Classification of Air Pollution Regimes in the Missouri Region

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by

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The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled

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and hereby certify that, in their opinion, it is worthy of acceptance.

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DEDICATED TO MY FAMILY

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COMMITTEE IN CHARGE OF CANDIDCY

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ABSTRACT

High air pollution concentrations are a major problem facing larger cities across the world. One such type of pollution is ground level ozone, which is formed through a reaction with heat or sunlight and nitrogen oxides. Ground level ozone has been shown to have adverse health and environmental impacts, such as irritation of the respiratory system or reduction in crop production.

High levels of ground level ozone have been linked to large-scale weather patterns both at the surface and in the upper atmosphere. For this reason, the main focus of this study was to analyze the atmospheric conditions that are associated with high concentrations of ground level ozone in Missouri. This information can be useful for air pollution forecasting in the state of Missouri and for air pollution modeling. Knowing the conditions favorable for the formation of ground level ozone could also provide a basis for pollution control and mitigation in Missouri.

The main objective was accomplished in three steps. First, an Air Quality Index for ground level ozone in Missouri was created using Environmental Protection Agency (EPA) procedures to help locate times when high ozone concentrations took place. Next, mixing heights, transport wind speeds, and ventilation rates were analyzed to determine their contributions to these high ozone concentrations. Finally, surface weather features and 500mb weather features were examined for each high pollution day to locate patterns at both levels.

Overall, the air quality in Missouri was found to be favorable. Only a few high ozone concentrations were found to have occurred during the ten-year study period. Mixing heights over Missouri were found to be fairly constant. However, using only mixing heights to predict high ozone days lacked reliability. In contrast, transport wind speeds were found to be highly variable. Overall, they offered a more reliable representation of when high ozone days would occur and were the most influential variable in the ventilation rate calculation. Ventilation rates also proved to be highly variable due to the fact that they are highly dependent on the transport wind speed. At the local level, ventilation rates were a reasonable indicator of when high ozone days would occur. Also, on the synoptic scale, ventilation rates were not as reliable at indicating when high ozone days would take place. At the surface, seven categories were found to be High to the North, High to the Northeast, High to the East, High to the Southeast, High to the South, High Over Missouri, and Miscellaneous Surface Features. At 500mb, four categories were found to be Ridge axis to the West, Ridge axis to the East, Ridge axis to both the East and West, and Zonal Flow.

Chapter 1

Introduction

With the industrialization of the United States, atmospheric pollutant concentrations have been on the rise and problems associated with these pollutants have also been on the rise. These pollutants come from many different sources, both point and mobile, and cause a variety of problems with both human and environmental health. One such pollutant is ground level ozone, which has become a problem in many cities across the United States. Studies have shown that certain atmospheric conditions are favorable for the formation of ground level ozone. Niemeyer (1960), Holzworth (1964 & 1967), and Miller (1967) have shown that these favorable atmospheric conditions are stable atmospheric conditions, low wind speeds, low mixing heights, temperature inversions, clear skies, and a large amount of incoming solar radiation. Forecasts of these favorable conditions coupled with measurements of air quality could provide a basis for pollution control and mitigation of its impacts (Niemeyer, 1960). A forecast of unfavorable atmospheric conditions could help alert interested parties, both public and private, to take precautionary measures (1960). This study will focus on the air quality of Missouri in the attempt to set a basis for the above-mentioned forecasting of favorable conditions.

1.1 Statement of Thesis

The main purpose of this study is to analyze the atmospheric conditions that are associated with high concentrations of ground level ozone in Missouri.

The main objective is accomplished in three ways. First, an Air Quality Index is created for three major cities in the state of Missouri. These cities are St. Louis, Kansas City, and Springfield. This part will help to give an understanding of when high ozone concentrations occur in these areas. Second, mixing heights, transport wind speeds, and ventilation rates for the area are analyzed to help determine their contribution to high ozone concentrations in Missouri. This part is important because these three atmospheric variables are often used to determine whether or not high ozone concentrations will occur in Missouri. Third, synoptic weather patterns, which are favorable for the formation of ground level ozone in the state of Missouri, are determined and classified, because synoptic weather features have been shown to contribute to high pollution concentrations in the areas that they influence.

The main hypothesis to be tested in this study is that the synoptic weather patterns that are associated with high ground level ozone concentrations can be manually classified using an environment to circulation approach with ozone concentration as a probe. A secondary hypothesis is that mixing heights, transport wind speeds, and ventilation rates will follow the criteria used in predicting possible high pollution levels on days when high ozone concentrations are present. The success of these hypotheses will generate a greater understanding of the link between synoptic weather conditions and high pollution concentrations in the state of Missouri. This information may also be used in the future to create predictive models to aid in alerting of high ozone concentrations in Missouri.

Chapter 2

Literature Review

2.1 Ground Level Ozone

Ozone is a gas that combines three oxygen atoms into a single molecule. It is created when a single atom of oxygen and a molecule of oxygen collide and form chemical bonds. Overall, there is very little ozone in the atmosphere, in fact, it represents just a small portion of total gas molecules in the atmosphere (Lutgens & Tarbuck, 2004). The distribution of ozone, however, is not uniform in the atmosphere. It occurs both in the Earth's upper atmosphere and at ground level. Ozone is well concentrated above the surface in a layer known as the stratosphere, which is found between 10 and 50km above the Earth's surface (Lutgens & Tarbuck, 2004). In the lowest portion of the atmosphere, ozone represents less than one part in 100 million of the total gas molecules in the lower atmosphere (2004).

Ozone occurs naturally in the Earth's upper atmosphere, where it forms a protective layer that shields us from the sun's harmful ultraviolet (UV) rays. The UV radiation from the Sun is sufficient in this part of the atmosphere to produce single atoms of oxygen, and there are enough other oxygen molecules to bring about the required collisions for ozone formation (Lutgens & Tarbuck, 2004). The presence of this layer of ozone in our atmosphere is crucial to those of us who dwell on Earth, because it absorbs the potentially harmful UV radiation from the sun (2004). If ozone did not filter a great deal of the UV radiation, our planet would be uninhabitable for most life (2004).

Although the naturally occurring ozone in the stratosphere is critical to life on Earth, ozone is regarded as a pollutant when produced at ground level because it can damage vegetation and be harmful to human health. In the lower atmosphere, ozone is formed when pollutants emitted by cars, power plants, industrial boilers, refineries, chemical plants, and other sources react chemically in the presence of sunlight (US EPA, 2003). For this reason, ozone at the surface is considered a secondary pollutant, because it is not emitted directly into the environment but instead forms through a set of chemical reactions, known as photochemical reactions (2003). Its production is a direct function of solar radiation and concentrations of precursor pollutants: nitric oxide, nitrogen dioxide, and volatile organic compounds (Dye et al., 1995). At the surface, ozone is a major component in a noxious mixture of gases and particles called photochemical smog (Lutgens & Tarbuck, 2004)

Because the reactions that create ozone are stimulated by solar radiation, its formation is limited to daylight hours (Lutgens & Tarbuck, 2004). For this reason, peaks in formation occur mainly in the afternoon hours especially during a series of hot, sunny, and calm days. Ozone formation levels are also highest during the warmer summer months. In general, high ozone concentrations frequently occur from the months of April to September when surface high-pressure systems produce intense sunlight, weak winds, shallow mixing depths, and high temperatures (Dye et al., 1995). However, the length of the ozone season varies from one part of the country to another. Areas in the Sunbelt of the American South and Southwest may experience problems throughout the year, while northern states, like North Dakota, have shorter ozone seasons, such as May through September (Lutgens & Tarbuck, 2004).

2.2 Health and Environmental Impacts

According to the United States Environmental Protection Agency (US EPA) (2003), about one in every three people in the United States is at a high risk of experiencing some of the problems associated with ground level ozone. Everyone who is active outdoors is at risk of experiencing these problems due to the fact that ozone is able to penetrate deeper into the more vulnerable parts of the lungs during physical activity (2003). One such group that is at high risk is active children, which is due to the fact that kids often spend a large part of their summers playing outdoors (2003). Another group at high risk is people that have existing respiratory diseases (2003). This group of people may experience health effects earlier and at lower ozone concentrations than other people may (2003). Even some healthy people are unusually sensitive to ozone (2003). They may experience the health effects of ground level ozone at more moderate levels of outdoor activity or at lower ozone levels than the average person (2003).

The health and environmental impacts of ozone are well known and documented (Lutgens & Tarbuck, 2004). According to the US EPA (2003), health effects attributed to ozone exposure include:

- Irritations of the respiratory system, which can cause coughing, throat irritation, and/or an uncomfortable sensations in the chest.

- Reductions in lung function and the ability to breathe in deeply.
- Aggravation of asthma.
- Increased susceptibility to respiratory infections.
- Inflammation and damage to the lining of the lungs. If this type of inflammation happens repeatedly over a long time period, lung tissue may become permanently scarred, resulting in permanent loss of lung function and a lower quality of life.

Several studies have been done on the health effects of ozone exposure. A three-year study by Frischer et al. (1999) investigated the long-term effects of ambient ozone on lung function in children. They found that long-term ambient ozone exposure might negatively influence lung function growth, which means that ozone would constitute a risk factor for premature respiratory morbidity during later life. Using ambient ozone data collected from local monitoring sites, Schwartz et al. (1989) reported a highly significant association between ozone and reductions in lung function for people living in areas where annual ozone concentrations exceeded 40 ppb. Other studies by Burnett et al. (1994) and White et al. (1994) were consistent in showing an association between high levels of ambient ozone and an increase in hospital admissions, particularly for asthma. Another study by Tolbert et al. (2000) in Atlanta tried to find a relation between air quality and pediatric emergency room visits for asthma. The study found evidence that supports the already accumulating evidence regarding the relation of air pollution to childhood asthma exacerbation.

Ozone also affects vegetation and ecosystems. Several of its effects on vegetation and ecosystems are listed below (Lutgens & Tarbuck, 2004):

- Reduced agricultural crop and commercial forest yields.
- Reduced growth and survivability of tree seedlings.
- Increased plant susceptibility to disease, pests, and other environmental stresses, such as harsh weather.
- Increased damage to the foliage of trees and other plants.
- Decreased aesthetic value of natural areas.

In many long-lived species, these effects may become evident only after many years or even decades, thus having the potential for long-term effects on forest ecosystems (2004).

2.3 National Ambient Air Quality Standards (NAAQS) and the Air Quality Index (AQI)

The Clean Air Act required the US EPA to set National Ambient Air Quality Standards for pollutants considered harmful to public health and the environment (US EPA, 2009). The Clean Air Act also established both primary and secondary air quality standards (2009). Primary standards set limits to protect public health, while secondary standards set limits to protect public welfare (2009). The US EPA Office of Air Quality Planning and Standards has set National Ambient Air Quality Standards for six principal pollutants, which are known as "criteria" pollutants (2009). These pollutants and their associated standards are listed below in Table 2.1.

Table 2.1: National Ambient Air Quality Standards for the six principal (criteria) pollutants (from US EPA).

	Primary Standards		Secondary Standards	
Pollutant	Level	Averaging Time	Level	Averaging Time
Carbon Monoxide	9 ppm	8-hour	None	
	35 ppm	1-hour		
Lead	0.15 ugm-3	Rolling 3-month average	Same Primary	
	1.5 ugm-3	Quarterly Average	Same Primary	
Nitrogen Dioxide	0.053 ppm	Annual Average	Same Primary	
PM10	150 ugm-3	24-hour	Same Primary	
PM2.5	15 ugm-3	Annual Average	Same Primary	
	35 ugm-3	24-hour	Same Primary	
Ozone	0.08 ppm	8-hour	Same Primary	
	0.12 ppm	1-hour	Same Primary	
Sulfur Dioxide	0.03 ppm	Annual Average	0.5 ppm	3-hour
	0.14 ppm	24-hour		

Under the Clean Air Act, the US EPA is also required to establish a nationally uniform air quality index for the reporting of air quality to the public (US EPA, 1999). The Index provides information on pollutant concentrations for ground-level ozone, particulate matter, carbon monoxide, sulfur dioxide, and nitrogen dioxide (1999). It is normalized across pollutants so that an Index value of 100 represents the level of health protection associated with the health-based standard for each pollutant, while an Index value of 500 represents the significant harm level (1999). All the index values can be seen in Table 2.2.

Table 2.2: Air Quality Index values and their associated descriptor and color scheme (from US EPA).

Index Values	Descriptor	Color
0 - 50	Good	Green
51 – 100	Moderate	Yellow
101 – 150	Unhealthy for Sensitive Groups	Orange
151 – 200	Unhealthy	Red
201 – 300	Very Unhealthy	Purple
301 - 500	Hazardous	Maroon

The Index has been adopted internationally and is used around the world to provide the public with information on air pollutants (1999). In 1997, the US EPA revised the ozone standards (1999). The 1-hour ozone standard was replaced with an 8-hour ozone standard (1999). The revised Index was developed with extensive coordination with public information, health, and air quality experts from state and local agencies (1999).

2.4 Atmospheric Conditions Favorable for Ground Level Ozone Formation

The most important factor influencing air pollution is the quantity of contaminants emitted into the atmosphere (Lutgens & Tarbuck, 2004). During most days, precursor emissions are generally similar, however, experience shows that even when emissions remain relatively steady for extended periods, air quality still varies from one day to the next (Dye et al., 1995). In fact, air pollution episodes are not generally the result of a drastic increase in the output of pollutants, but instead they occur because of changes in certain atmospheric conditions (1995). Two of the most important atmospheric conditions affecting the dispersion of pollutants are the strength of the wind and the stability of the air. These factors are critical because they determine how rapidly mixing will dilute pollutants.

Wind speed plays a major role in determining how well pollutants will be dispersed. The volume of air into which contaminants are emitted is directly proportional to wind velocity, and the concentration of contaminants is generally inversely proportional to wind speed (Niemeyer, 1960). This means that the concentration of pollutants increases as wind speed decreases (1960). If the wind speed doubles, other conditions being equal, the pollutants are emitted into twice the volume of air downstream from the source (1960). Air pollution problems seldom occur when winds are strong but rather are associated with periods when winds are weak or calm. A second aspect of how wind speed influences air quality is through turbulence (Lutgens & Tarbuck, 2004). Stronger winds result in more turbulent air, which helps mix polluted air more rapidly with the surrounding air, thereby causing the pollution to be more dilute (2004). In constrast, when winds are light, there is little turbulence and the concentration of pollutants remains high (2004). Studies by Holzworth (1967), Miller (1967), and Niemeyer (1960) all show how important wind speeds are in determining pollution potential for a city. Holzworth (1967) also details a method to find the wind speed (also referred to as the transport wind speed) in the mixing layer. This process involved averaging the wind speeds at all the available atmospheric standard levels from the surface to the top of the mixing layer.

Whereas wind speed governs the amount of air into which pollutants are initially mixed, atmospheric stability determines the extent to which vertical motions will mix the pollution with cleaner air above (Lutgens & Tarbuck, 2004). The vertical distance between Earth's surface and the height to which air movements through convection extend is called the mixing depth (2004). When air is stable, air motions through convection are suppressed and mixing depths are suppressed (2004). In comparison, an unstable atmosphere promotes vertical air movements and greater mixing depths (2004). As a general rule, larger mixing depths lead to better air quality (2004). When the mixing depth is several kilometers above the surface, pollutants are mixed through a large volume of cleaner air and dilute rapidly, however, when the mixing depth is shallow, pollutants are confined to a much smaller volume of air and concentrations can reach unhealthy levels (2004). A study by Holzworth (1964) confirms this fact. The study found that high pollutant concentrations occurred on days with mixing depths less than 1500m. Because heating of Earth's surface by the Sun enhances vertical air movements, mixing depths are usually greater during the afternoon hours (Lutgens & Tarbuck, 2004). For this same reason, mixing depths during the summer months are typically greater than during the winter months. The above-mentioned study by Holzworth (1964) also helped to confirm this fact. The study found that mean maximum mixing depths are generally least in December and January when they are mostly between 200-800m and are greatest during May through August when they exceed 3000m. Holzworth (1964 and 1967) and Miller (1967) both describe ways of calculating the maximum height of the mixing layer. The maximum mixing height for a given day can be estimated by use of the 12Z radiosonde temperature profile plotted on a thermodynamic chart. If a dry adiabat is followed from the maximum temperature for the day to the temperature profile, the height above ground at the point where this dry adiabat intersects the morning sounding is the maximum mixing height for that day. Use of this sounding procedure provides an approximation because it assumes that there has been no significant advection since the time of the sounding.

Another measure of how well pollutants will be dispersed from their source is the Ventilation Index. It is also commonly used in determining how well smoke will disperse from its source for fire weather events (Chandler, 2003). Ventilation rates are a function of the average wind speed in the mixing layer and the height of the mixing layer (2003). These two variables help to determine how conductive the atmosphere is to dispersing pollutants from their sources. A Ventilation Index can be found for both the morning and afternoon. Index values are often higher in the afternoon due to increased mixing heights. A study in North Saanich, British Columbia (2003) showed that the Ventilation Index was a useful tool in determining how well smoke would be dispersed from its source. The National Weather Service at Grand Junction, CO provides a table of standards that help to determine if ventilation rates will inhibit the dispersion of pollutants (Web-site 3).

A common weather pattern that promotes poor air quality is a temperature inversion. An inversion is that condition in the atmosphere when the temperature increases with height (Niemeyer, 1960). It represents a situation in which the atmosphere is very stable and the mixing depth is significantly restricted (1960). They are often associated with warm air overlying cooler air acting as a lid that prevents upward movement, which in turn leaves the pollutants trapped in a relatively narrow zone near the ground. Many extensive and long-lived air-pollution episodes are linked to temperature inversions that develop in association with the sinking air that characterizes centers of high air pressure (Lutgens & Tarbuck, 2004). In this situation as the air sinks to lower altitudes, it is compressed, which causes its temperature to rise (2004). Because turbulence is almost always present near the ground, this lowermost portion of the atmosphere is generally prevented from participating in the general subsidence (2004). This enables an inversion to develop aloft between the lower turbulent zone and the subsiding warmer layers above (2004).

A study by Niemeyer (1960) showed the importance of the above mentioned atmospheric conditions in causing poor air quality. In this study, a set of empirical criteria, that embodied the meteorological conditions associated with slowly moving anticyclones, was selected as a foundation for forecasting air pollution potential. These criteria were: surface winds less than 8 knots, winds at no level below 500mb level greater than 25 knots, subsidence below 600mb level, and simultaneous occurrence of the above with the forecast continuance of these conditions for 36 hours or more. Six case studies were found to meet the all the criteria during the study time period and the meteorological conditions for each case were analyzed. Niemeyer (1960) produced a major conclusion based on the findings of this study. The examination of the air quality data for the periods in which the weather was monitored showed that the highest concentrations of pollutants, with few exceptions, occurred in those periods when the criteria were met (1960).

