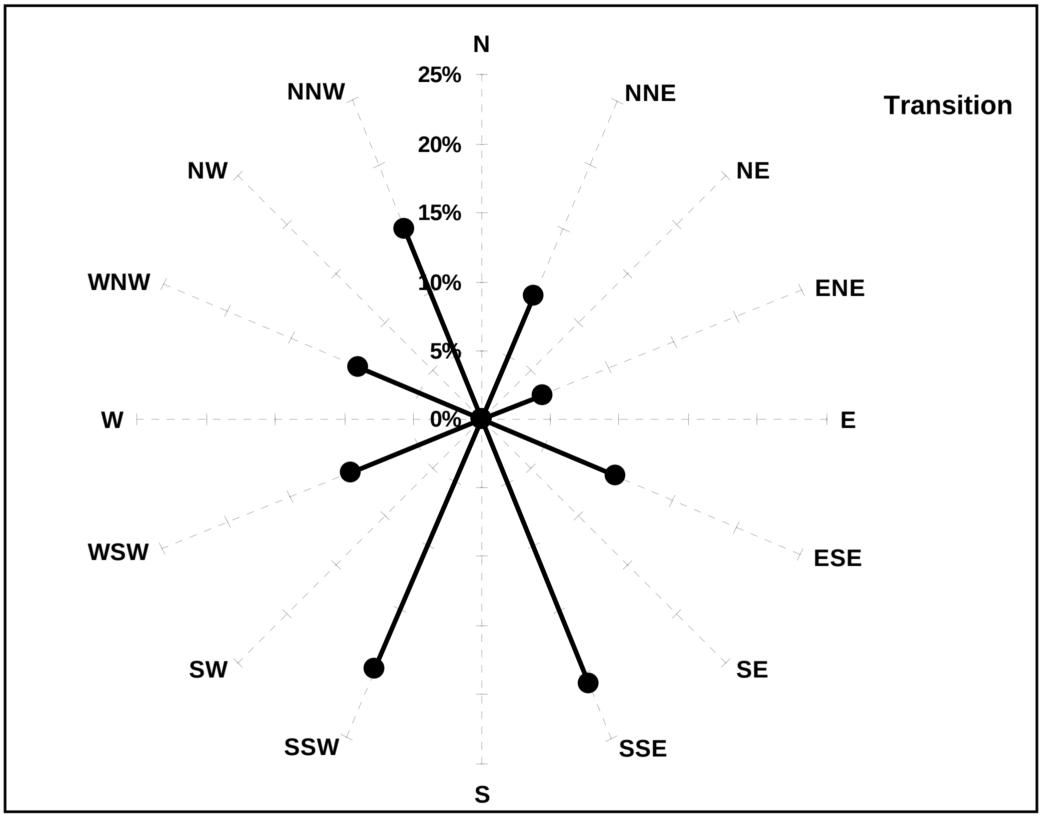
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