2.5 Manual Classification of Weather Systems

Yarnal (1993) describes manual classification as a subjective process that relies on an investigator’s knowledge and judgement. He describes two manual classification approaches that can be used when dealing with synoptic climatology, an environment to circulation approach and a circulation to environment approach. An environment to circulation approach allows investigators to use the surface environment to control the manual selection of the circulation data. The main emphasis of this approach is that the classification is not independent of the environmental response, but instead, the classification process is constrained by the knowledge of the surface environment. A circulation to environment approach allows an investigator to first manually classify the atmospheric circulation data and then relate it to the environmental data. The main emphasis of this approach is that the environmental data are not controlling the classification of the circulation data, but instead, the classification of the circulation data is independent of the environmental response. Yarnal (1993) also lists several positives and negatives to the use of manual classification. The positives of manual classification include:

- Investigators can produce a manual classification without a computer.
- The investigator can tailor the manual classification to the exact needs of the data and research.

- The investigator can control the classification process completely.

The negatives of manual classification include:

- Manual classification is labor intensive.
- Manual classification techniques are often hard to duplicate.

An example of an environment to circulation classification approach can be see in a study by Dye et al. (1995). This study examined the meteorological and air quality conditions on two days in order to diagnose the processes responsible for transporting ozone and ozone precursors within the Lake Michigan Air Quality Region (LMAQR). The two days used in the study were June 26, 1991 and July 18, 1991. Both of these days had many ozone high ground level ozone concentrations. The meteorological conditions on June 26, 1991 were favorable for high ozone production with a surface high-pressure system located off the Atlantic seaboard and an upper-level ridge over the region. Southerly winds occurred at the surface and aloft throughout the day. Surface winds were generally less than 3 m/s. Winds aloft were southwesterly at 7-10 m/s throughout the day. The synoptic weather conditions on July 18, 1991 were also typical of historical episodes with a surface high-pressure system located southeast of the LMAQR and a 500mb ridge located over the region. This synoptic pattern resulted in weak winds, warm temperatures, a subsidence inversion, and clear to scattered skies, which were all favorable conditions for producing high ozone concentrations. The winds were from the southwesterly direction and were less than 5m/s throughout the whole day. The winds aloft were also weak. Dye et al. (1995) produced several conclusions based on the findings of this study. First, the analysis showed that ozone and precursor transports were largely affected by the presence of stable air in the conduction layer over Lake Michigan. Secondly, strong stability limited dispersion of pollutants in the lower atmosphere and produced high ozone concentrations.

An example of a circulation to environment classification approach can be see in a study by McKendry (1994). The study had two principal goals. The first was to describe the relationship between synoptic scale circulation and O_3 concentrations in the Lower Fraser Valley (LFV) of southwestern British Columbia. The second was to demonstrate the importance of consideration of the three-dimensional structure of the atmosphere. In the present study, the Kirchhofer sum of squares technique is applied to a normalized grid of the Pacific Northwest region for daily mean sea level (MSL) pressure and 500mb height fields for the period January 1978 to September 1992. The classification procedure as performed on the data set produced 17 MSL and 18 500mb synoptic types accounting for 97.2% and 93.8% of total days, respectively. McKendry (1994) produced several conclusions based on the findings of this study. First, summertime daily maximum O_3 concentrations in Vancouver appear to be strongly modulated by the synoptic scale atmospheric circulation. Secondly, what is significant in the Pacific Northwest is that such conditions are associated not with a stagnating surface anticyclone, but with the development of a low-level thermal trough in combination with an upper-level ridge. Thirdly, the present analysis highlights the extent to which particular surface circulation types may be associated with a wide range of 500mb types.

Chapter 3

Methodology

3.1 Study Focus

Ground level ozone formation can be affected by several factors on the synoptic and large-scale. These factors include but are not limited to wind speeds at the surface, at 850mb, and at 500mb, along with atmospheric stability for the region. Synoptic weather patterns, such as the presence of a high-pressure system, can play a role in the formation of ground level ozone. This is due to the fact that the synoptic weather patterns have a controlling presence over smaller scale weather patterns. This study will attempt to determine and classify which atmospheric conditions and synoptic weather patterns that are associated with the formation of ground level ozone in the state of Missouri.

3.2 Area of Study

This study focuses on three of the major cities in Missouri. These cities are Kansas City, St. Louis, and Springfield. Kansas City is located on the western edge of Missouri and is partially located in Kansas. St. Louis is on the eastern edge of Missouri and is partially located in Illinois. Springfield is located in the southwestern part of Missouri. Figure 3.1 shows the locations of the three cities involved in the study. In these three cities, ground level ozone monitoring is done regularly by the Missouri Department of Natural Resources (MODNR) and each city contains several monitoring stations.

Figure 3.1: Map of Missouri that shows the locations of the three cities used in the study. (Map found at http://www.united-states-map.org/map/missouri-map.jpg)

For the city of St. Louis, three monitoring stations were chosen for this study. These stations are located in the West Alton (northern), East St. Louis (southeastern), and Sunset Hills (southwestern) parts of the city to form a triangle around the city. These monitoring stations were chosen because they contain complete data sets for the ten year period that is being studied. Figure 3.2 shows the locations of the monitoring stations located within the city of St. Louis.

Figure 3.2: Map of the city of St. Louis that shows the locations of the three ozone monitoring stations in the city. (Map from http://www.stlouisrental.us/images/st_louis_missouri.jpg)

For the city of Springfield, two monitoring stations were chosen for the study. These stations are located at Hillcrest High School (northern) and on South Charleston Avenue (southwestern). These monitoring stations were chosen because they are the only two ground level ozone monitoring stations present in the city. The Hillcrest High School monitoring station contains a complete ten-year data set for the study time period. The monitoring station on South Charleston Avenue contains a six-year data set for the ten-year study period.

Figure 3.3 shows the locations of the monitoring stations located within the city of Springfield.

Figure 3.3: Map of the city of Springfield that shows the locations of the two ozone monitoring stations in the city.
(Map from http://www.weather-forecast.com/locationmaps/Springfield1.10.jpg)

For the city of Kansas City, four monitoring stations were chosen. These stations are located in Liberty (northeastern), the KCI Airport (northwestern), Olathe (southwestern), and the JKF Recreation Center (central) parts of the city in order to offer the most coverage. The monitoring stations in Liberty and at the JFK Recreation Center contain a complete data set for the ten year period that is being studied. The monitoring station at KCI Airport contains a data set containing eight years in the study period. For this reason, the monitoring station at Olathe was used to fill in the missing two years of the KCI Airport data set.

Figure 3.4 shows the locations of the monitoring stations located within the city of Kansas City.

Figure 3.4: Map of the city of Kansas City that shows the locations of the four ozone monitoring stations in the city.
(Map from http://www.st-george-church.org/ImageFiles/Maps/KC_Map.gif)

3.3 Data

The data used in this study were ten-year sets of averaged hourly ground level ozone concentrations for the cities of Kansas City, Springfield, and St. Louis. The concentrations were measured in parts per million (ppm) for each station. For each year, the data set ran from the beginning of April to the end of September. This time frame was chosen due to the fact that it covers the warm seasons for the state of Missouri when most high pollution days occur. The ozone data were obtained from the Missouri Department of Natural Resources (MODNR). Listed below in Table 3.1 are the monitoring stations located in each city and for which years they contain monitoring data.

Table 3.1: The locations of the ozone monitoring stations in each of the three cities and the data set that each of them contains.

City	Location of Station	Data Set
St. Louis	Sunset Hills	1998 to 2007
	East St. Louis	1998 to 2007
	West Alton	1998 to 2007
Kansas City	KCI Airport	1998 to 2005
	JFK Recreation Center	1998 to 2007
	Liberty	1998 to 2007
	Olathe	2006 to 2007
Springfield	South Charleston	1998 to 2003
	Hillcrest High School	1998 to 2007

Weather data used in this study was obtained from archived weather maps. The 12Z surface pressure maps along with 500mb pressure maps were obtained from the National Oceanic and Atmospheric Administration (NOAA) Central Library U.S. Daily Weather Maps Project (Web-site 1). From these maps, wind speeds, wind directions, synoptic weather features, and flow patterns for the surface and 500mb were taken for each specific high pollution day. Mixing height data and mixing layer wind speeds were obtained from archived temperature soundings for Springfield, Missouri. Springfield was chosen due to fact that it is the only location in the state where radiosondes are launched on a regular basis. The archived 12Z temperature soundings came courtesy of the University of Wyoming (Web-site 2).

3.4 Forming an Air Quality Index

An Air Quality Index for ground level ozone was created using the procedure outlined in the EPA's *Guidelines for the Reporting of Daily Air Quality – the Air Quality Index* (2006). An index value was found for each day and monitoring site involved in the study.

The first part of this process involved converting the averaged hourly ground level ozone levels to averaged daily values. Averaged daily values were calculated by selecting the highest continuous 8-hour average for each day. Kansas City, St. Louis, and Springfield are only required to report 8-hour concentrations in accordance with EPA guidelines. For this reason, the 8-hour average was favored over the 1-hour average. The 8-hour average then became the daily average ozone concentration for each monitoring day.

Next, averaged daily values were converted to their associated index values. This was completed using US EPA standards found in the EPA's *Guidelines for the Reporting of Daily Air Quality – the Air Quality Index* (2006). The standards are set forth in an equation that is used to compute the index values. Equation 1 shows the equation used by the US EPA to convert concentration values into index values.

$$I_p = \frac{I_{Hi} - I_{Lo}}{BP_{Hi} - BP_{Lo}}(C_p - BP_{Lo}) + I_{Lo} \qquad (1)$$

Where I_p = the AQI value for the pollutant
C_p = the rounded concentration calculated for the pollutant
BP_{Hi} = the breakpoint value that is greater than or equal to C_p
BP_{Lo} = the breakpoint value that is less than or equal to C_p
I_{Hi} = the AQI value corresponding to the break point value greater than or equal to C_p
I_{Lo} = the AQI value corresponding to the break point value less than or equal to C_p

The equation uses breakpoint values to discern when certain values should be used in the equation based on the concentration of ozone found in the area. Breakpoint values are assigned values that represent a certain category a pollutant concentration can fall into. If the pollutant falls into the category, the numbers at the high end and low end of the breakpoint category are used in the equation. The numbers that were used in the equation were based on the concentrations found using the 8-hour daily average. Table 3.2 shows the breakpoint values and index values used in the calculation of the index value for each ground level concentration.

Table 3.2: Breakpoint concentration levels and the associated AQI values used in the equation (from US EPA).

O3 (ppm) 8-hour	AQI	Category Description
0.000 – 0.064	0 – 50	Good
0.065 – 0.084	51 – 100	Moderate
0.085 – 0.104	101 – 150	Unhealthy for Sensitive Groups
0.105 – 0.124	151 – 200	Unhealthy

After the AQI values were calculated, they were assigned color values based on which air quality category the values fell into. This helps make days with high pollution levels easily discernable from days with low pollution levels for the public. Table 3.3 shows the color scheme used to describe the calculated index values for ozone.

Table 3.3: Color schemes and category description for different AQI categories (from US EPA).

AQI	Category Description	Color
0 – 50	Good	Green
51 – 100	Moderate	Yellow
101 – 150	Unhealthy for Sensitive Groups	Orange
151 – 200	Unhealthy	Red

3.5 Mixing Heights, Transport Wind Speeds, and Ventilation Rates

Afternoon mixing heights were found using 12Z temperature soundings for Springfield, which is the only city in Missouri that regularly launches radiosondes. The Springfield sounding was also used to find the mixing heights for Kansas City and St. Louis. This is allowable because this study is only looking for high and low mixing heights; exact values are not necessarily important for these means. This is also allowable because this study is looking at the synoptic scale, so the values should be similar across the state of Missouri.

The procedure for finding the afternoon mixing height involves taking the maximum predicted temperature for the afternoon and raising a parcel from it dry adiabatically until it meets the 12Z temperature sounding. The height at which the parcel intersects the temperature sounding is the afternoon mixing height for the sounding. Conversely, to calculate the maximum afternoon temperature using a morning sounding, a parcel is first taken from the 850mb height to the surface dry adiabatically. This point represents the maximum temperature for that day. Due to the fact that these two variables are found on a sounding in a similar manner, the daily afternoon mixing heights used in this study were the 850mb heights on the morning temperature soundings. Several assumptions have to be made in order for this process to work. First, finding the mixing height this way assumes that there will be clear skies allowing for maximum daytime heating in the region. Second, this process assumes that the maximum temperature, as predicted for the temperature sounding, for the day was met. These assumptions are allowable because clear skies and large amounts of incident solar radiation are often associated with the passage of a high-pressure system over the region.

Using this procedure, the afternoon mixing heights for each high pollution day were found using the Springfield 12Z temperature soundings and were then put into two categories. Following criteria listed in Holzworth (1972), afternoon mixing heights less than 1500m were marked as significant while mixing heights greater than 1500m were marked as not significant. This was done because Holzworth (1972) found that many high pollution days occurred when afternoon mixing heights were below 1500m.

Along with the afternoon mixing heights, the transport wind speeds in the mixing layer were determined. The transport wind speed in the mixing layer was calculated by averaging all the wind speeds from the surface to the 850mb level.

The wind speeds were averaged using radiosonde data from Springfield, MO. After the transport wind speeds in the mixing layer were found, they were put into two categories following criteria outlined in Holzworth (1972). Transport wind speeds of less than $4ms^{-1}$ were marked as significant while transport wind speeds of more than $4ms^{-1}$ were marked as not significant. This was done because Holzworth (1972) found that many high pollution days occurred when transport wind speeds were below $4ms^{-1}$.

Ventilation rates were calculated by multiplying the afternoon mixing height by the transport wind speed in the mixing layer. Mixing heights were found using the procedure stated above. Also, mean wind speeds in the mixing layer were found using the procedure listed above. These values were all found using Springfield 12Z temperature soundings for each high ozone day. After the ventilation rates were found each high pollution day, they were put into categories. The breakdown of these categories is listed in Table 3.4. These categories came courtesy of the National Weather Service at Grand Junction, CO (Web-site 3).

Table 3.4: Ventilation rate categories from the National Weather Service at Grand Junction, CO. Ventilation rate units are in m^2s^{-1}. (Web-site 3)

Ventilation Rate (m^2s^{-1})	Category Description	Color
<6272	Poor	Red
6272 -- 9408	Fair	Yellow
9409 – 15680	Good	Green
15681 – 23520	Very Good	Light Blue
>23520	Excellent	Blue

Mixing heights, transport wind speeds, and ventilation rates were then compared against high ozone days in an attempt to determine how well they could predict high ozone concentrations. Also, mixing heights and transport wind speeds were compared in order to determine which variable has greater influence in the ventilation rate calculation.

3.6 Classification Procedure

Days with an AQI value of 50 or above were used in the classification process. For each day that fell into the above category, both 12Z surface pressure and 500mb pressure maps were analyzed. During the map analysis, Missouri was set as the center reference point for each of the maps. At both pressure levels, locations of synoptic weather features were noted with respect to Missouri. Wind flow patterns at both pressure levels were examined and direction of the flow was noted. At 500mb, the location of the jet with respect to Missouri and its overall flow pattern was examined for each high pollution day. After the synoptic weather patterns were noted at each pressure level, the elevated ozone days were then placed into different categories. At the surface, each day was then placed into a category based on the location of a high-pressure system with respect to Missouri. At 500mb, each day was placed into a category based on the location a ridge axis in the overall flow with respect to Missouri. Each category was then analyzed to determine how they are linked to high ozone levels in Missouri.

After each surface category was found for high ozone days, they were compared to days when ozone concentrations were lower than the threshold values. Percentages of the number of occurrences of each category for high and low ozone days were found in order to determine a frequency of when each category was associated with a high pollution day or a low pollution day. This was done for five years of the study period, 2003 through 2007. This information will help to set an even stronger basis for potential high pollution day forecasting in Missouri.

Chapter 4

Climatology

4.1 Air Quality Index

After the Air Quality Index was calculated for each city, a total of 555 days with high ground level ozone concentrations were found in the ten-year study period. These 555 days represent days in which ground level ozone concentrations equal to or exceed the "moderate" (yellow) level of the US EPA's Air Quality Standards. During the ten-year study period, St. Louis experienced high ozone concentrations on 395 of the 555 possible days, while Kansas City experienced high ozone concentrations on 335 of the 555 possible days. The city of Springfield experienced high ozone concentrations on 200 of the 555 possible days. Figure 4.1 shows the total number of days that fall into each AQI category.

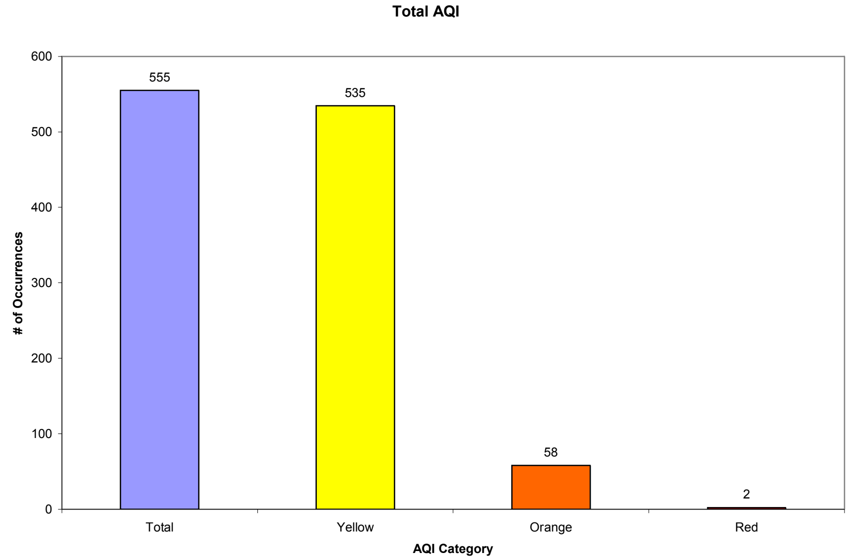

Figure 4.1: Total number of days that fall into each AQI category for the study period.

Of these 555 days, yellow-levels occurred on 535 of the possible days for at least one of the cities. “Unhealthy for sensitive groups” (orange) levels occurred on 58 of the possible days for at least one of the cities. “Unhealthy” (red) levels occurred on two of the possible days for at least one of the cities. St. Louis experienced orange-levels on 42 days in the ten-year study period, while Kansas City experienced orange-levels on 20 days in the ten-year study period. Springfield experienced orange-levels on just six days in the ten-year period. The largest number of the orange-level days took place in the years 1999 and 2002. St. Louis was the only city that experienced red-level ozone concentrations. These days took place in the years 1999 and 2003. Figure 4.2 shows the AQI value breakdown for each city in the study.

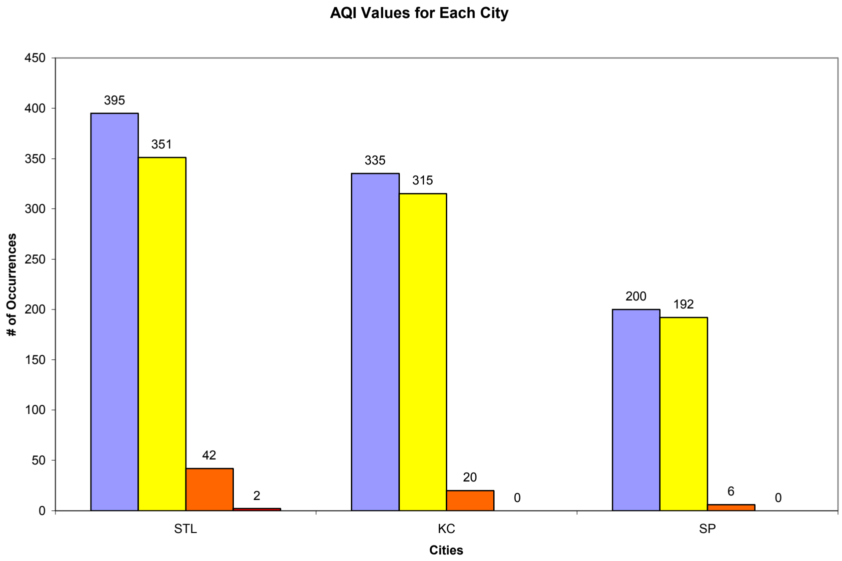

Figure 4.2: AQI category breakdown for each city in the study period. The blue column represents the total number of high ozone days. The yellow, orange, and red columns represent their respective AQI categories.

4.2 Mixing Heights

Over Missouri, the mixing height was found to be fairly constant with little variability in its height. Overall, for the ten-year period, the average Mixing height for elevated pollution days was found to be 1550m with a standard deviation of 30m. High ozone concentrations often fall on days when the mixing height is more than two standard deviations above or below the yearly mean, which makes them significantly different from other days. Figure 4.3 shows the yearly breakdown for the average mixing height and its associated standard deviation.

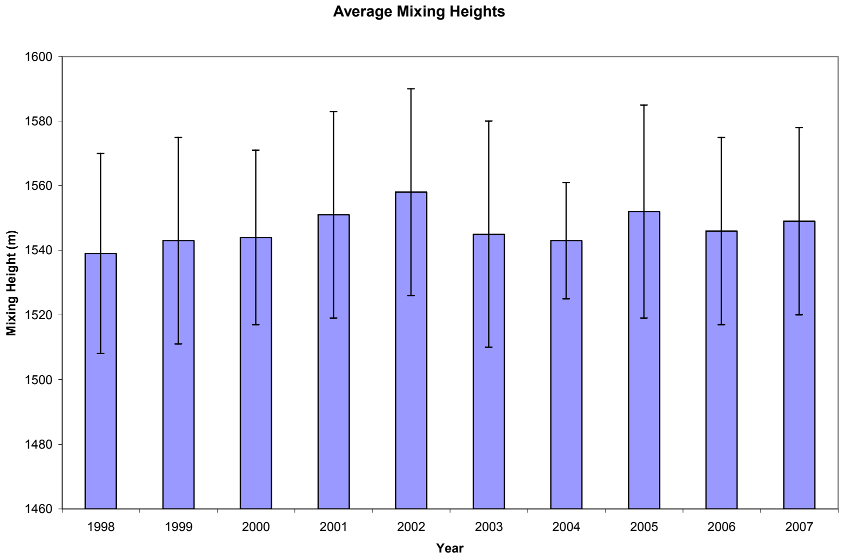

Figure 4.3: Yearly breakdown of average mixing heights with the associated standard deviations.

Each year during the ten-year study period contained several days with mixing heights below 1500m. The years 1998 and 2005 had the most days with mixing heights below 1500m, while the year 2004 had zero days with mixing heights below 1500m. Figure 4.4 shows the yearly breakdown for the number of days with mixing heights below 1500m.

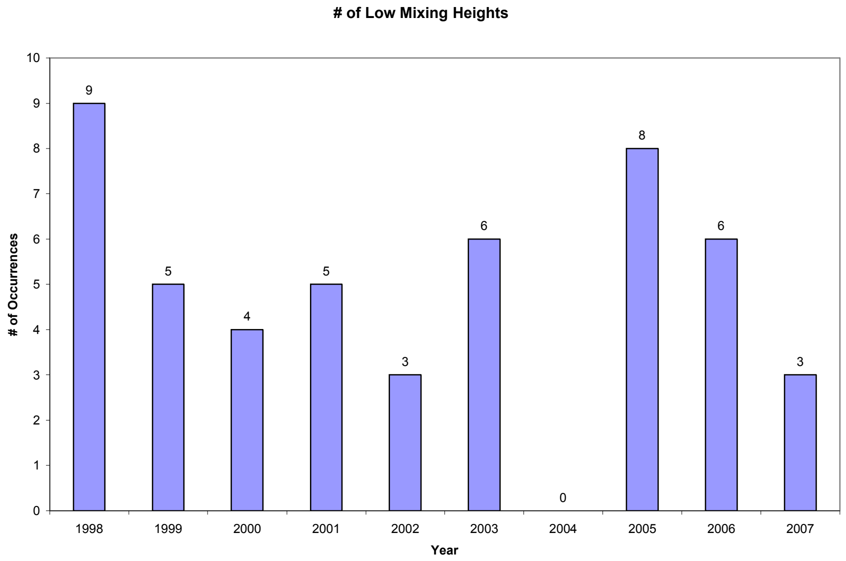

Figure 4.4: Yearly breakdown of the number of days with mixing heights below 1500m.

The lowest mixing height during the ten-year period was found in 2006. Figure 4.5 shows the yearly breakdown of the lowest mixing.

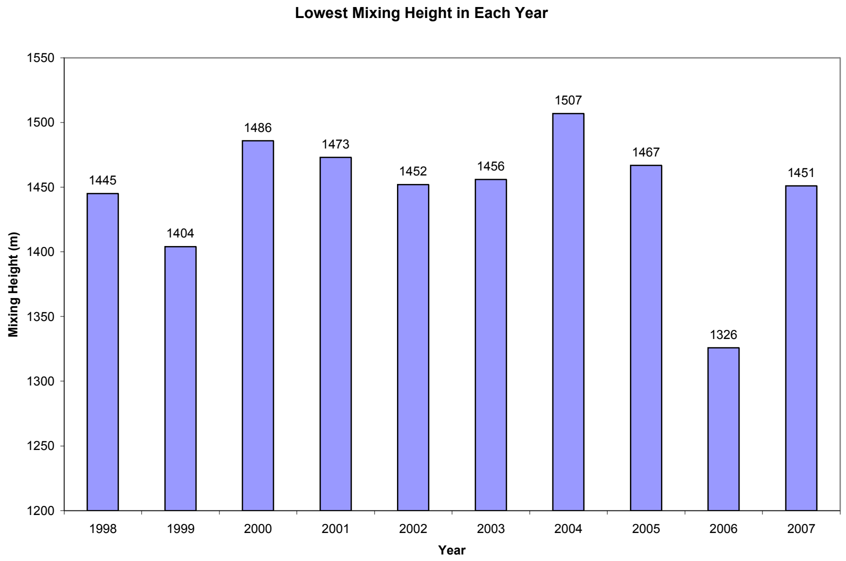

Figure 4.5: The lowest mixing heights for each year of the ten-year study period.

When compared to days with high ozone concentrations, mixing heights were able to account for approximately 10% of the days. Figure 4.6 shows the yearly breakdown of the percentage of high ozone days that low mixing heights were able to account for.

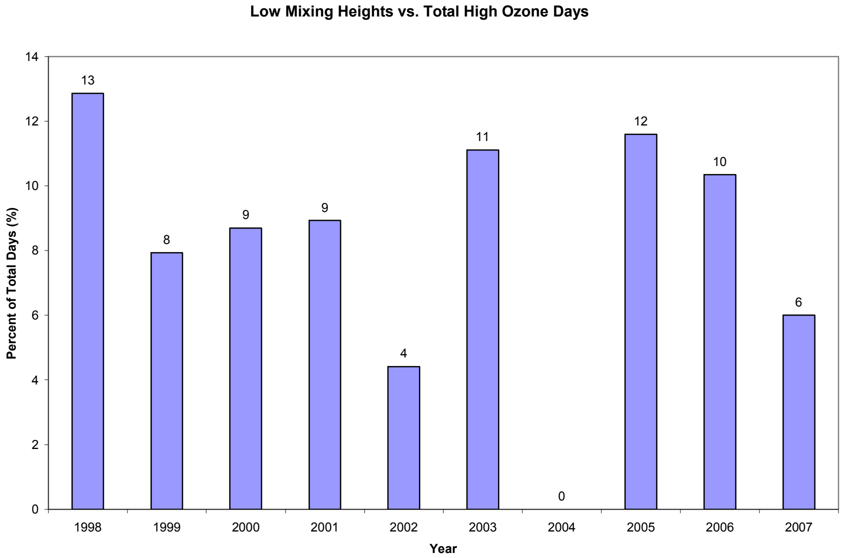

Figure 4.6: Yearly breakdown of the percentage of high ozone days that low mixing heights account for.

4.3 Transport Wind Speeds

On the other hand, the transport wind speeds over Missouri are highly variable on the average and vary greatly form day to day. Overall, for the ten-year period, the average transport wind speed for high pollution days was found to be $7ms^{-1}$ with a standard deviation of $4ms^{-1}$. Figure 4.7 shows the yearly breakdown for the average mixing height and its associated standard deviation.

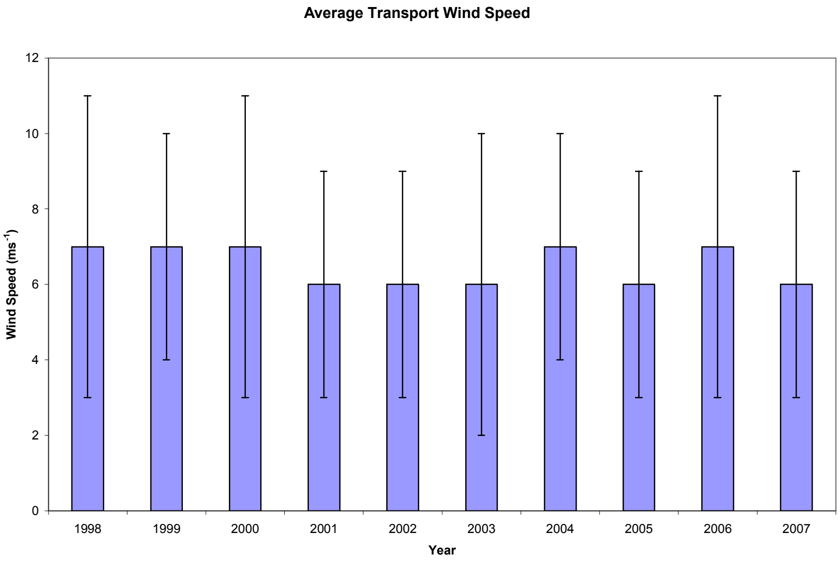

Figure 4.7: Yearly breakdown of the average transport wind speed and the associated standard deviation.

Each year during the ten-year study period contained several days with transport wind speeds below 4ms^{-1}. The years 2002 and 2005 had the most days with transport wind speeds below 4ms^{-1}. Figure 4.8 shows the yearly breakdown for the number of days with transport wind speeds below 4ms^{-1}.

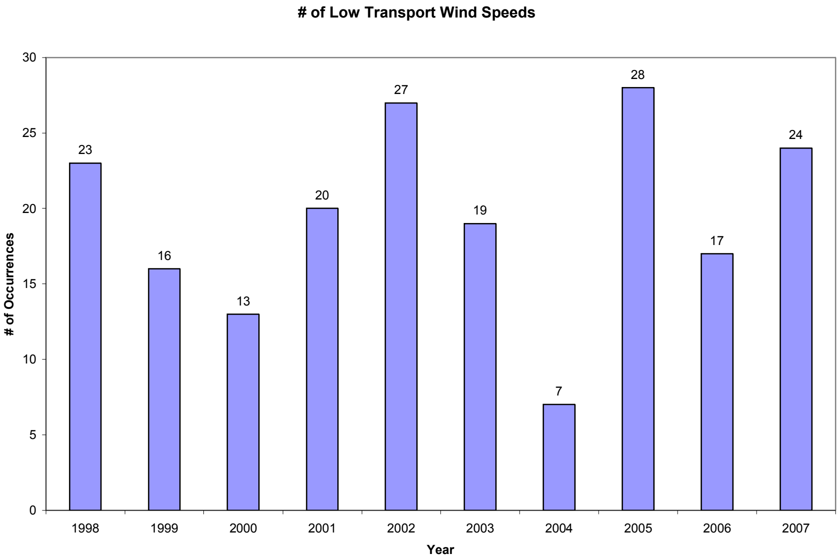

Figure 4.8: Yearly breakdown of the number of days with transport wind speeds below 4ms^{-1}

The lowest transport wind speed of 1ms^{-1} during the ten-year period was found in the years 1999, 2002, 2005, 2006, and 2007. Figure 4.9 shows the yearly breakdown of the lowest transport wind speed for each year.

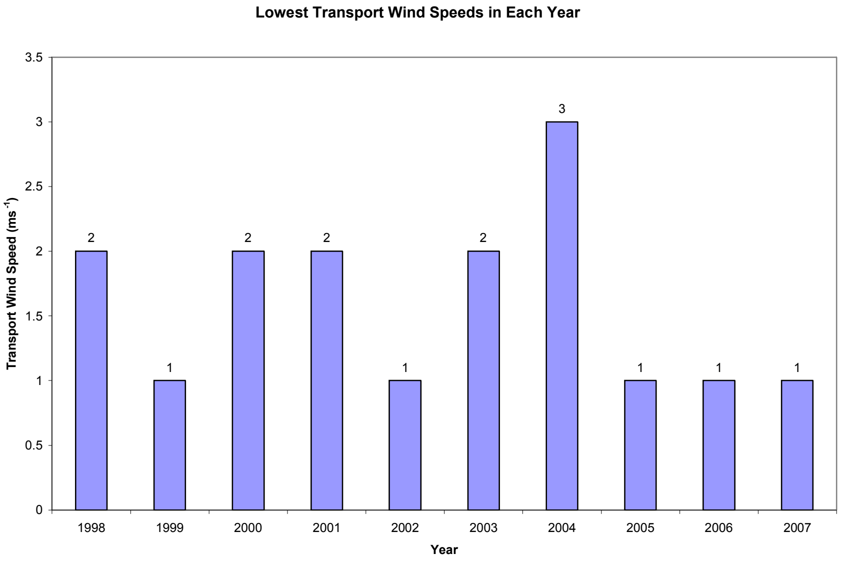

Figure 4.9: Yearly breakdown of the lowest transport wind speeds.

When compared to days with high ozone concentrations, low transport wind speeds account for approximately 35% of the days. In the year 2007, 48% of the high ozone days were accounted for by the transport wind speed. In the year 1999, only 25% of the high ozone days were accounted for by the transport wind speed. Figure 4.10 shows the yearly breakdown of the percentage of high ozone days that low transport wind speeds were able to account for.

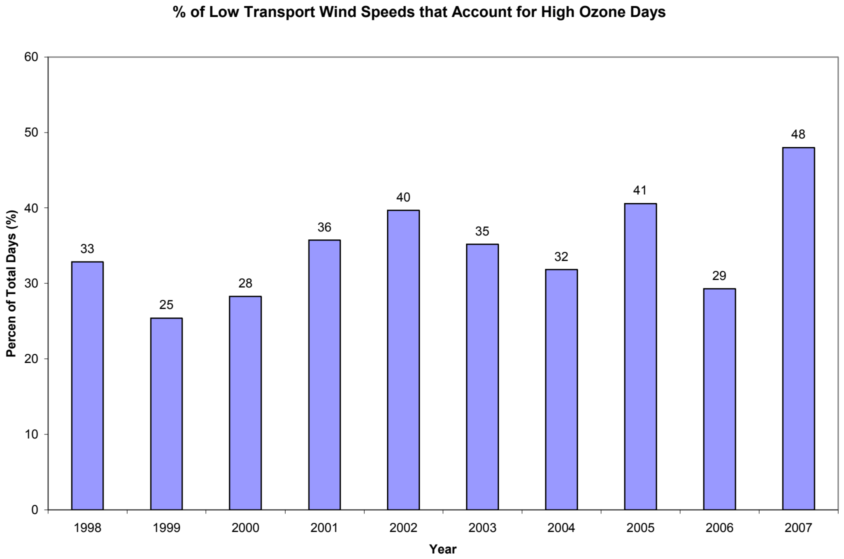

Figure 4.10: Yearly breakdowns of the percentage of the high ozone days that low transport wind speed days were able to account for.

4.4 Ventilation Rates

Overall, for the ten-year period, the average ventilation rate for high ozone days was found to be 10000m^2s^{-1} with a standard deviation of 5000m^2s^{-1}. Figure 4.11 shows the yearly breakdown of the average ventilation rate.

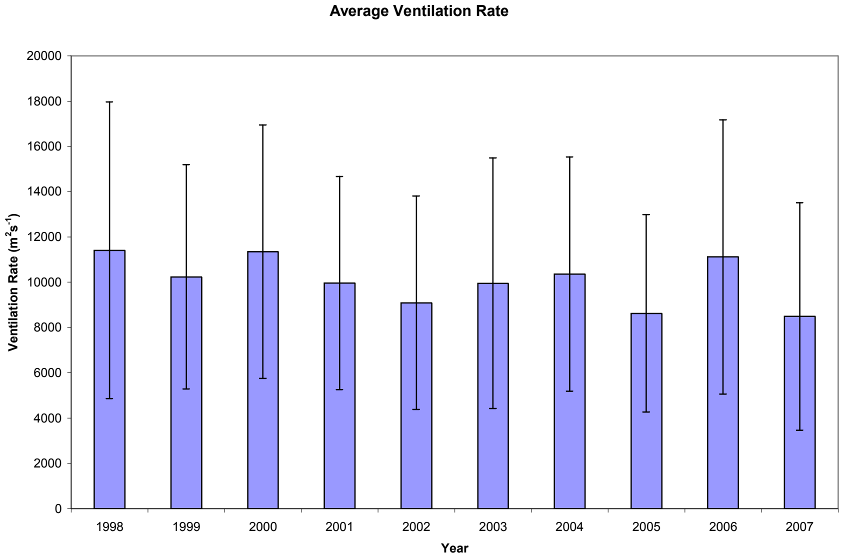

Figure 4.11: Yearly breakdowns of average ventilation rate and the associated standard deviation.