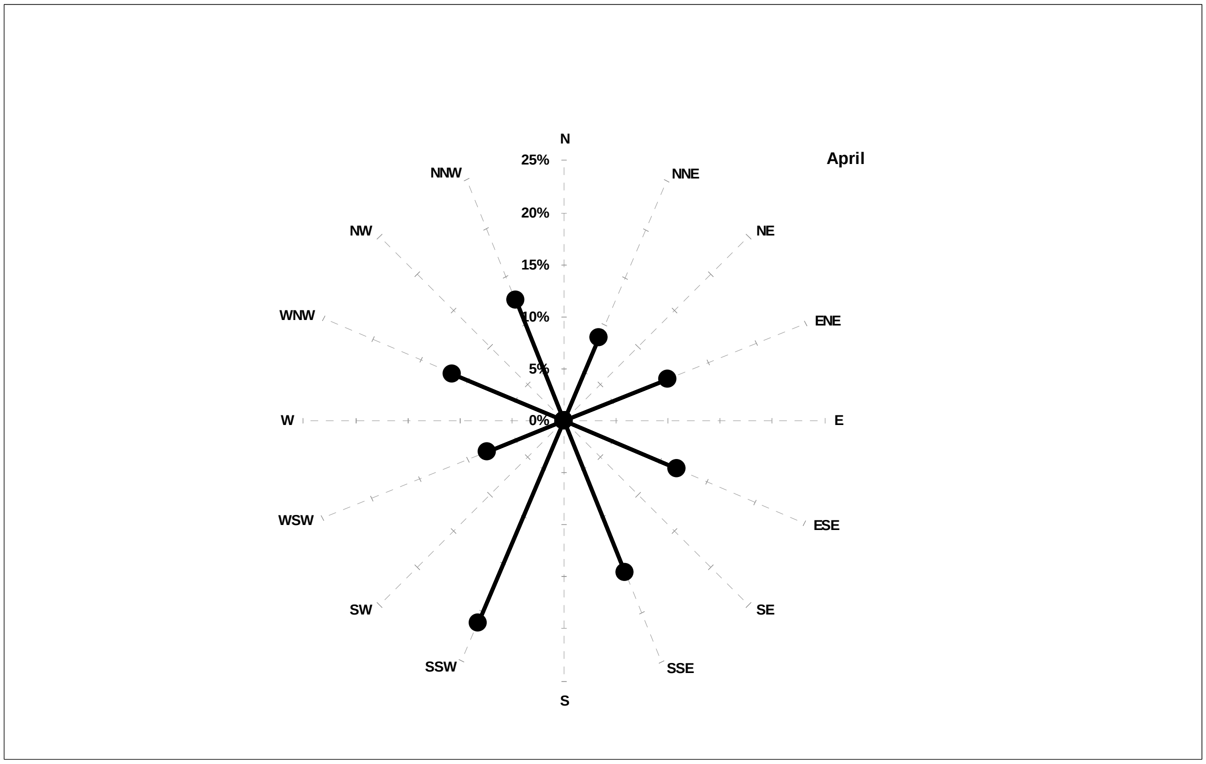
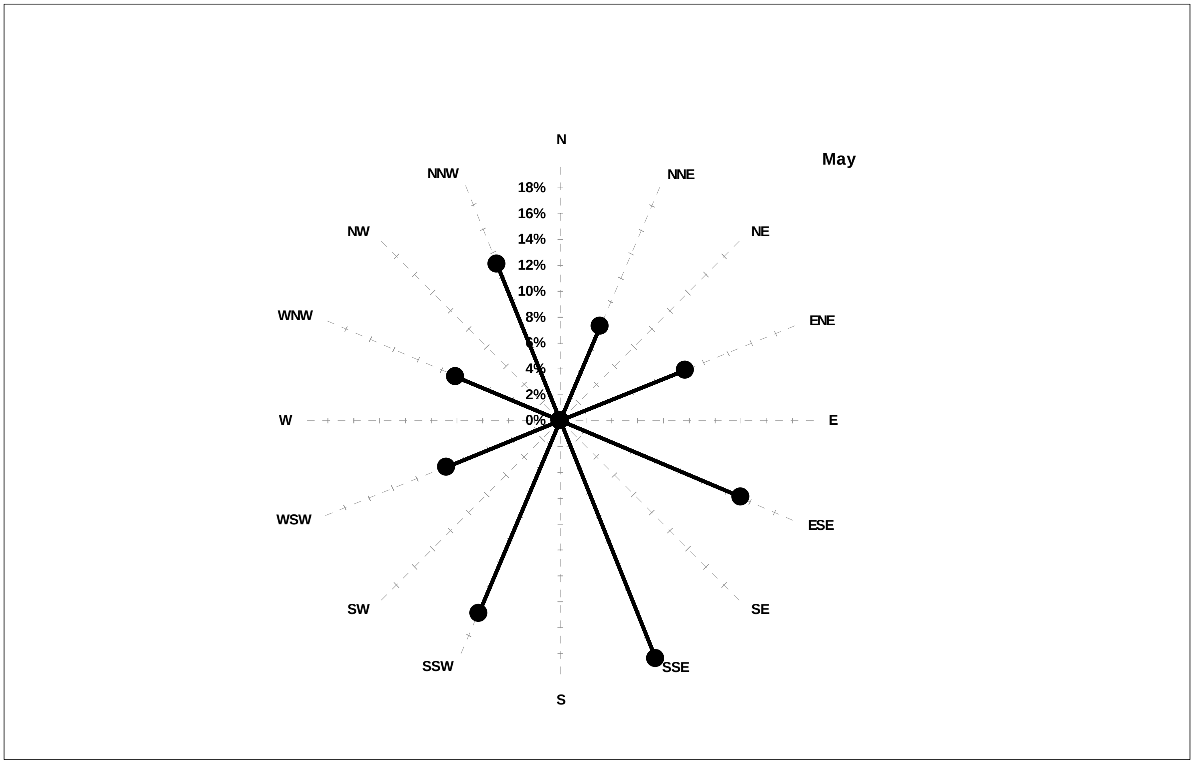
Appendix C.