Each year during the ten-year study period contained several days with ventilation rates in the poor or fair category. The year 2005 had the most days with the ventilation rates in the poor or fair category. The year 2004 had the fewest days with poor or fair ventilation rates. Figure 4.12 shows the yearly breakdown for the number of days with poor or fair ventilation rates.

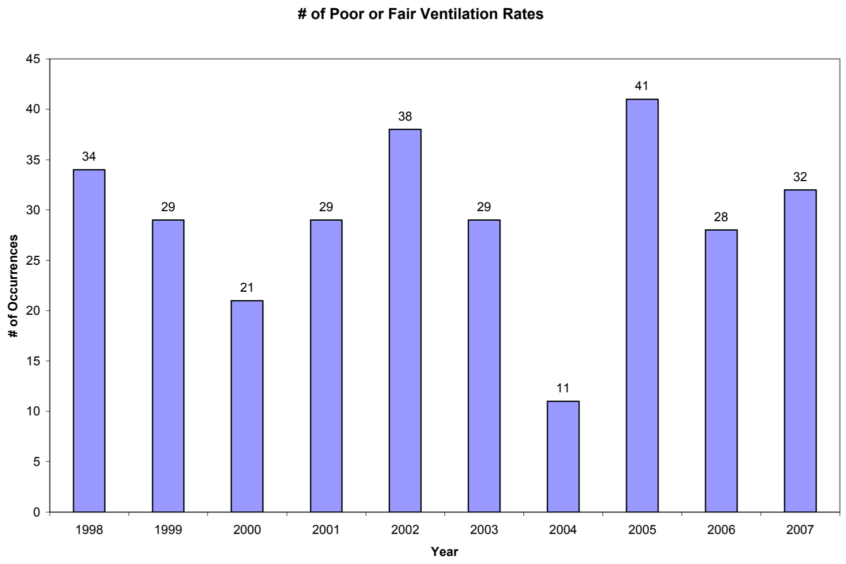

Figure 4.12: Yearly breakdowns of the total number of days with ventilation rates in the poor or fair categories.

There are also several extended periods of poor or fair ventilation rates for each year during the ten-year study period. The years 2002, 2005, and 2006 have the most extended periods of poor or fair ventilation rates with four each. The year 2004 has the fewest periods of poor or fair ventilation rates with zero. Table 4.1 shows the yearly breakdown of the extended periods of poor or fair ventilation rates.

Table 4.1: Extended periods of poor or fair ventilation rates for each year of the ten-year study period.

Year	Extended periods of low or poor ventilation rates
1998	July 9 to 14, August 12 to 16
1999	August 25 to 29
2000	August 30 to September 2
2001	August 4 to 8, August 12 to 16
2002	June 22 to 25, July 13 to 16, August 27 to 31, September 4 to 7
2003	June 15 to 18, August 14 to 19
2004	None
2005	June 18 to 23, July 7 to 11, July 29 to August 1, August 6 to 10
2006	July 14 to 19, July 23 to 26, July 31 to August 3, August 13 to 17
2007	July 23 to 26, July 31 to August 3, August 13 to 17

The lowest ventilation rate during the ten-year period was found in the years 1999, 2002, 2005, and 2007. Figure 4.13 shows the yearly breakdown of the lowest ventilation rate for each year.

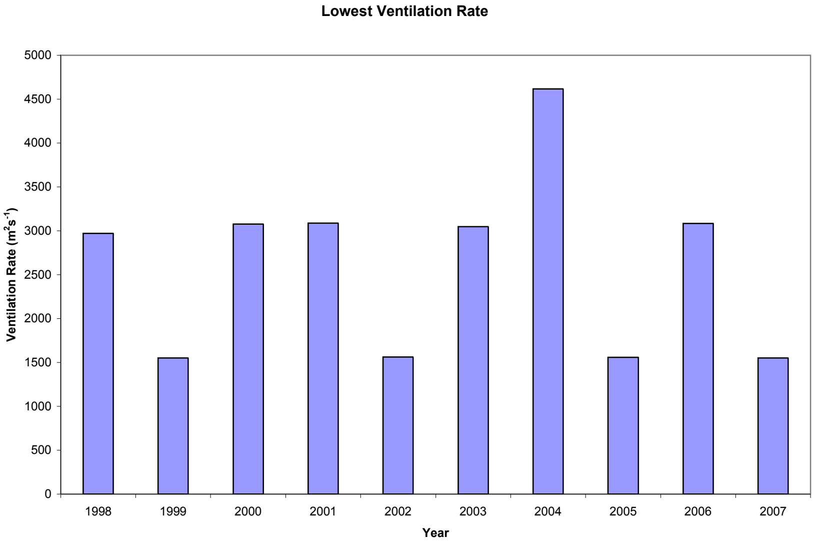

Figure 4.13: Yearly breakdowns of the lowest ventilation rates.

When compared to days with high ozone concentrations on the synoptic scale, poor or fair ventilation rates accounted for approximately 50% of the days. Figure 4.14 shows the yearly breakdown of the percentage of high ozone days that poor or fair ventilation rates were able to account for. While, figure 4.15 shows poor or fair ventilation rates that match with high ozone days.

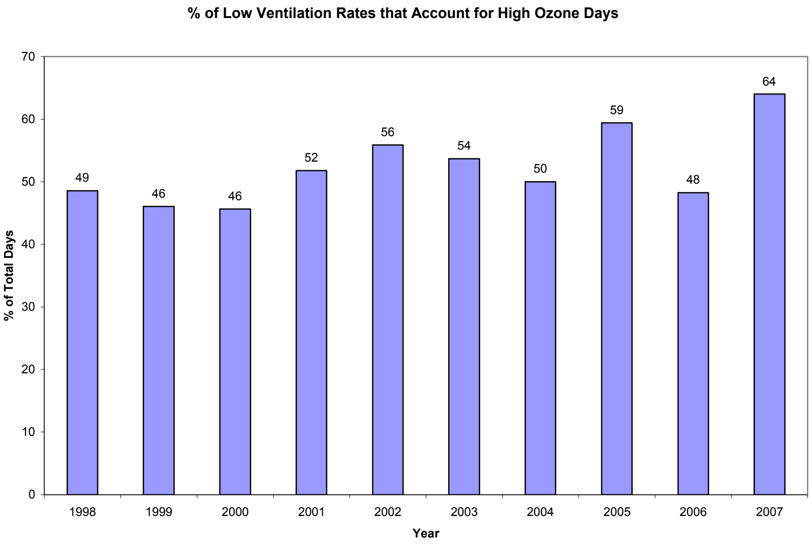

Figure 4.14: Percentage of poor or fair ventilation rates that account for high ozone days.

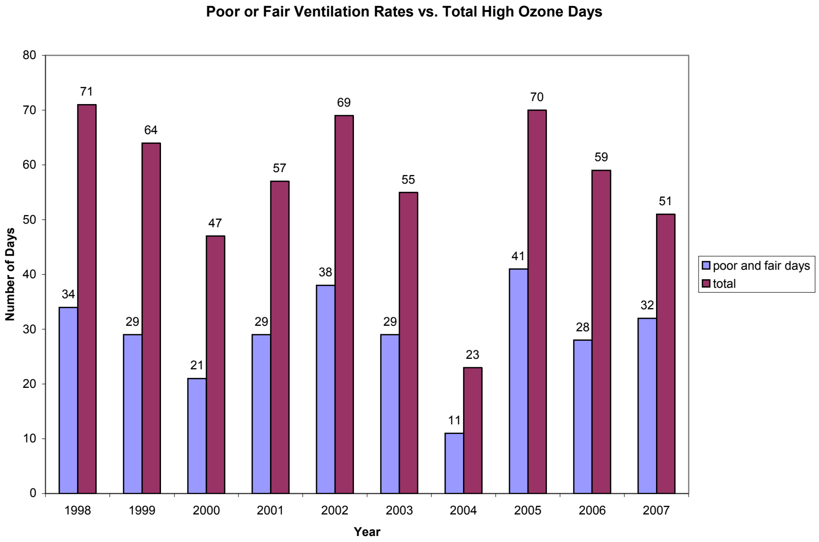

Figure 4.15: Number of poor or fair ventilation rates that match with high ozone days.

To compare how ventilation rates are effective at predicting high ozone concentrations at the local level, poor or fair ventilation rates were compared to high ozone days for Springfield. In most years poor or fair ventilation rates were able to account for over 50% of the high ozone days. In the years 1998 and 2004, poor or fair ventilation rates accounted for less than 50% of the high ozone days in that year. Figure 4.16 shows the number of high ozone days that match with poor or fair ventilation rates along with the percentage that these days make up of the total.

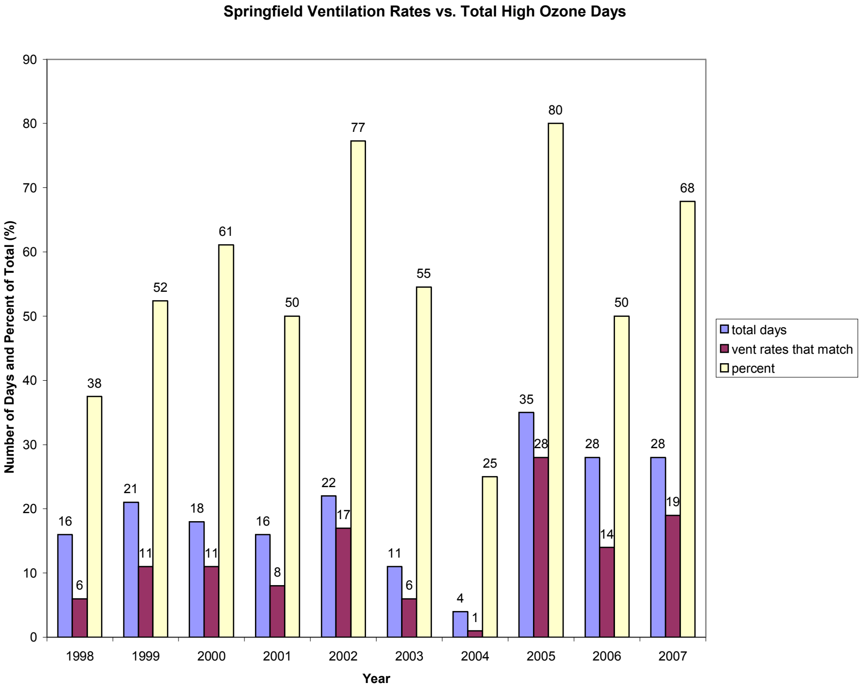

Figure 4.16: The number of poor or fair ventilation rates that match with high ozone days and the percent of the total high ozone days.

4.5 Analysis of Ventilation Rate Calculations

In order to determine which atmospheric variable contributes the most to the calculation of the ventilation rate, the number of low mixing heights and low transport wind speeds were compared with the number of poor or fair ventilation rates. When compared, transport wind speeds account for all the poor or fair ventilation rates, while low mixing heights only account for a small number of poor or fair ventilation rates. Figure 4.17 shows the number of low transport wind speeds that account for poor or fair ventilation rates. Figure 4.18 (next page) shows the number of low mixing heights that account for poor or fair ventilation rates.

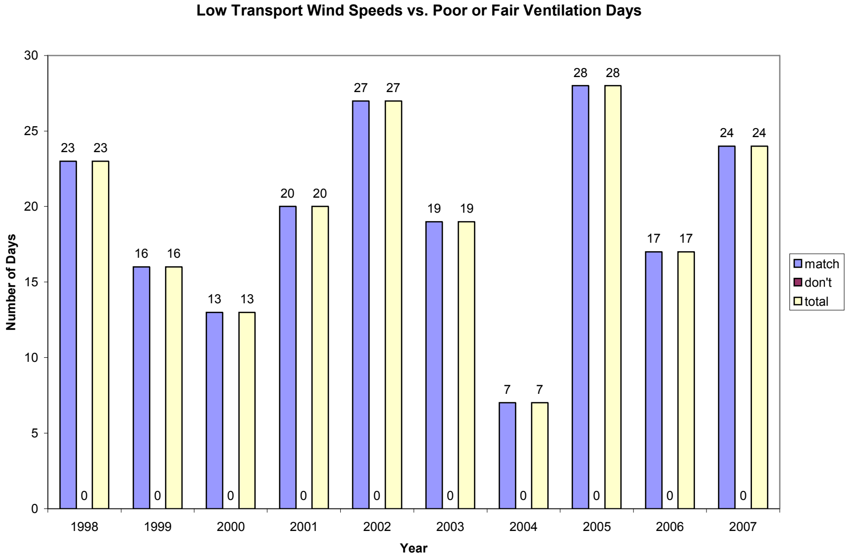

Figure 4.17: The number of low transport wind speed days that match and do not match with poor or fair ventilation days.

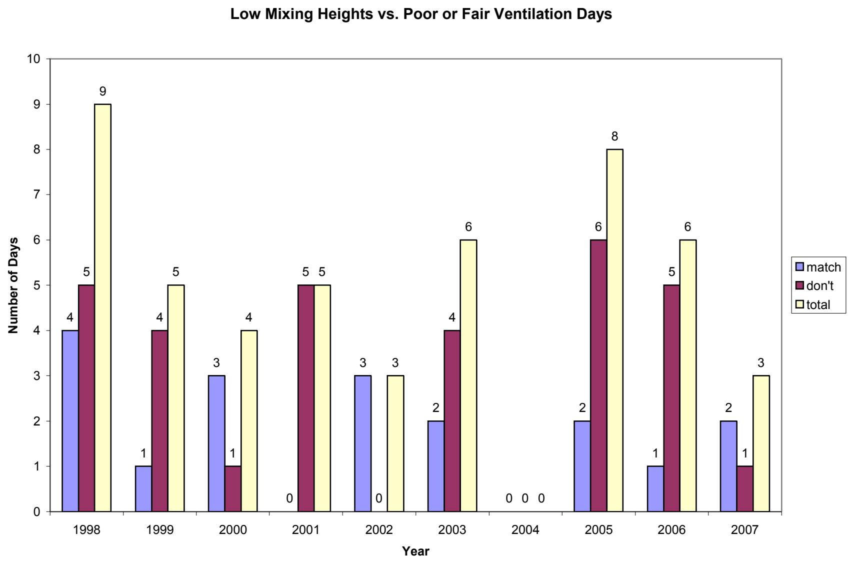

Figure 4.18: The number of low mixing height days that match and do not match with poor or fair ventilation rate days.

4.6 ENSO Influences

El Nino-Southern Oscillation (ENSO) events have been shown to affect the synoptic scale weather patterns across the United States. Table 4.2 shows the number of high ozone days and the ENSO phase for each year of the ten-year study period. For the three El Nino years in the data set, the average number of high ozone days was 62, while for the two La Nina years, the average number of high ozone days was 61. For the five Neutral years in the data set, the average number of high ozone days was 59. During three El Nino years, the average number of orange-level days was seven, while for the two La Nina years, the average number of orange-level days was six. During the five Neutral years, the average number of orange-level days was five. When an El Nino year transitioned to a La Nina year (1998 to 1999), the number of high ozone days stayed relatively constant. During a transition from a La Nina year to a Neutral year (2000 to 2001), the number of high ozone days slightly increased. When a Neutral year transitions to an El Nino year (2002 to 2003), the number of high ozone days showed a slight decrease in number. During a transition from an El Nino year to a Neutral year (2003 to 2004), the number of high ozone days showed a large decrease in the number of elevated ozone days. Finally when a Neutral year transitions to an El Nino year (2006 to 2007), the number of high ozone days showed a slight decrease in the number of elevated ozone days.

Table 4.2: The number of elevated ozone days for each year of the ten-year study period and the ENSO phase for each year.

Year	ENSO Phase	# of red days	# of orange days	# of yellow days
1998	El Nino	0	11	65
1999	La Nina	1	8	62
2000	La Nina	0	4	46
2001	Neutral	0	1	56
2002	Neutral	0	16	62
2003	El Nino	1	2	54
2004	Neutral	0	0	23
2005	Neutral	0	6	70
2006	Neutral	0	4	59
2007	El Nino	0	5	49

Chapter 5

Categorization

5.1 Surface Categories

Synoptic scale surface features have been shown to influence the occurrence of high ozone days in large cities. For this study, these surface features were put into categories based on the position of high-pressure systems around the state of Missouri. High-pressure systems, particularly when Missouri is located on the backside of a high, seem to be the most favorable for high ground level ozone days in the state. At the surface, seven categories were found to exhibit an influence over causing high ground level ozone days. The seven surface categories include:

1. High-pressure system to the North of Missouri
2. High-pressure system to the Northeast of Missouri
3. High-pressure system to the East of Missouri
4. High-pressure system to the Southeast of Missouri
5. High-pressure system to the South of Missouri
6. High-pressure system over Missouri
7. Miscellaneous weather patterns when no high is present

Each category has a different effect on the surface flow patterns and weather for Missouri. Below are descriptions of each category, how they affect the surface flow of Missouri, and their influence in causing high ground level ozone days. Note: Due to the fact that multiple cities can have high ozone concentrations on the same day, the numbers used below in the describing how many high ozone days are present in Missouri may not add up correctly.

5.1.1 High to North

The first category deals with a high-pressure system located to the north of Missouri. Some common locations for this high are over the states of Minnesota, Wisconsin, Iowa, and the Canadian provinces of Manitoba and Ontario. When the high is located in this direction, the predominant surface flow pattern over Missouri comes from a general easterly direction. The surface flow can vary from the northeast, east, or southeast directions based on the strength and location of the high. This flow pattern can be attributed to the clockwise circulation around high-pressure systems. Elevated ground level ozone concentrations are often a direct result of this flow pattern bringing warmer air from the east and southeast to the region. Figure 5.1 shows the general layout for a high-pressure system located to the north of Missouri.

Figure 5.1: The general layout for a high-pressure system located to the north Missouri.

Overall, this category had the second lowest occurrence of the seven possible categories. In the ten-year period, it was found to take place a total of 41 times. This category had an even number of occurrences for each year of the ten years, with the exception of two years. In 1999, it had the largest number of occurrences, while in 2004, it experienced its lowest number of occurrences. The year 2004 was a particularly cool year, which helped to limit the total number of high ozone days, while 1999 was a warmer year, which helped to increase the total number of high ozone days. Figure 5.2 shows the number of occurrences for each year of the ten-year data set.

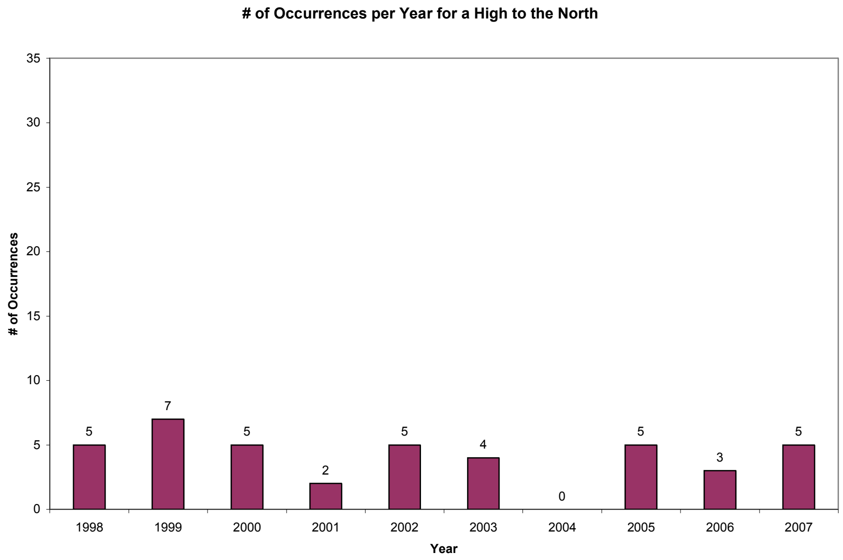

Figure 5.2: The number of occurrences per year for a high-pressure system located to the north of Missouri.

During each year, this category reached a peak in the number of occurrences during the end of the warm season, the month of August. Figure 5.3 shows the number of occurrences in each month of the yearly data set.

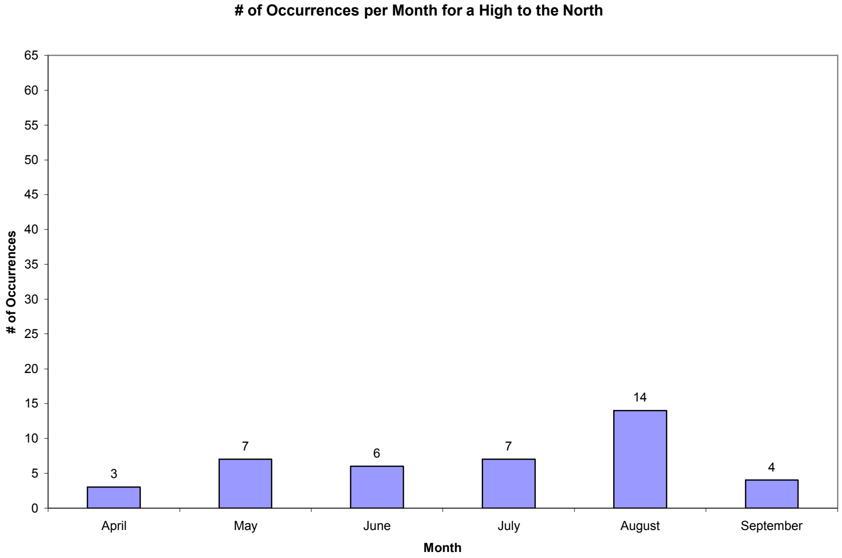

Figure 5.3: The number of occurrences per month for a high-pressure system located to the north of Missouri.

During the ten-year period, this category was linked to a total of 41 high ground level ozone days. Of these 41 days, 40 days climbed to the yellow-level for the three cities in Missouri. It also triggered three orange-level air quality events. St. Louis was affected on all three of these days, while Springfield was affected on just one of these days. Kansas City had no orange-level air quality days during this category. No red-level air quality days were reported at any of the cities during this category. All three cities in Missouri were affected evenly be this category. St. Louis and Kansas City each had 24 high ground level ozone days, while Springfield had high ground level ozone concentrations on 23 of the total days.

5.1.2 High to Northeast

The second category consists of a high-pressure system located to the northeast of Missouri. Some common locations for this high are over the states of New York, Michigan, Pennsylvania, and Maine. When the surface high is located to the northeast, surface flow patterns are predominantly from the general easterly direction. The surface flow can be from the northeast, east, or southeast direction depending on the general location and strength of the high. However, surface flow from the southeast is the most common pattern. High ground level ozone concentrations are often a direct result of this flow pattern bringing warmer air from the east and southeast to the region. Figure 5.4 shows the general layout for a high-pressure system located to the northeast of Missouri.

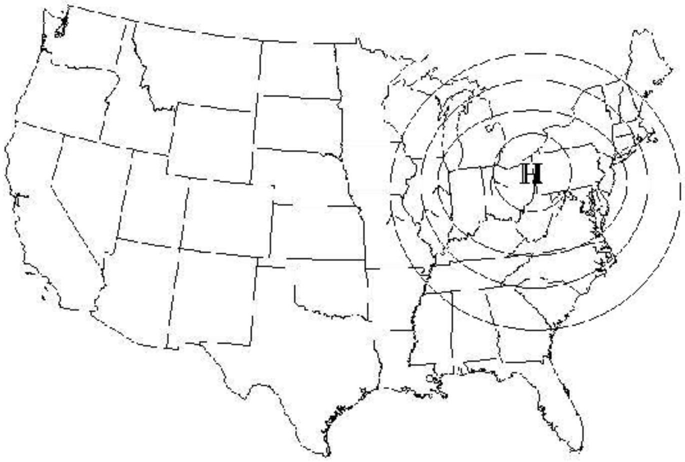

Figure 5.4: The general layout for a high-pressure system located to the northeast of Missouri.

This category had the largest number of occurrences out of the seven categories. It was found to take place a total of 192 times in the ten-year data set. This category had peaks in its number of occurrences during the years 1999, 2002, 2005, and 2007. The highest peak took place in 2005. In the year 2004, a minimum number of occurrences were experienced, when only six events were observed. The year 2004 was a particularly cool year, which helped to limit the total number of high ozone days experienced in Missouri. Figure 5.5 shows the number of occurrences found for each year of the ten-year period.

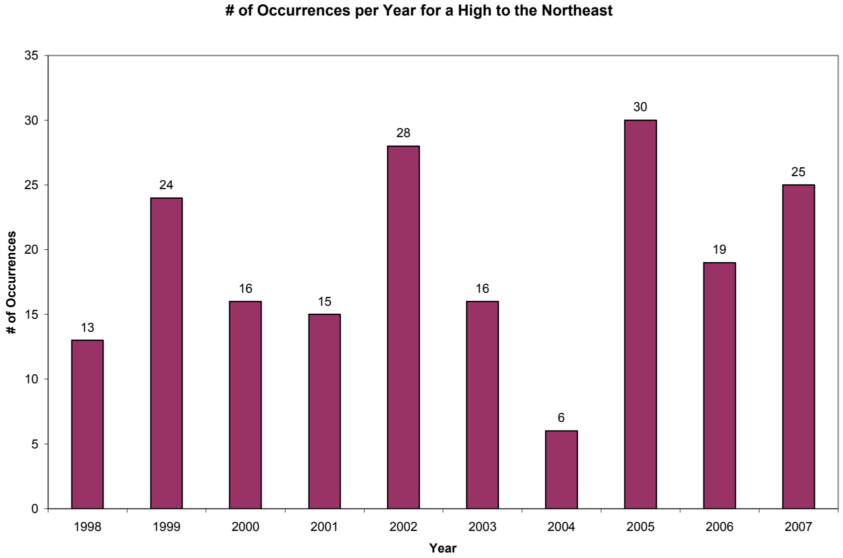

Figure 5.5: The number of occurrences per year for a high-pressure system located to the northeast of Missouri.

This category seems to peak during the end of the warm season, the month of August, which is directly related to warmer temperatures protruding northward during this time. Figure 5.6 shows the number of occurrences in each month of the yearly data set.

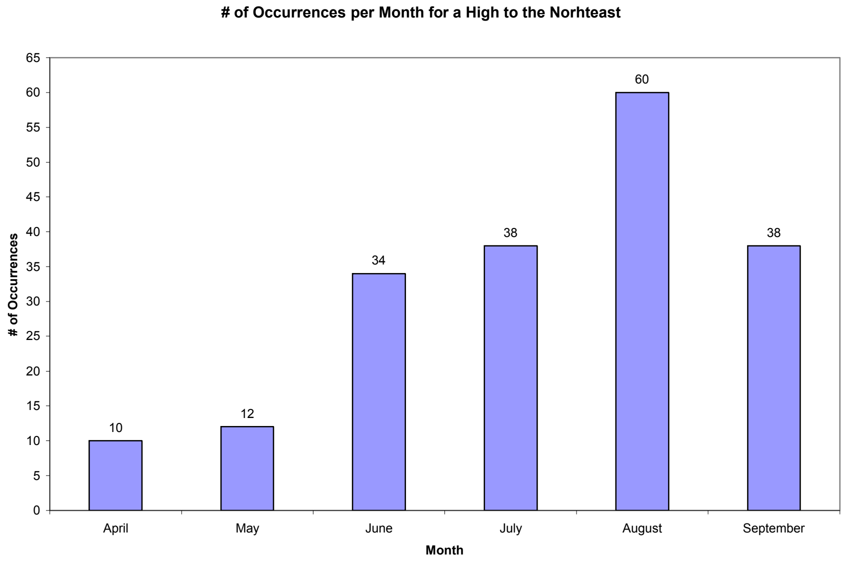

Figure 5.6: The number of occurrences per month for a high-pressure system located to the northeast of Missouri.

Overall, a high to the northeast was linked to a total of 192 high ground level ozone days. Of these 192 days, 184 of them were yellow-level days. This category also triggered nineteen orange-level events. Of these nineteen orange-level days, St. Louis was affected on fifteen days. Springfield was affected on just one day and Kansas City experienced eight orange-level days. One red-level day was reported at St. Louis during this category, while Kansas City and Springfield experience no red-level events. A high to the northeast affected the city of St. Louis the most. St. Louis experienced high ground level ozone days on 151 out of the 192 possible days. Kansas City had the second highest number of high ground level ozone days with 112, while Springfield experienced high concentrations on 73 of the possible days.

5.1.3 High to East

The third category deals with a high-pressure system being located to the east of Missouri. This high takes a common residence over the states of Kentucky, West Virginia, and Virginia. When a high is located to the east, surface flow patterns are predominantly from a southerly direction, in general. High ground level ozone concentrations are often a direct result of this flow pattern bringing warmer air from the south and southeast to the region. The general layout for a high-pressure system located to the east of Missouri is shown in Figure 5.7.

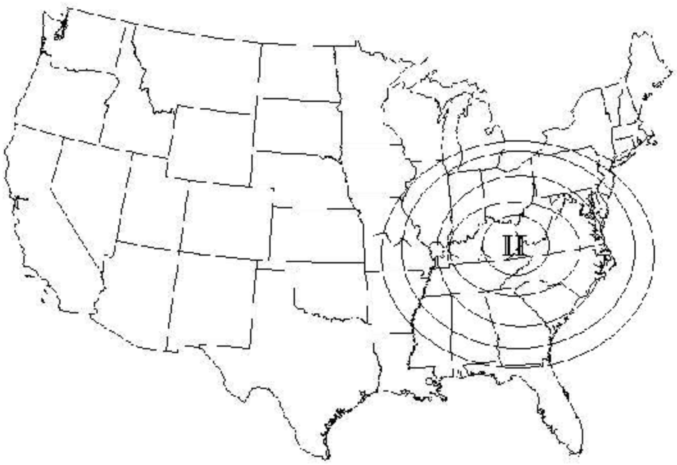

Figure 5.7: The general layout of a high-pressure system located to the east of Missouri.

A center of high-pressure located to the east had the second highest number of occurrences out of the seven categories. During the ten-year study period, it was found to occur 107 times. For this category, the largest number occurrences took place in 1998, while in 2004, the lowest number of occurrences was recorded. Otherwise, this category had an even amount of occurrence for the other years in the ten-year period. The year 1998 was a warmer one, which helped to increase the total number of high ozone days. Figure 5.8 shows the number of occurrences during each year of the ten-year study period.

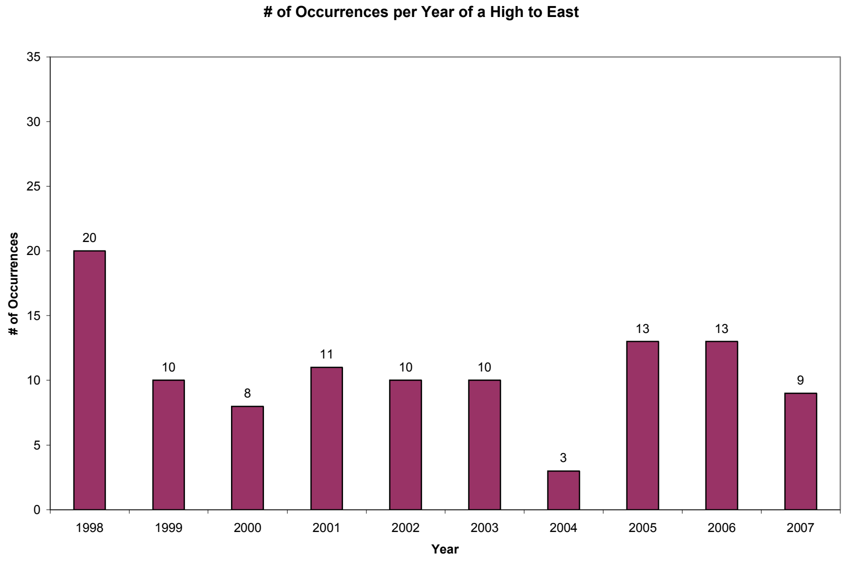

Figure 5.8: The number of occurrences per year for a high-pressure system located to the east of Missouri.

During a year, it reached peaks in the number of occurrences during the middle to end of the warm season, in the months of June, July, and August. This is directly related to warmer temperatures protruding northward during this time. Figure 5.9 shows the number of occurrences in each month of the yearly data set.

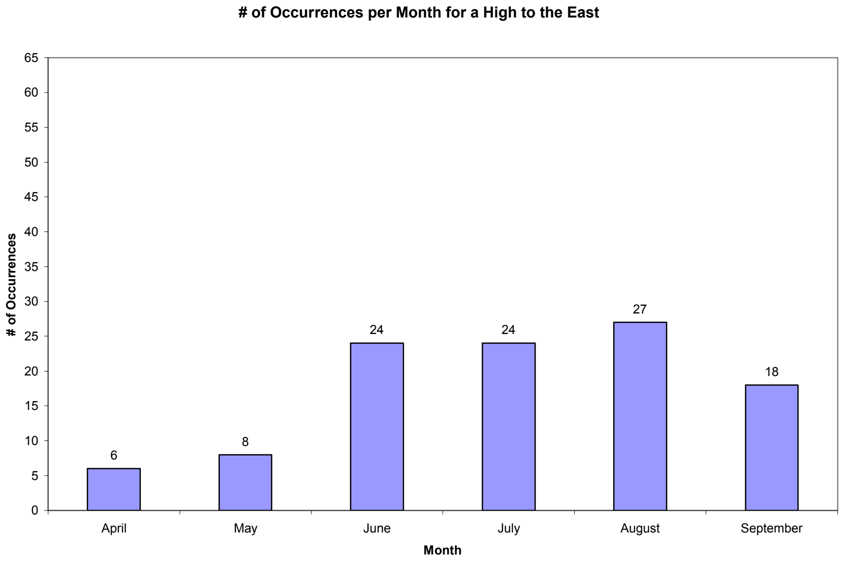

Figure 5.9: The number of occurrences per month for a high-pressure system located to the east of Missouri.

Of the 107 total days, 105 of the days were yellow-level days. This category also triggered fifteen orange-level events. Of these fifteen orange-level days, St. Louis experienced twelve, while Springfield experienced just one orange-level day. Kansas City experienced five orange-level days during this type of category. No red-level days were reported at any of the cities during this category. The cities of St. Louis and Kansas City experienced a similar number of high ground level ozone concentrations during this category. They had 79 and 73 high ground level ozone days respectively. Springfield experienced high concentrations on only 38 of the possible days.

5.1.4 High to Southeast

The next category deals with a high-pressure system being located to the southeast of Missouri. This high commonly resides over the states of Georgia, Florida, Tennessee, and South Carolina. When it is located in this area, the surface flow over Missouri can either be from the southwest, south, or southeast largely depending on the strength and location of the high. High ground level ozone concentrations are often a direct result of this flow pattern bringing warmer air from the south, southwest, and southeast to the region. Figure 5.10 shows the general layout for a high-pressure system located to the southeast of Missouri.

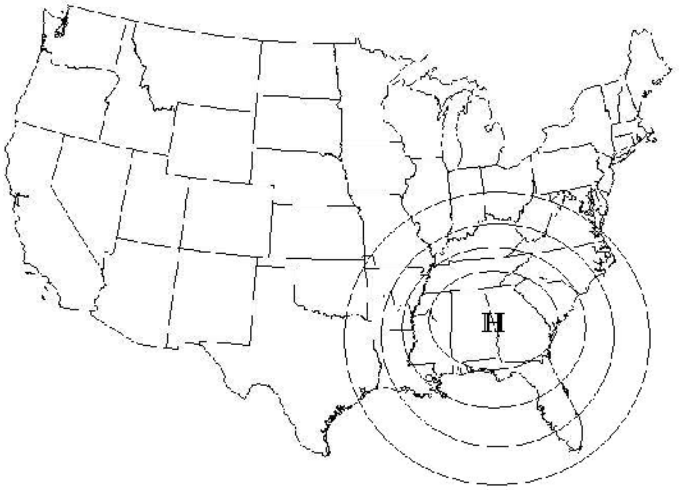

Figure 5.10: The general layout of a high-pressure system located to the southeast of Missouri.

During the ten-year study period, a high to the southeast took place a total of 76 times. Peaks in the number of occurrences of this category can be seen in the years 1998, 2001, 2002, and 2006. This category had its lowest number of occurrences in the year 2007. Figure 5.11 shows the number of events for each year of the ten-year data set.

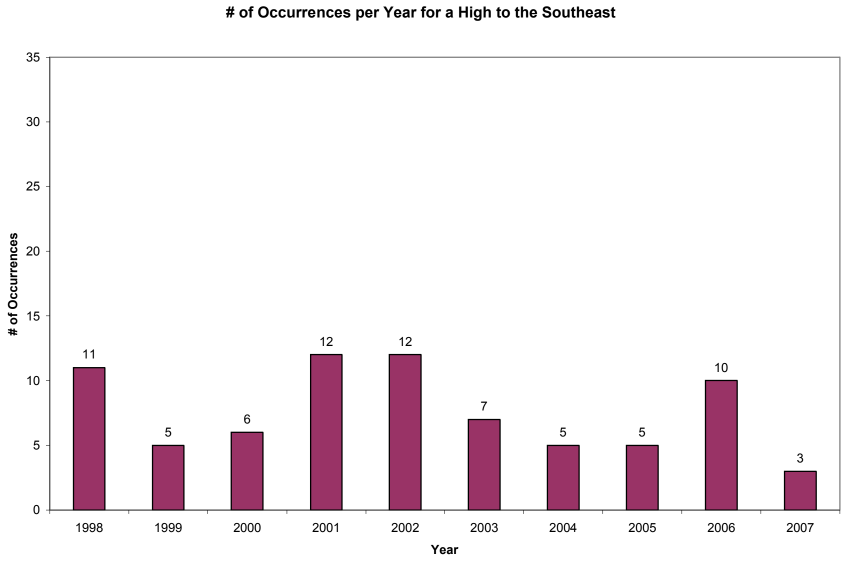

Figure 5.11: The number of occurrences per year for a high-pressure system located to the southeast of Missouri.