Mean Monthly Period of Record Wind Roses for Kansas City

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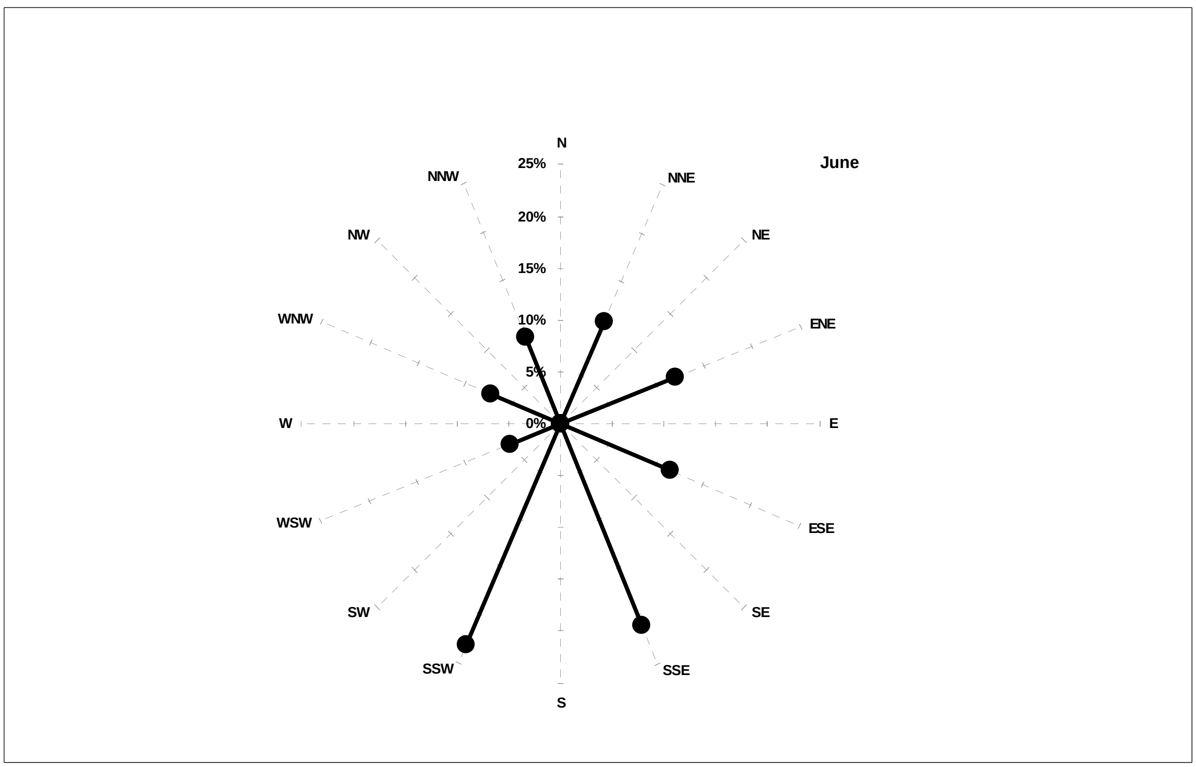
4%
2%
0%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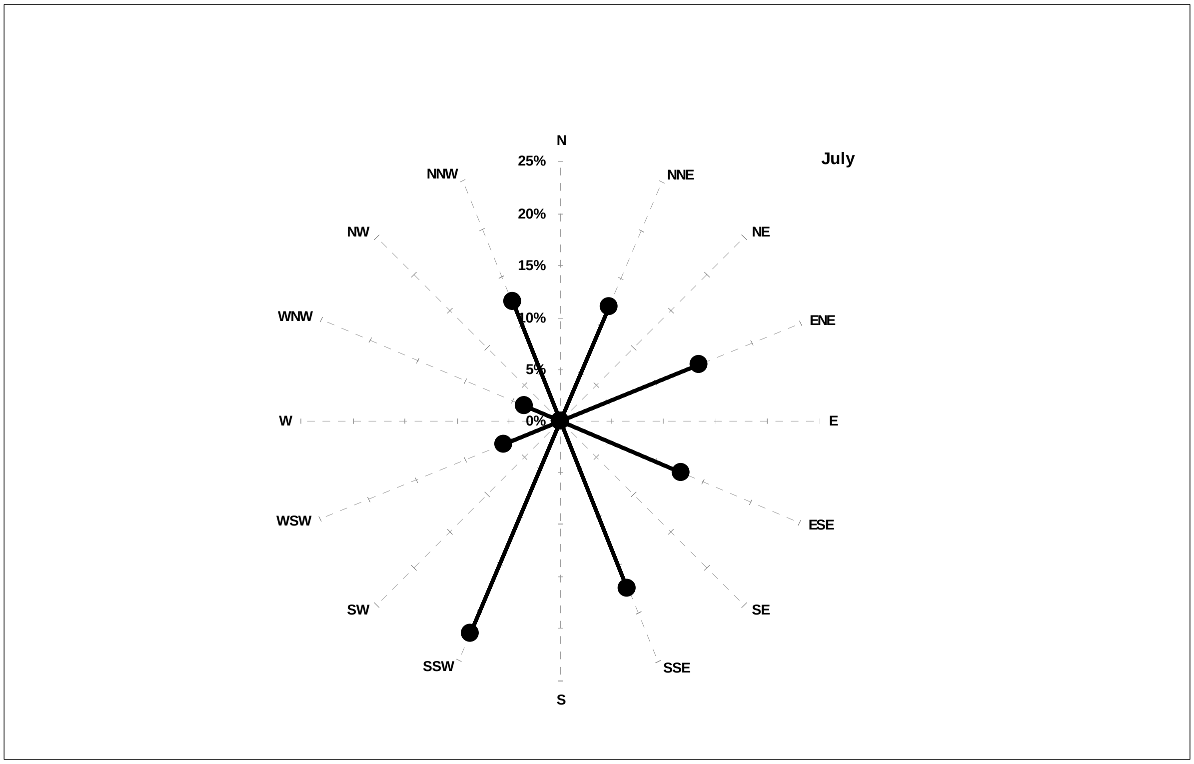