On a yearly basis, a high to the southeast reached its peak during the middle to end of the warm season, in the months of July and August. This increase in the number of occurrences can be related to warmer temperatures protruding northward during this time. Figure 5.12 relates the number of occurrences in each month of the yearly data set.

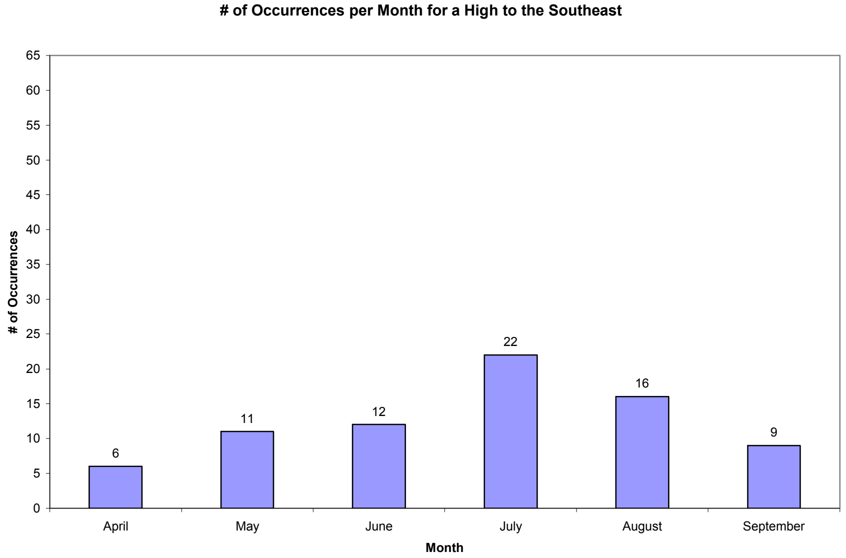

Figure 5.12: The number of occurrences per month for a high-pressure system located to the southeast of Missouri.

In total, a high to the southeast of Missouri was linked to 76 high ground level ozone days in Missouri. Of these 76 days, this category triggered a total of 71 yellow-level days and a total of nine orange-level events. During these nine days, St. Louis experience three high ground level ozone days, while Springfield only experienced high concentrations on two days. However, this was the largest number of orange-level events experienced by the city of Springfield. In total, Kansas City experienced four orange-level days during this category. One red-level day was reported at St. Louis during this category and was the only red-level day that was reported. Overall, this category caused high ground level ozone concentrations in St. Louis the most, which was then followed by Kansas City. St. Louis and Kansas City experienced a total of 58 and 36 high concentration days respectively, while Springfield had elevated concentrations on just 23 of the possible days.

5.1.5 High to South

The next category deals with a high-pressure system located to the south of Missouri. Some common locations of this high have it over the states of Louisiana, Arkansas, and Mississippi. The most common surface flow is out of the south or southwest during this category and is largely based on the strength and location of the high. Also, St. Louis often experiences surface flow from the West during this type of flow pattern. High ground level ozone concentrations are often a direct result of this flow pattern bringing warmer air from the South and Southwest to the region. Figure 5.13 shows the general layout for when a high-pressure system is located to the South of Missouri.

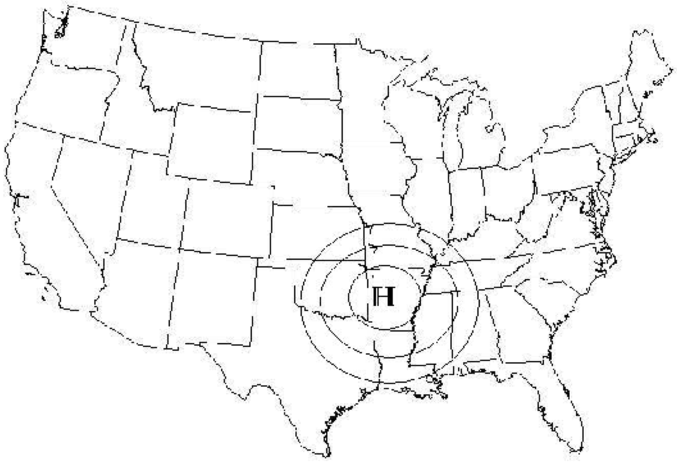

Figure 5.13: The general layout of a high-pressure system located to the south of Missouri.

Overall, a high to the south of Missouri had the third lowest number of occurrences during the ten-year period. It was found to occur only 44 times in the ten-year data set. It was found to occur evenly throughout the ten years, with peaks in the number of occurrences taking place in 1999 and 2005 and valleys in the number of occurrences taking place in 2000 and 2003. In these years, only two events and one event were observed respectively. Figure 5.14 shows the number of occurrences in each year of the ten-year study period.

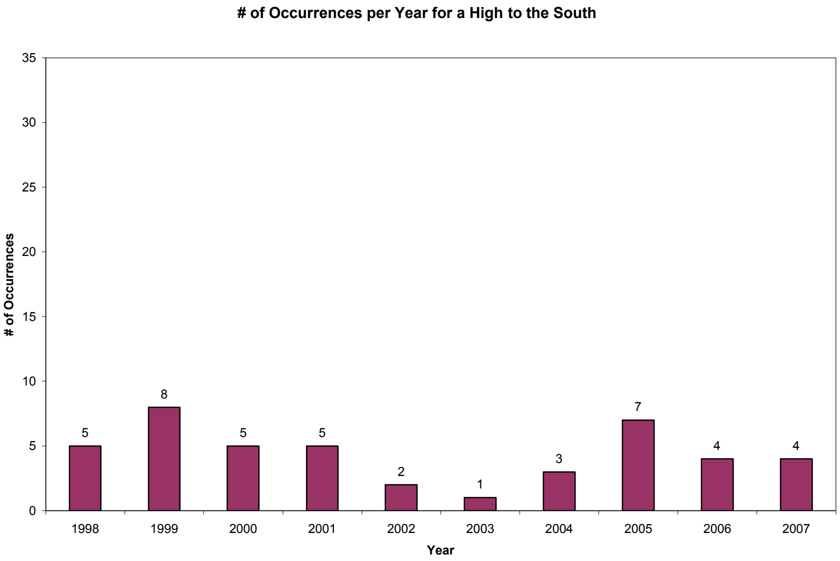

Figure 5.14: The number of occurrences per year for a high-pressure system located to the south of Missouri.

During the year, this category seems to peek during the middle of the warm season, primarily in the month of July. In this month, eighteen of the 44 high ground level ozone days took place, which is directly related to warmer temperatures protruding northward during this time. Figure 5.15 shows the number of occurrences in each month of the yearly data set.

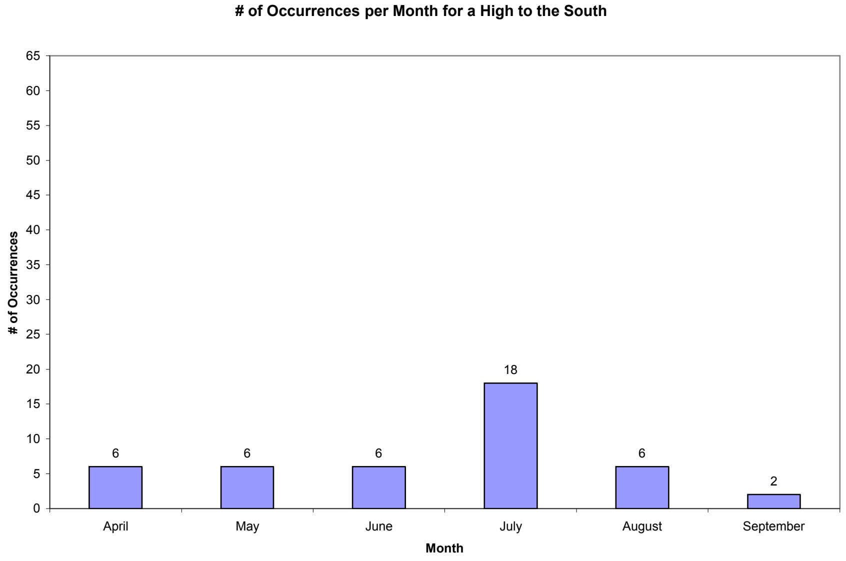

Figure 5.15: The number of occurrences per month for a high-pressure system located to the south of Missouri.

In total, this category was linked a total of 44 high ground level ozone days. Out of 44 high days, a high to the south of Missouri triggered a total of 44 yellow-level days. In contrast, it only triggered one orange-level event. On this one day, both St. Louis and Kansas City experienced high ground level ozone concentrations. Springfield experienced no orange-level days during this type of category. Also, no red-level days were reported at any of the cities during this category. Overall, this category seemed to have an even effect on the cities of Kansas City and St. Louis. These cities each had 32 and 26 high pollution days respectively, while Springfield had high ground level ozone concentrations on only sixteen of the possible days.

5.1.6 High over Missouri

This next category deals with the presence of a high-pressure system over the state of Missouri. The center of the high can assume various positions over the state, which makes the predominant surface flow pattern highly variable. In areas close to the center of high-pressure, the flow pattern is calm. Other areas around the high have flow patterns based on their respective locations to its center and the clockwise circulation around the high-pressure system. High ground level ozone concentrations are often a direct result of this flow pattern causing stagnant air conditions over the state of Missouri. Figure 10 shows the general layout for when a high-pressure system is located over the state of Missouri.

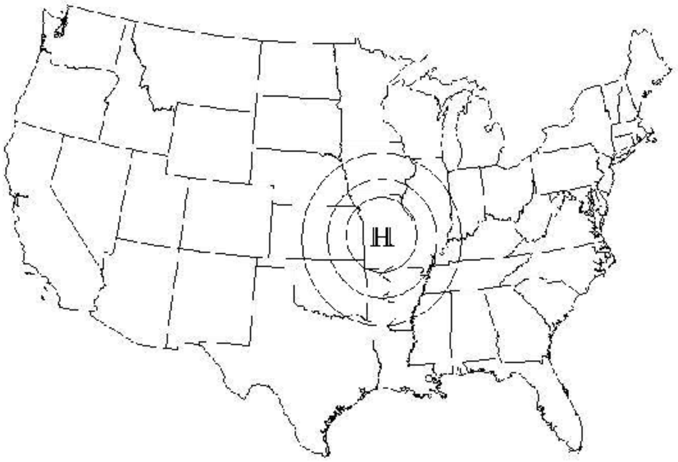

Figure 5.16: The general layout for a high-pressure system located over the state of Missouri.

Overall this category had the lowest number of occurrences out of the seven categories. It was found to take place only 28 times during the ten-year study period. It was found to occur in low numbers throughout each year of the ten-year period, with the largest number of occurrences taking place in 1998 and 2006. In these years, both eleven events and six events took place respectively. In 2000, no high ground level ozone events were observed. Figure 5.17 shows the number of occurrences in each year of the ten-year study period.

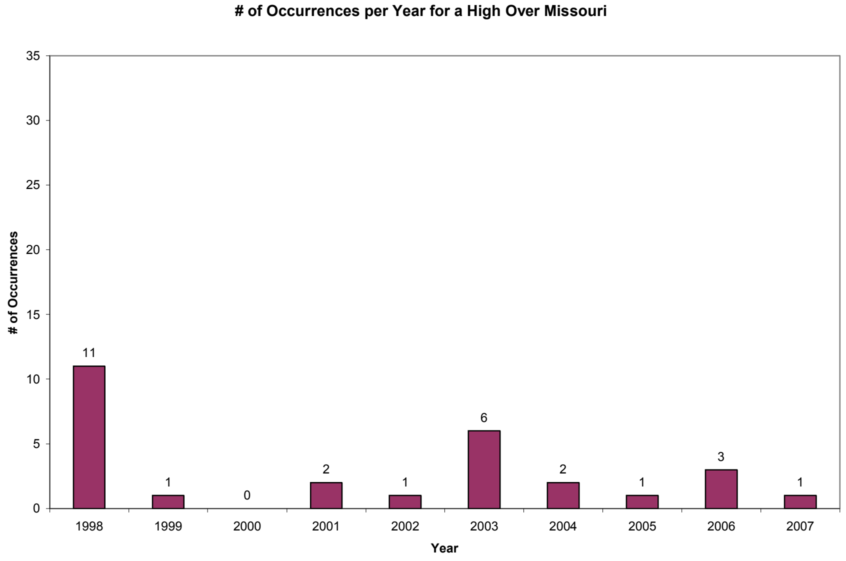

Figure 5.17: The number of occurrences per year for a high-pressure system located over Missouri.

During each year, this category reached peak in its number of occurrences during the middle to end of the warm season, in the months of July and August. Figure 5.18 shows the total number of occurrences for each month of the yearly data set.

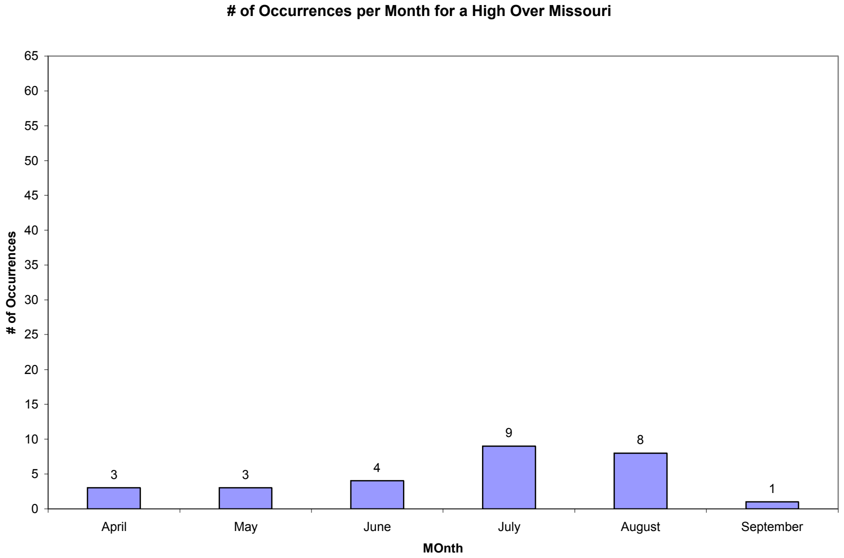

Figure 5.18: The number of occurrences per month for a high-pressure system located over Missouri.

In total, this category was linked to a total of 28 high ground level ozone days. Out of these 28 days, it triggered a total of 27 yellow-level days. In contrast, a high over Missouri only triggered three orange-level events. Of these three orange-level days, St. Louis experienced high ozone concentrations on two of the days, while Kansas City experienced high ozone concentrations on just one day. Springfield experienced no orange-level concentrations during this type of category. No red-level days were reported at any of the cities during this category. A high over Missouri had an even effect on the cities of St. Louis and Kansas City. St. Louis and Kansas City each had twenty-one and eighteen high ozone days respectively, while Springfield had high ozone concentrations on only ten of the possible days.

5.1.7 Miscellaneous Surface Features

This surface category consists of a situation when no high-pressure system is located around the state of Missouri and other surface features cause high ozone concentrations in Missouri. There is large variability in the types and locations of surface features that effect Missouri during these events. This means that there is also a large variability in the flow patterns associated with this category. The most common surface flow pattern is from the south and is commonly associated with the most common surface feature of this category, a low pressure system to the north, northeast, or northwest of Missouri with a warm front to the north, northeast, or northwest of Missouri also. Other surface features were also found take place during this category. These surface categories include:

- Low to the North of Missouri with a stationary front
- Low to the West of Missouri
- High to the West or Northwest of Missouri
- Low to the East of Missouri
- Low to the Northeast/North/Northwest of Missouri with no front
- Low to the Southeast of Missouri
- Low over Missouri
- A stationary front to the North of Missouri

High ground level ozone concentrations are often a direct result of these various surface flow patterns bringing warmer air from the South to the region. Figure 5.19 shows the general layout for the most common surface feature that is associated with this category.

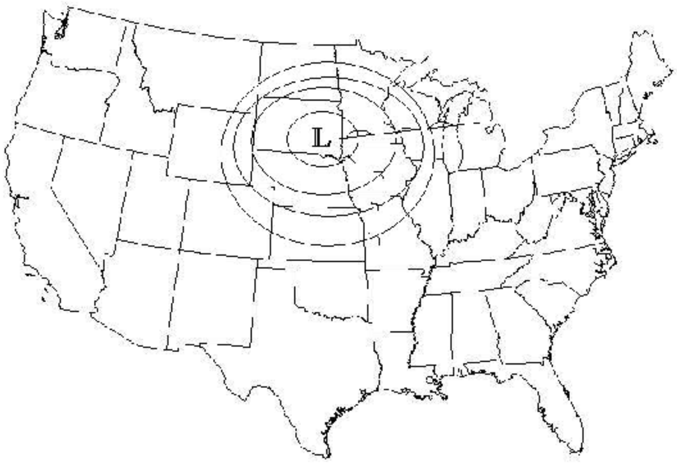

Figure 5.19: The general layout for a low-pressure system to the north with a warm front to the north.

Overall, this category was found to take place 67 times during the ten-year study period. Peaks in the number of occurrences took place in the years 2001, 2002, and 2003, while the lowest number of occurrences took place during the years 2004 and 2007. Figure 5.20 shows the number of occurrences in each year of the ten-year study period.

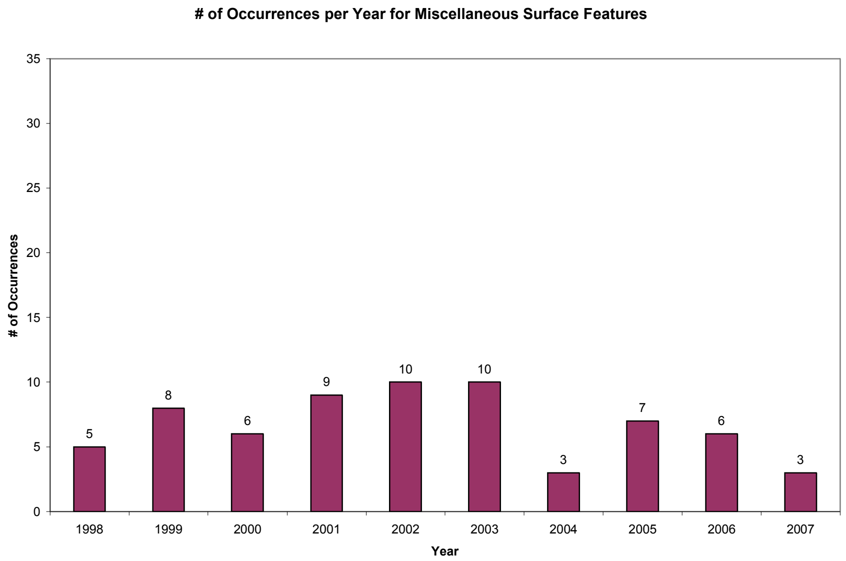

Figure 5.20: The number of occurrences per year for the miscellaneous surface features that affect Missouri when a high-pressure system is not present.

During the year, this category seems to peak during the middle to end of the warm season, in the months of June, July, and August. Figure 5.21 (next page) shows the number of occurrences in each month of the yearly data set.

In total, this category was linked to 67 high ground level days in Missouri. Of these 67 days, it triggered a total of 64 yellow-level days and a total of eight orange-level events. Of these eight orange-level days, St. Louis experienced high ozone concentrations on six days, while Springfield experienced high ozone concentrations on just one day. Kansas City experienced one orange-level day during this type of category. No red-level days were reported at any of the cities. This category caused a similar number of high ozone days for the cities of St. Louis and Kansas City. St. Louis and Kansas City each had 39 and 37 high ozone days respectively, while Springfield had high ozone concentrations on only seventeen of the possible days.

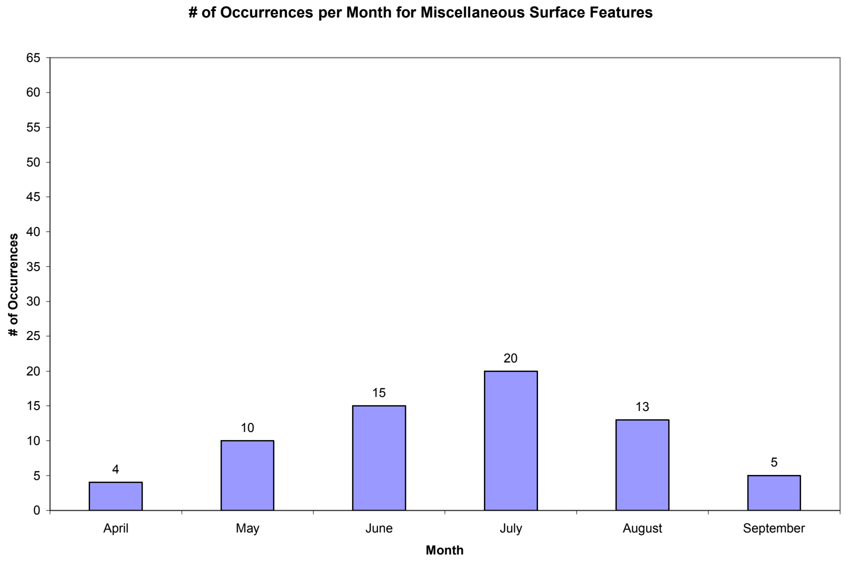

Figure 5.21: The number of occurrences per month for the miscellaneous surface features that affect Missouri when a high-pressure system is not present.

5.2 500mb Categories

Upper atmosphere synoptic scale, particularly at 500mb, features have been shown to drive what is happening at the surface. For this study, 500mb synoptic scale features were examined to gain insight into which features caused high ozone concentrations in Missouri. Ridges in the 500mb flow were the primary features noted in this study. A ridge at 500mb is usually associated with a high-pressure system at the surface. At 500mb, four categories were found.

1. A ridge axis to the West of Missouri
2. A ridge axis to the East of Missouri

3. Ridge axes to the East and West of Missouri
4. Zonal flow

Each of these upper atmosphere categories has a different effect and contribution to the surface flow patterns and weather for Missouri. Below are descriptions of each 500mb category, how they impact the upper atmospheric and surface flow of Missouri, and their influence in causing high ground level ozone days. Note: Due to the fact that multiple cities can have high ozone concentrations on the same day, the numbers used below in the describing how many high ozone days present in Missouri may not add up correctly.

5.2.1 Ridge Axis to West of Missouri

The first category deals with a ridge in the 500mb flow to the west of Missouri. During this flow regime, a ridge axis is located to the west of Missouri in the overall 500mb flow pattern. During this category, the predominant 500mb flow pattern experienced by the cities in Missouri is out of the general northwest direction. Based on the location of the ridge, the 500mb flow over Missouri can also be from the general north direction. During this category, the 500mb flow is often similar for all three cities. The ridge to the west helps to push a high at the surface into a position where it can cause high ozone concentrations in Missouri. Figure 5.22 shows the general layout for a ridge in the 500mb flow located to the west of Missouri.

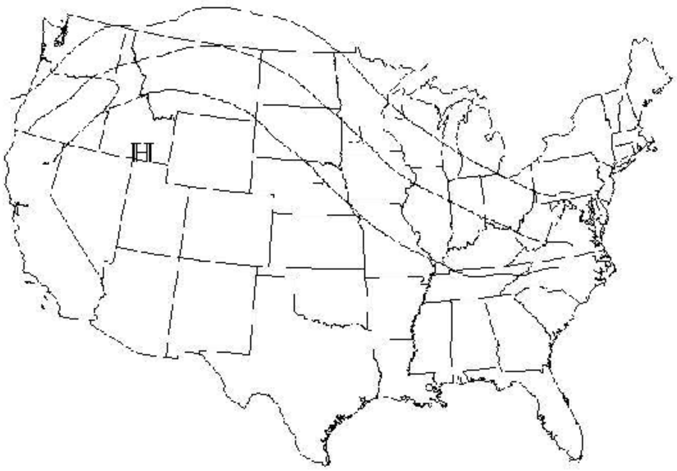

Figure 5.22: The general layout of a ridge axis located to the west of Missouri in the 500mb flow.

Overall, this category had the highest number of occurrences of the four upper atmosphere categories. In total, it was found to occur 231 times during the ten-year study period. Out of the ten-year study period, the highest number of occurrences for this category were found to take place during the years 1998, 1999, 2002, and 2005. The lowest number of occurrences for this category was found to occur during the year 2004. This is directly related to 2004 being a particularly inactive year and the other years being particularly active years. Figure 5.23 shows the number of occurrences in each year of the ten-year study period.

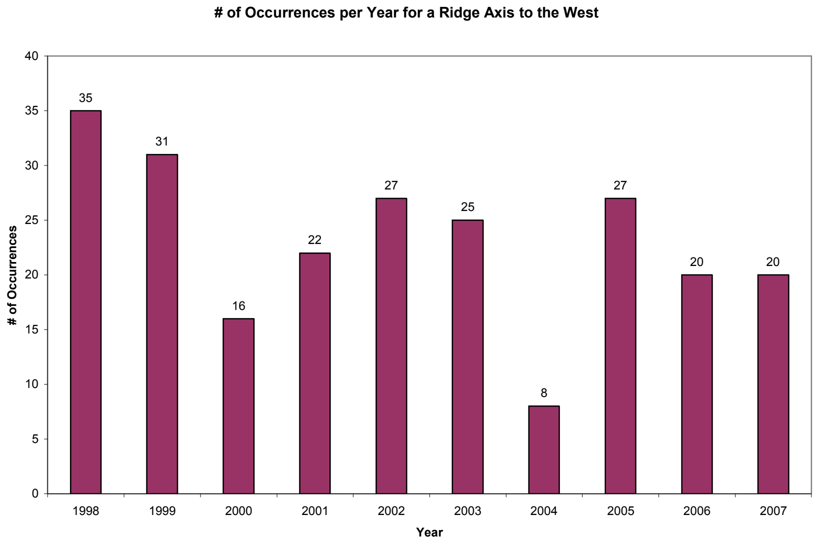

Figure 5.23: The number of occurrences per year for a ridge axis located to the west of Missouri.

On a yearly basis, this category seems to peak during the middle to end of the warm season, the months of July and August. Figure 5.24 shows the number of occurrences for each month of the yearly period.

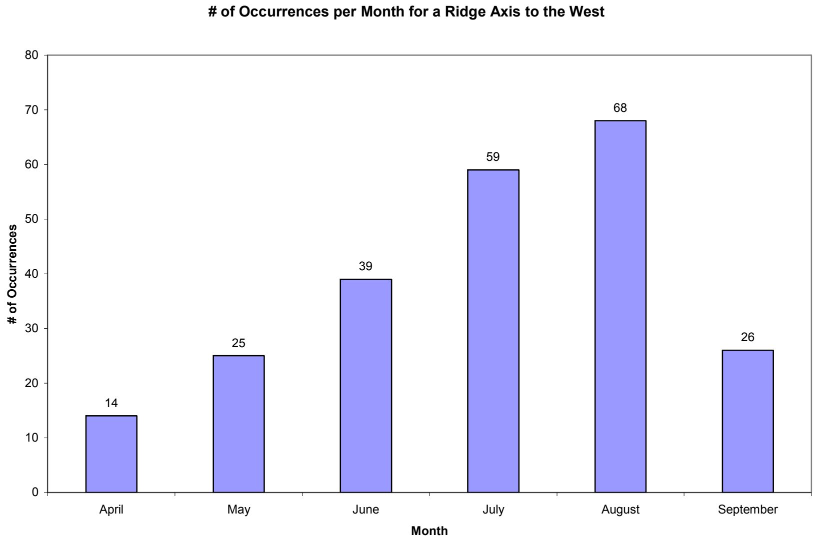

Figure 5.24: The number of occurrences per month for a ridge axis located to the west of Missouri.

This type of 500mb flow had a large influence on all seven surface categories. In particular, in accounted for almost all of the highs to the north of Missouri and the highs over Missouri. This is related to the ridge pushing the surface high from west to east across the United States. Figure 5.25 relates the number of occurrences of each surface category during this type of 500mb flow.

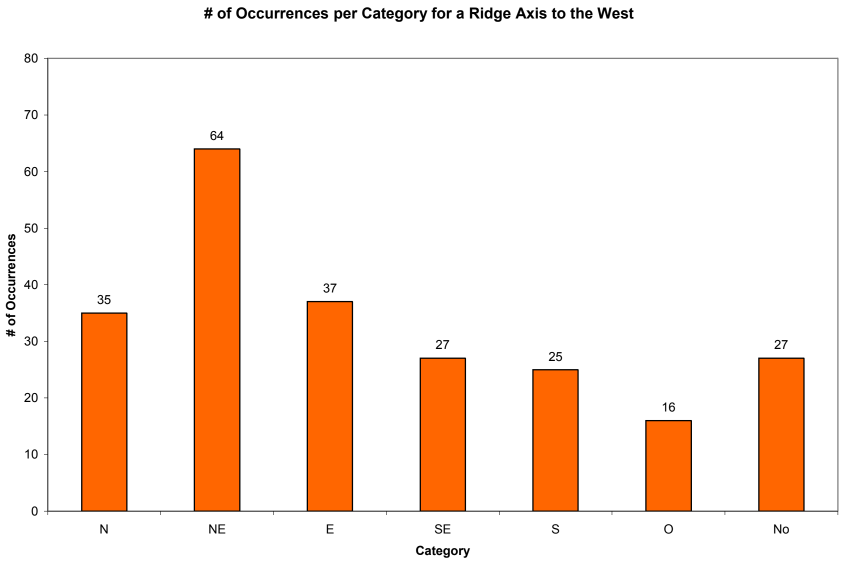

Figure 5.25: The number of occurrences of each surface category during a ridge axis located to the west of Missouri.

In total, this category was linked to 231 high ozone days in Missouri. Of these 231 high ozone days, 222 of the days fell into the yellow-level. This category was also linked to 21 orange-level events. Of these 21 orange-level days, St. Louis experienced high ozone concentrations on fourteen of the days, while Springfield only experienced high ozone concentrations on four of the possible days. Kansas City experienced high ozone concentrations on nine of the days. During this category, no red-level ozone days were recorded at any of the cities.

5.2.2 Ridge Axis to East of Missouri

The next upper atmospheric category consists of a ridge to the east of Missouri in the overall 500mb flow. During this 500mb flow regime, a single ridge is located to the east of Missouri. During this category, the flow at 500mb is commonly from the general southwest direction. Based on the position of this ridge, flow at 500mb can also be from the general south direction. During this category, the 500mb flow is often similar for all three cities. Figure 5.26 shows the general layout for a 500mb ridge to the east of Missouri. The ridge to the east already helped to push a high at the surface past Missouri and is pulling it into a position, particularly to the northeast, where it can cause high ozone concentrations in Missouri.

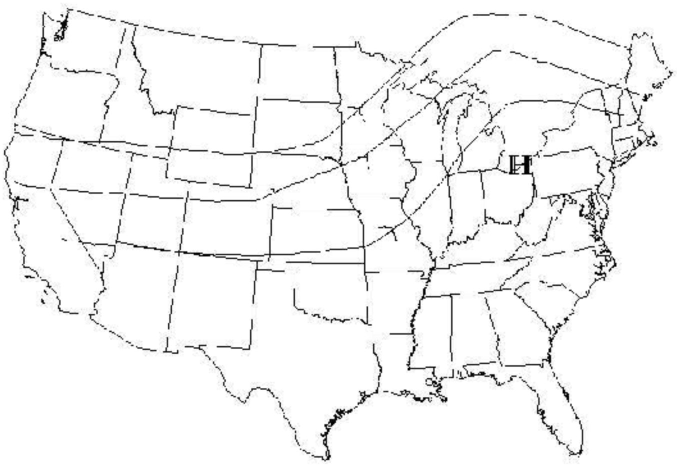

Figure 5.26: The general layout for a ridge axis located to the east of Missouri in the 500mb flow.

Out of the four categories, this category had the second lowest number of occurrences. Overall, it was found to occur 137 times during the ten-year study period. Two peaks in the number of occurrences for this category were found to occur during the years 1999 and 2005. The lowest number of occurrences for this category was found to take place during the year 2004. Figure 5.27 shows the number of occurrences in each year of the ten-year study period.

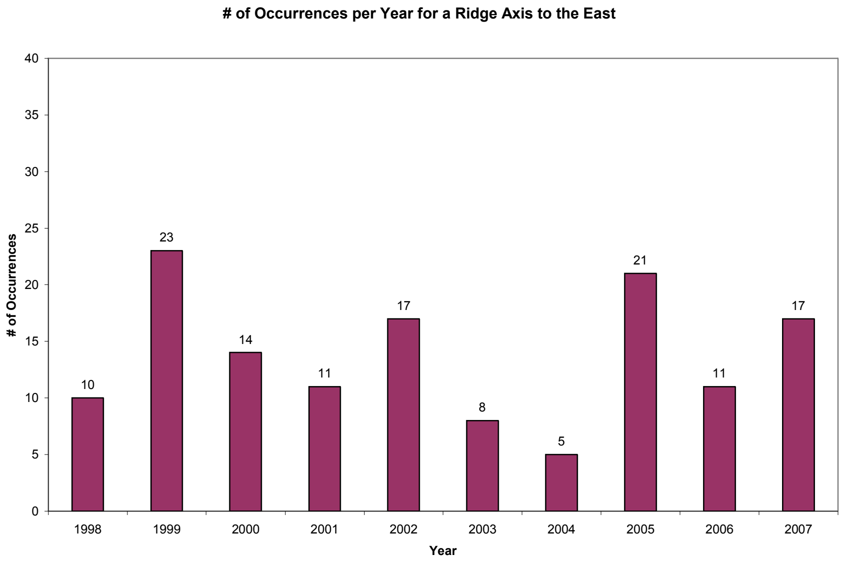

Figure 5.27: The number of occurrences per year for a ridge axis located to the east of Missouri.

For the yearly data set, this category was found to peak during the middle to end of the warm season, the months of June, July, August, and September. This is related to the northward propagation of warm air that occurs at this time of year. Figure 5.28 shows the number of occurrences for each month of the yearly period.

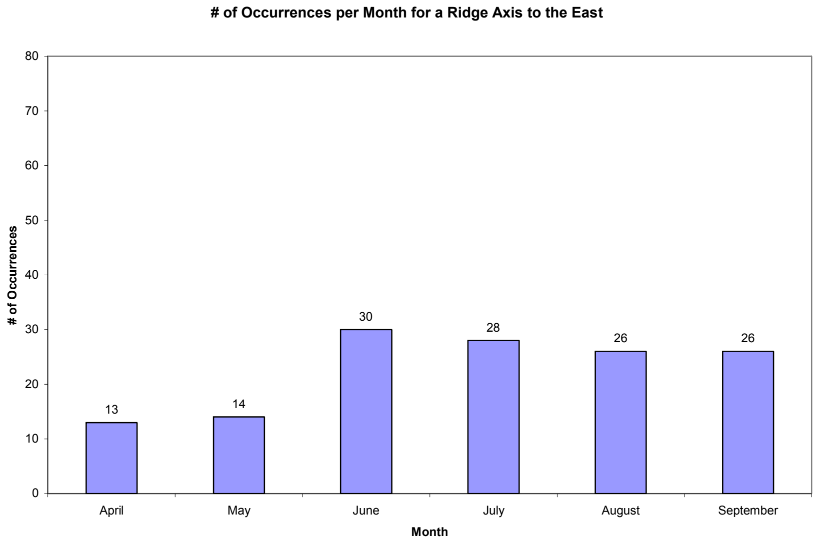

Figure 5.28: The number of occurrences per month for a ridge axis located to the east of Missouri.

This category had a relatively large effect on determining the number of occurrences of a high to the northeast of Missouri, which is related to the ridge pulling the surface high along with it. Figure 5.29 relates the number of occurrences of each surface category during this type of 500mb flow.