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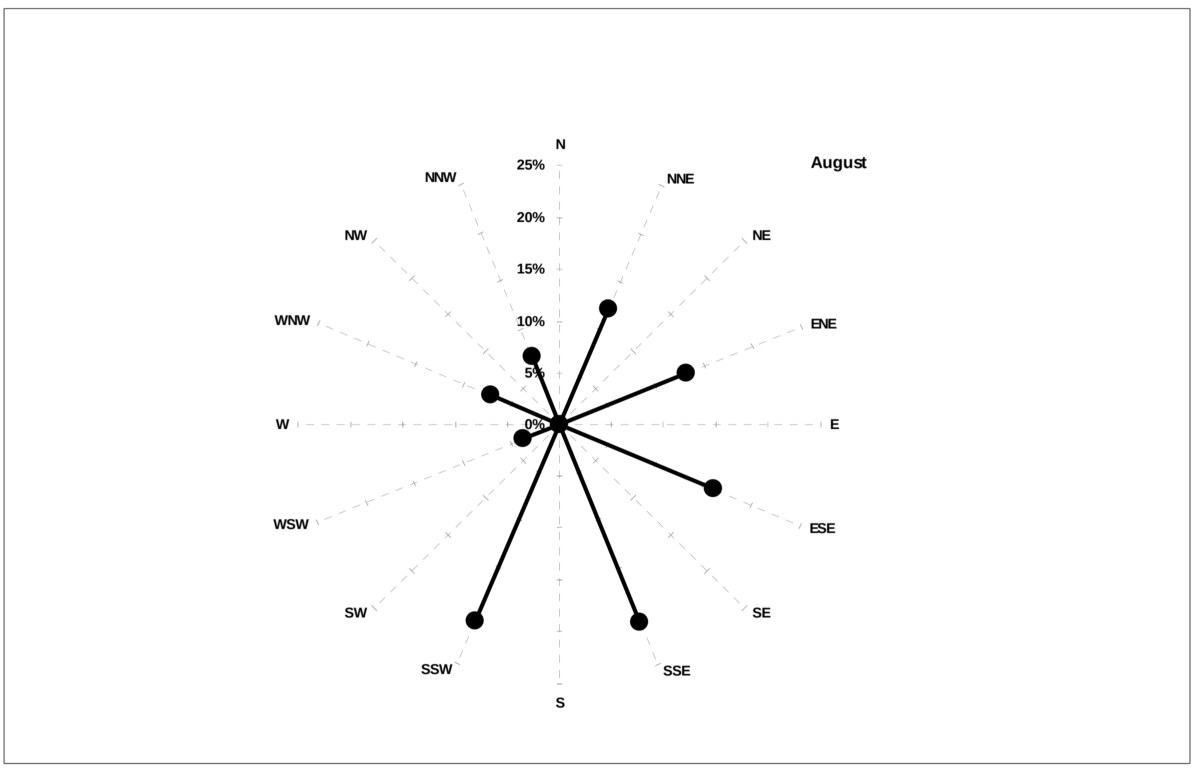
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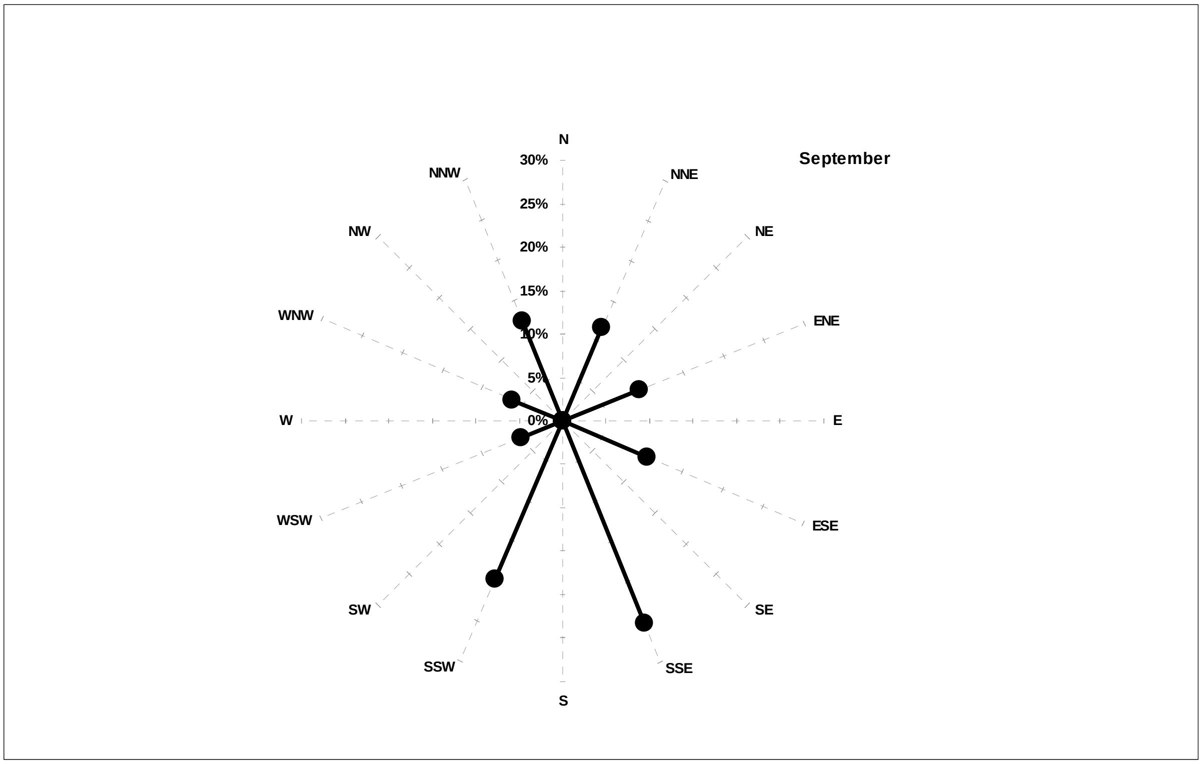
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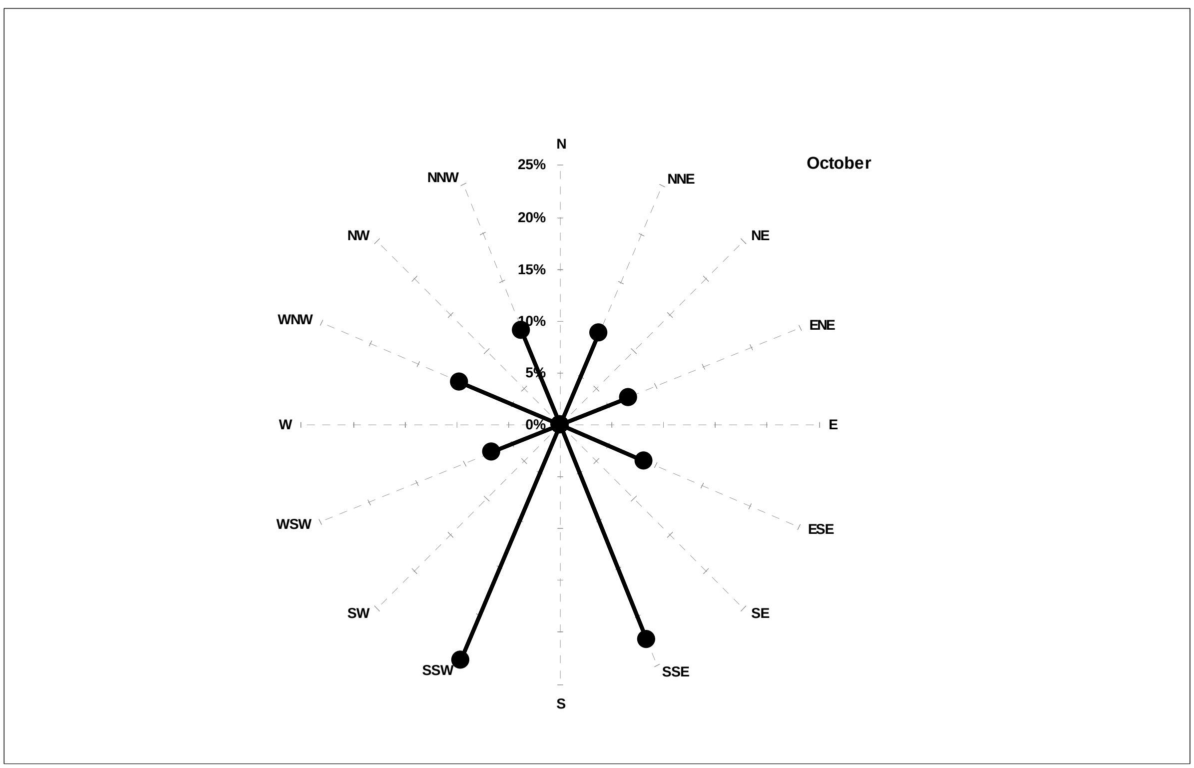
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SSW
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WSW
W
WNW
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20%
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10%
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References

American Meterological Society (AMS). 2000. Glossary of Meteorology. 2nd edition. Allen Press. New York.

Athanasiadis, I. N., Kaurlasos, V. G., Mitkas, P. A., & Petridis, V. (2003). Applying machine learning techniques on air quality data for real-time decision support. Gdansk, Poland. 51-57.

Barry, R. G. (1987). Synoptic climatology. In J. E. Oliver, & R. W. Fairbridge (Eds.), *The encyclopedia of climatology* (pp. 823-828). New York: Van Nostrand Reinhold Company, Inc.

Barry, R. G., & Perry, A. H. (1973).*Synoptic climatology: Methods and applications*. London: Methuen & Co, Ltd.

Blanchard, C. (2004). Spatial and temporal characterization of particulate matter. In P. McMurry, M. Shepherd & J. Vickery (Eds.), *Particulate matter science for policy makers* (pp. 191-234). Cambridge, UK: University of Cambridge.

Bragg, T. B., & Hulbert, L. C. (1976).Woody plant invasion of unburned Kansas bluestem prairie. *Journal of Rangeland Management, 29*(1), 19-24.

Briman, L., Friedman, J. H., Olshen, R. A., & Stone, C. J. (1984).*Classification and regression Trees*
. Monterey, CA: Wadsworth and Brooks/Cole Advanced Books and Statistical Software.

Butler, J. D. (1979). *Air pollution chemistry*. New York, NY: Academic Press Inc. Ltd.

Carroll, R. J., Chen, R., George, E. I., Li, T. H., Newton, H. J., Schmiediche, H., (1997). Ozone exposure and population density in harris county, texas. *Journal of the American Statistical Association, 92*(438), 392-404.

Chamberlain, A. C. (1953). Aspect of travel and deposition of aerosol and vapor clouds. London: Harwell.

Chu, C. (1962). The pulsation of world climate during historical times.*ActaMeteorologicaSinica, 31*, 275-288.

Control emmissions technologies - transport & dispersion of air pollutants. (2010). Retrieved 01/30, 2011, from http://earth1.epa.gov/air/oaqps/eog/course422/ce1.html

Court, A. (1957). Climatology: Complex, dynamic and synoptic. *Annals of the Association of American Geographers, 47*, 125-136.

Cramer, H. E. (1957).A practical method for estimating the dispersion of atmospheric contaminants. Hartford, CT. C33-C55.

Crutzen, P. J. (1988). Tropospheric ozone: An overview. In I. S. A. Isaksen (Ed.), *Tropospheric ozone: Regional and global scale interactions* (pp. 3-32). Dordrecht, Holland: D. Reidel Publishing Company.

Dabberdt, W. F., &Carrol, M. A. (2003). Meteorological research needs for improved air quality forecasting: Report of the 11th prospectus development team of the U.S. weather research program. *U.S. Weather Research Program,*

Daly, A., &Zannetti, P. (2007).*An introduction to air pollution - definitions, classifications, and history* The Arab School for Science and Technology.

Davis, R. E., Normile, C. P., Sitka, L., Hondula, D. M., Knight, D. B., Gawtry, S. P. (2009). A comparison of trajectory and air mass approaches to examine ozone variability. *Atmospheric Environment,* , 1-11.

Diver, F. (10/07/2010). *Personal communication* Kansas Department of Health and Environment.

Draxler, R. R., & Hess, G. D. (January, 2004). *Description of the HYSPLIT 4 modeling system (NOAA technical memorandum ERL ARL-224).* Retrieved 2/19, 2011, from http://www.arl.noaa.gov/data/web/models/hysplit4/winXP/arl-224.pdf

Ebi, K. L., & McGregor, G. (2008).Climage change, tropospheric ozone and particulate matter, and health impacts. *Environmental Health Perspectives, 116*(11), 1449-1455.

Air Pollution Control Act, (1955).

Fick, A. (1855). Uber Diffusion.*Annalen der Physik (Leipzig), 172*, 59-86.

Finlayson-Pitts, B. J., & Pitts, J. N. (1997). Tropospheric air pollution: Ozone, airborne toxics, polycyclic aromatic hydrocarbons, and particles. *Science, 276*, 1045-1051.

Greenfield, S. M. (1957). Rain scavenging of radioactive particulate matter from the atmosphere. *Journal of Atmospheric Science, 14*, 115-125.

Haagen-Smit, A. J., Bradley, C. E., & Fox, M. M. (1953).Ozone formation in photochemical oxidation of organic substances. *Industrial Engineering Chemistry, 45*, 2086-2089.

Halliday, E. C. (1961). A historical review of air pollution.*Air pollution* (46th ed., pp. 9-38). Geneva, Switzerland:

Hay, J. S., &Pasquill, F. (1957).Diffusion from a fixed source at a height of a few hundred feet in the atmosphere. *Journal of Fluid Mechanics, 2*, 299-310.

Heidorn, K. C. (1978) A chronology of important events in the history of air pollution meteorology to 1970. *Bulletin of the American Meteorological Society, 59*(12), 1589-1597.

Holben, B. N., Tanre, D., Smirnov, A., Eck, T. F., Slutsker, I., Abuhassan, N. (2001). An emerging ground-based aerosol climatology: Aerosol optical depth from AERONET. *Journal of Geophysical Research, 106*, 12067-12097.

Hothorn, T., Hornik, K., &Zeileis, A. (2006).*Party: A laboratory for recursive partitioning*

Hothorn, T., Hornik, K., &Zeileis, A. (2006). Unbiased recursive partitioning: A conditional inference framework. *Journal of Computational and Graphical Statistics,* Retrieved from http://statmath.wu-wien.ac.at/~zeileis/papers/Hothorn+Hornik+Zeileis-2006.pdf

Jacobs, W. C. (1946). Synoptic climatology. *Bulletin of the American Meteorological Society, 27*, 306-311.

Kalkstein, L. S., Nichols, M. C., Barthel, D. C., & Greene, S. J. (1996). A new spatial synoptic classification: Application to air-mass analysis.*International Journal of Climatology, 16*, 983-1004.

Leenhouts, B. (1988). Assessment of biomass burning in the conterminous united states.*Conservation Ecology, 2*(1), 2009.

Lenn, C. (1948). General atmospheric pollution, Los Angeles smog. *American Journal of Public Health, 38*, 962-965.

Machta, L. (1960). Meteorological aspects of large scale air pollution. *Public Health Reports* 4, 307-312.

McClellan, R., &Jessiman, B. (2004).Health context for management of particulate matter. In P. McMurry, M. Shepherd & J. Vickery (Eds.), *Particulate matter science for policy makers: A NARSTO assessment* (pp. 69-101). Cambridge, UK: Cambridge University Press.

McKee, D. J. (1994). Tropospheric ozone: What it is and how it is formed. In D. J. McKee (Ed.), *Tropospheric ozone: Human health and agricultural impacts* (pp. 3-7) Lewis Publishers.

McMurry, P., Shepherd, M., & Vickery, J. (2004). *Particulate matter science for policy maker: A NARSTO assessment* (pp. 7-52). Cambridge, UK: Cambridge University.

Mingers, J. (1987). Expert systems - rule induction with statistical data. *Journal of the Operations Research Society, 38*(1), 39-47.

Monin, A. S. (1959). Smoke propagation in the surface layer of the atmosphere. *Advances in Geophysics, 6*, 331-343.

Niemeyer, L. E. (March, 1960). Forecasting air pollution potential. *Monthly Weather Review,* , 88-96.

Nilsson, E. D., Paatero, J., & Boy, M. (2001).Effects of air masses and synoptic weather on aerosol formation in the continental boundary layer.*Tellus B, 53*, 462-478.

O. Reynolds. (1894). On the dynamical theory of incompressible viscous fluids and the determination of the criterion. *Philosophical Transactions of the Royal Society of London, 186*, 123-164.

Ott, E. R. (1967). Analysis of means - A graphical procedure. *Industrial Quality Control, 24*, 101-109.

P. Brimblecombe. (2001). Urban air pollution. In P. Brimblecombe, & R. Maynard (Eds.), *The urban atmosphere and its effects* (pp. 1-19). London, UK: Imperial College Press.

Pidwirny, M., &Budikova, D. (2010).Atmospheric composition.In K. Vranes (Ed.), *Encyclopedia of earth*. Washington, D.C.: National Council for Science and the Environment.

Pielke, R. A. (2011). Atmosphere. *Encyclopedia Britannica Online,* , 01/30/2011.

Pope, C. A. (2000). Review: Epidemiological basis for particulate air pollution health standards.*Aerosol Science and Technology, 32*(1), 4.

Power, H. C., Sheridan, S. C., &Senkbeil, J. C. (2006).Synoptic climatological influences on the spatial and temporal variability of aerosols over North America. *International Journal of Climatology, 26*, 723-741.

Reynolds, O. (1883). An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous, and the law of resistance in parallel channels. *Philosophical Transactions of the Royal Society of London, 174*, 935-982.

Richardson, L. F. (1920). The supply of energy from and to atmospheric eddies. *Proceedings of the Royal Society of London, Series A, 97*(686), 354-373.

Roberts, O. F. T. (1923). The theoretical scattering of smoke in a turbulent atmosphere. *Proceedings of the Royal Society of London, Series A, 104*, 640-654.

Roman, A. (2007). Air pollution control act of 1955, United States. In P. Saundry (Ed.), *Encyclopedia of earth* (). Washington, D.C.: American Meteorological Society.

Shahgedanova, M., Burt, T. P., & Davies, T. D. (1998).Synoptic climatology of air pollution in Moscow. *Theoretical and Applied Climatology, 61*, 85-102.

Sheridan, S. C. (2011). , 2011, from http://sheridan.geog.kent.edu/ssc.html

Smirnov, A., Holben, B. N., Dubovik, O., O'Neill, N. T., Remer, L. A., Eck, T. F. (2000). Measurement of atmospheric optical parameters on U.S.Atlantic coast sites, ships, and bermuda during TARFOX. *Journal of Geophysical Research, 105*, 9887-9901.

Smirnov, A., O'Neill, N. T., Royer, A., Tarussov, A., & McArthur, B. (1996). Aerosol optical depth over Canada and the link with synoptic air mass types. *Journal of Geophysical Research, 101*, 19299-19318.

Smirnov, A., Royer, A., O'Neill, N. T., &Tarussov, A. (1994).A study of the link between synoptic air mass type and atmospheric parameters. *Journal of Geophysical Research, 99*, 20967-20982.

Taylor, G. I. (1921). Diffusion by continuous movements. *Proceedings of the London Mathematical Society, 20*(2), 196-202.

Technology transfer network (TTN) air quality system. (2010). , 2010, from http://www.epa.gov/ttn/airs/airsaqs/

Temperature inversion graphic. (2011). Retrieved 2/13/2011, 2011, from www.ec.gc.ca

Whitten, R. C., & Prasad, S. S. (1985). Introduction.In R. C. Whitten, & S. S. Prasad (Eds.), *Ozone in the free atmosphere* (pp. 1-10). New York: Van Nostrand Reinhold Company, Inc.

Yarnal, B. (1994). Synoptic climatology in environmental analysis: A Primer. London, England: Wiley.

Yu, S., Saxena, V. K., Wenny, B. N., DeLuisi, J. J., Yue, G. K., &Petropavlovskikh, I. V. (2000). A study of the aerosol radiative properties needed to compute direct aerosol forcing in the southeastern United States. *Journal of Geophysical Research, 105*, 24739-24749.

Yu, S., Zender, C. S., &Saxena, V. K. (2001). Direct radiative forcing and atmospheric absorption by boundary layer aerosols in the southeastern U.S.: Model estimates on the basis of new observations. *Atmospheric Environment, 35*(23), 3967-3977.