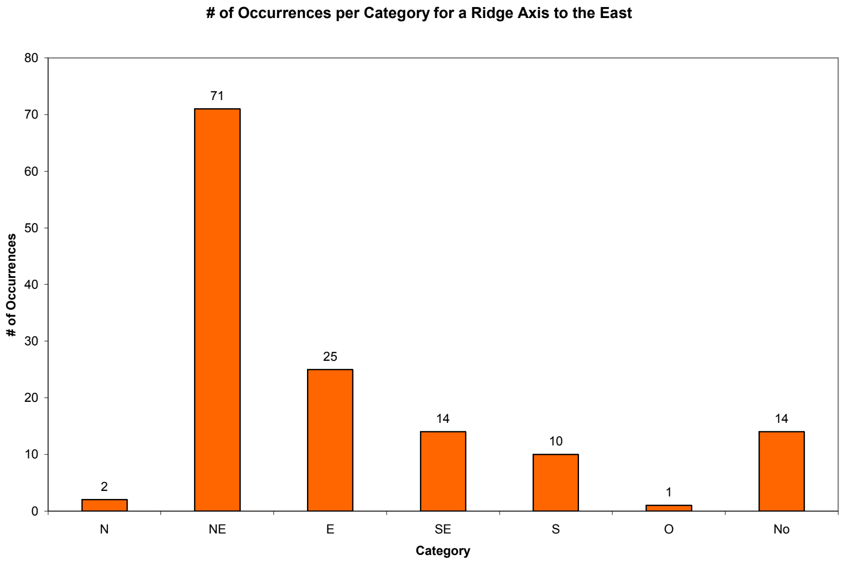

Figure 5.29: The number of occurrences of each surface category during a ridge axis located to the east of Missouri.

Overall, this category was linked to a total number of 137 high ozone days in Missouri. Of these 137 high ozone days, 132 of these days fell into the yellow-level. A ridge to the east of Missouri was also linked to nineteen orange-level events. Of these fifteen days, St. Louis experienced high ozone concentrations on seventeen of the days, while Kansas City experienced high ozone concentrations on five of the possible days. Springfield did not experience any orange-level days during this category. When a ridge is to the East of Missouri, one red-level day was reported at the city of St. Louis.

5.2.3 Ridge Axis to both East and West of Missouri

The next category deals with the presence of a ridge axis to both the east and west of Missouri at 500mb. During this flow regime, a ridge in the 500mb flow exists to both the east and west of Missouri commonly separated by a trough. During this category, there are two predominant flow patterns in the overall 500mb flow and they are largely based on the position of the trough between the two ridges. First, cities located on the backside of the trough experience northwestern or northern 500mb flow. While, cities located on the front side of the trough experience 500mb flow from the southwest or south directions. During this category, the 500mb flow is often different between the three cities, with Kansas City and Springfield often having northwest flow and St. Louis often having southwest flow. However, these flow patterns change with the position of the 500mb trough. This type of 500mb flow pattern can either push or pull surface highs into the correct positions to cause high ozone concentrations in

Missouri. Figure 5.30 shows the general layout for this type of 500mb flow regime.

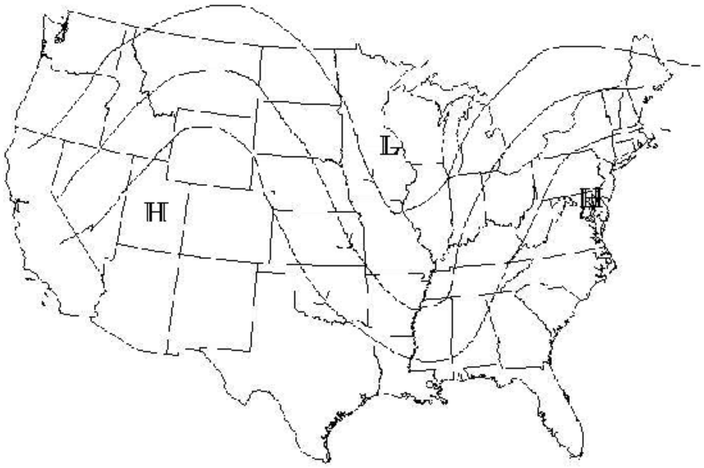

Figure 5.30: The general layout for a ridge axis located to both the east and west of Missouri in the 500mb flow.

Overall, this category had the lowest number of occurrences of the four upper atmosphere categories. It was found to take place a total of 48 times during the ten-year study period. Three peaks in the number of occurrences of this category occurred during the years 2002, 2005, and 2006. Two low points in the number of occurrences of this category occurred during the years 2001 and 2004. Figure 5.31 shows the number of occurrences in each year of the ten-year study period.

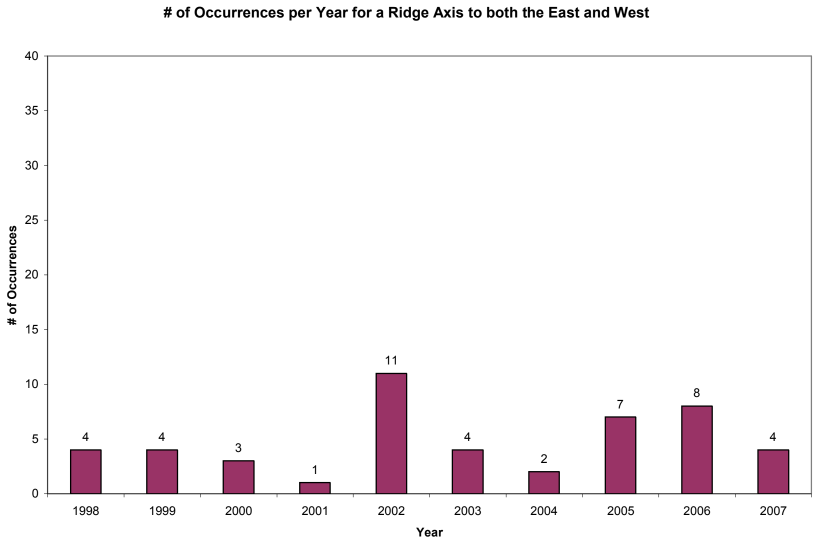

Figure 5.31: The number of occurrences per year for a ridge axis located to both the east and west of Missouri.

On a yearly scale, this category was found to peak during the middle to end of the warm season, the months of June, July, and August. Figure 5.32 shows the number of occurrences for each month of the yearly period.

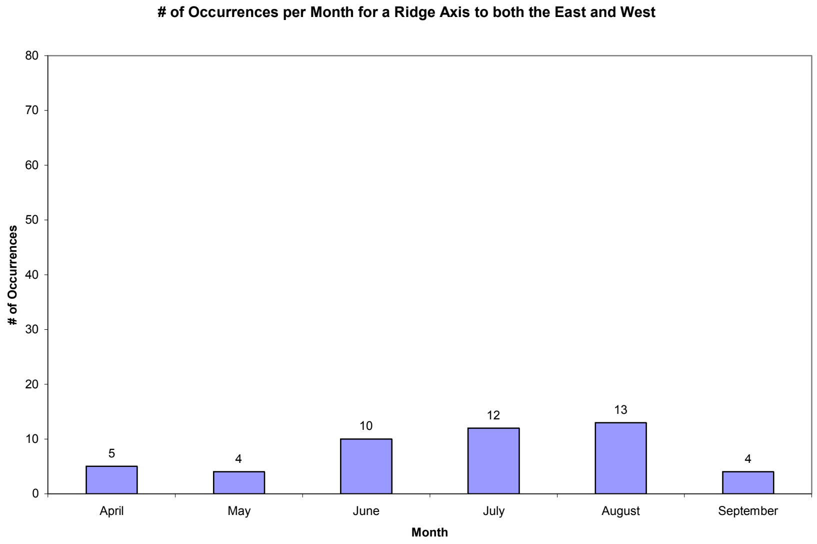

Figure 5.32: The number of occurrences per month for a ridge axis located to both the east and west of Missouri.

This type of upper atmosphere flow in general has the lowest effect on all the surface categories. However, the highest number of occurrences during this type of flow was achieved by a high to the northeast of Missouri. Figure 5.33 relates the number of occurrences of each surface category during this type of 500mb flow.

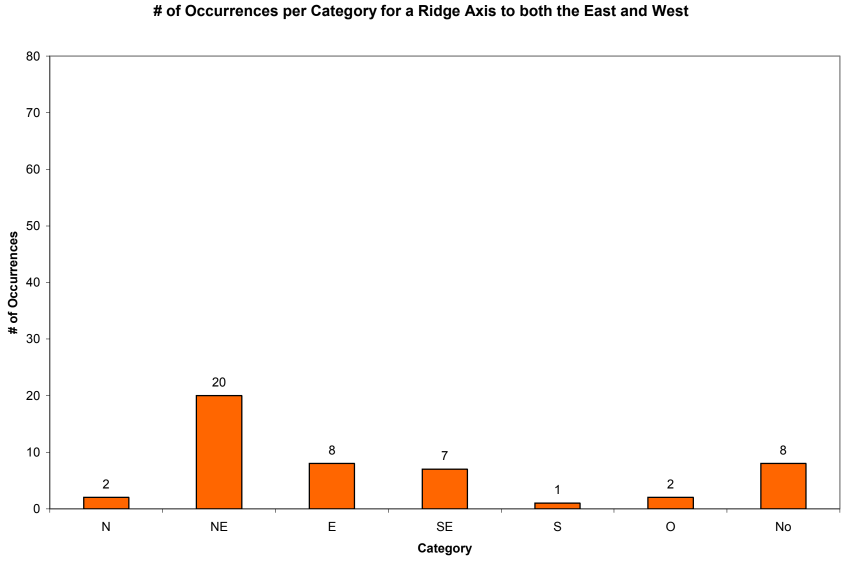

Figure 5.33: The number of occurrences of each surface category during a ridge axis located to both the east and west of Missouri.

In total, this category was linked to 48 high ozone days in Missouri. Of these 48 high ozone days, 46 of them were yellow-level days. This category was also linked to three orange-level events. Of these three orange-level days, St. Louis experienced high ozone concentrations on all three days, while Springfield and Kansas City did not experience any high ozone concentrations during this type of 500mb flow regime. During this category, no red-level days were reported at any of the cities in Missouri.

5.2.4 Zonal Flow

The next category consists of zonal flow at 500mb over Missouri. During a zonal flow regime, there are no ridges or troughs in the overall 500mb flow pattern. During this category, the predominant 500mb flow pattern is out of the general westerly direction. If there is a slight tilt in the overall flow, it can also be from the northwest or southwest directions. During this category, the 500mb flow is often similar for all three cities. This type of 500mb flow allows for some variability in the type of surface flow that will be experienced in the state of Missouri. Figure 5.34 shows the general layout for a zonal flow regime over Missouri at 500mb.

Figure 5.34: The general layout for zonal flow over Missouri at 500mb.

Overall, this category had the second highest number of occurrences of the four upper atmosphere categories. In total, it was found to occur 139 times during the ten-year study period. Peaks in the number of occurrences for this category were found during the years 1998, 2001, and 2006. Two low points in the number of occurrences for this category were found during the years 1999 and 2004. Figure 5.35 shows the number of occurrences in each year of the ten-year study period.

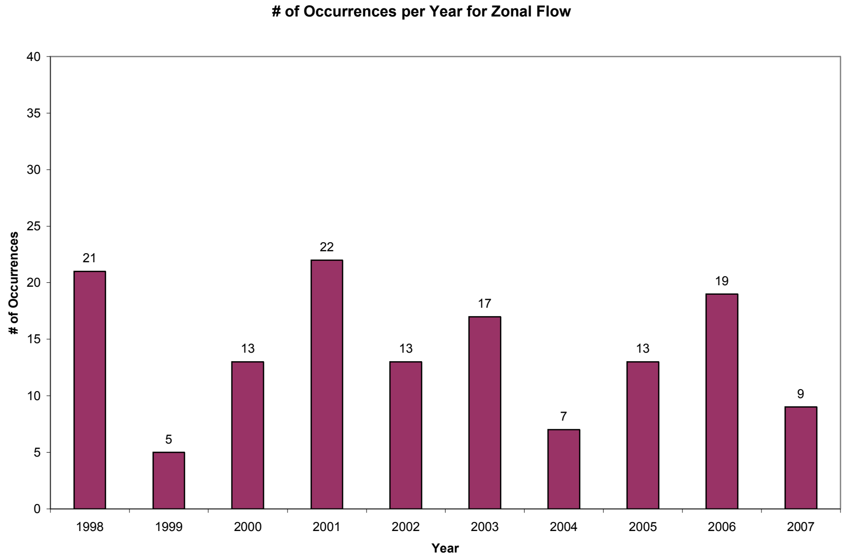

Figure 5.35: The number of occurrences per year for 500mb zonal flow over Missouri.

On a yearly basis, this category seems to peak during the middle to end of the warm season, the months of July and August. Figure 5.36 shows the number of occurrences for each month of the yearly period.

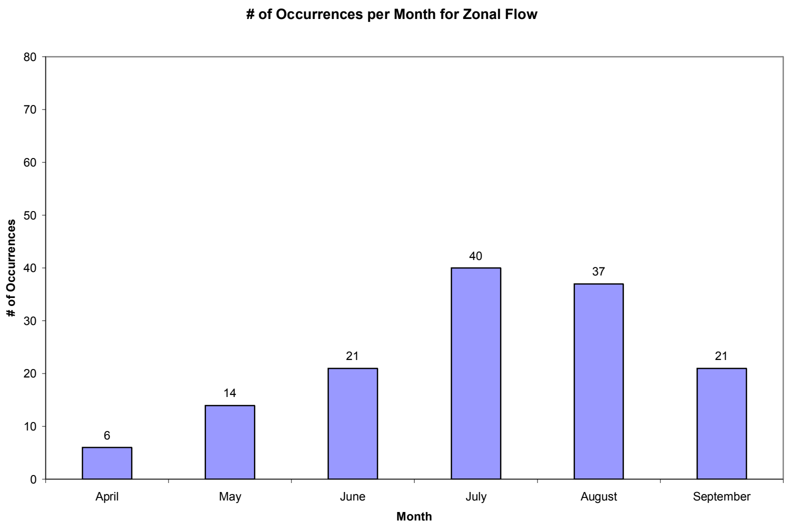

Figure 5.36: The number of occurrences per month for 500mb zonal flow over Missouri.

Overall, this type of 500mb can allow for a variety of surface categories to occur. In particular, surface features that deal with highs to the northeast, east, and southeast of Missouri have large number of occurrences during this type of flow scheme. Figure 5.37 relates the number of occurrences of each surface category during this type of 500mb flow.

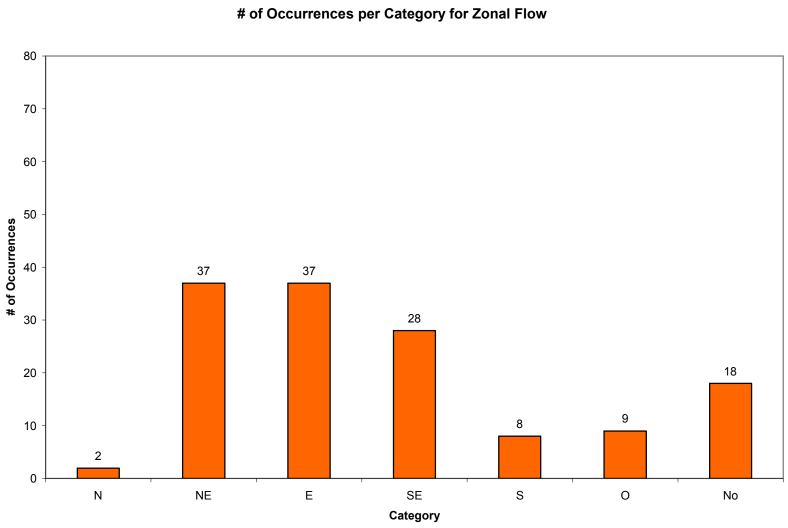

Figure 5.37: The number of occurrences of each surface category during 500mb zonal flow over Missouri.

Overall, this category was linked to a total number of 139 high ozone days in Missouri. Of these 139 high ozone days, it triggered 135 yellow-level days. This category was also linked to fifteen orange-level events. Of these fifteen orange-level days, St. Louis experienced high concentrations on eight of the days, while Springfield experienced high concentrations on just two of the days. Kansas City experienced high ozone concentrations on six of the days. During this category, one red-level day was reported at St. Louis.

5.3 Frequency of High Pollution Days

During the last five years of the ten-year study period, the miscellaneous surface features category had the largest rate of occurrence. It occurred 32% of the time during the five-year period. A high-pressure system to the Northeast of Missouri had the second largest rate of occurrence at 23% of the time. A high-pressure system to the North, East, and southeast of Missouri had similar rates of occurrence, which hovered around 10% of the time. A high-pressure system to the South and Over Missouri had the lowest rates of occurrence at around 5% of the time. These rates of occurrence take into account both days with high ozone concentrations and days with low ozone concentrations. In total, a specific surface category could have taken place on 915 possible days during the five-year study period. Figure 5.38 shows the percent rate of occurrence for each surface category during the five-year examination period.

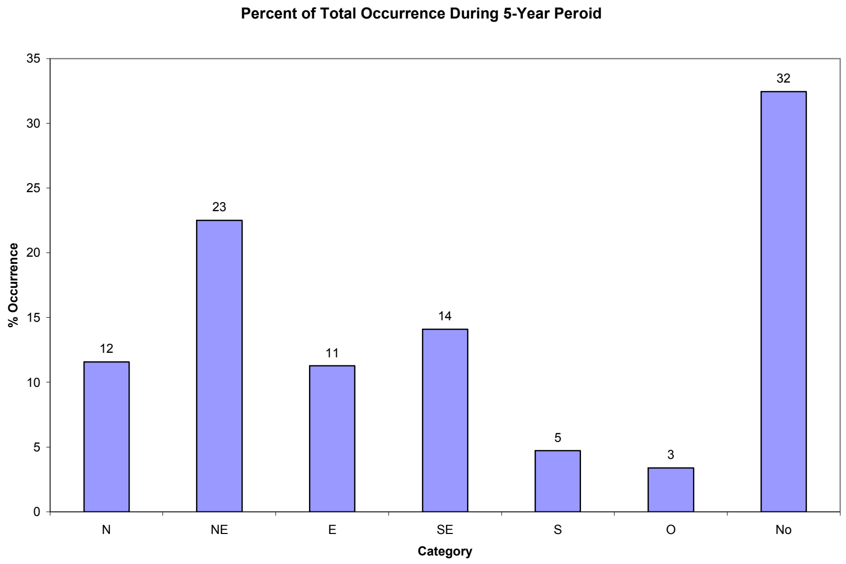

Figure 5.38: Percent rate of occurrence for each surface category during the last five years of the ten-year study period.

Also during this five-year period, the miscellaneous surface feature category was associated with the largest rate of causing low concentrations of ground level ozone. During this category, 90% of the time that it occurred it was associated with a low ozone concentration. Only 10% of the time that it occurred it was associated with high ozone concentrations. Similar patterns can be seen in the categories consisting of a high to the north and to the southeast. During these categories, roughly 80% of the time they occurred they were associated with a low ozone concentration. Only 20% of the time they occurred were they associated with high ozone concentrations. The other surface categories had around the same rate of occurrence of high and low ozone concentrations. Roughly 50% of the time they occurred they were associated with a high ozone concentrations. The other 50% of the time they were associated with low ozone concentrations. Figure 5.39 shows the percent rate of occurrence of high and low ozone concentrations for each surface category.

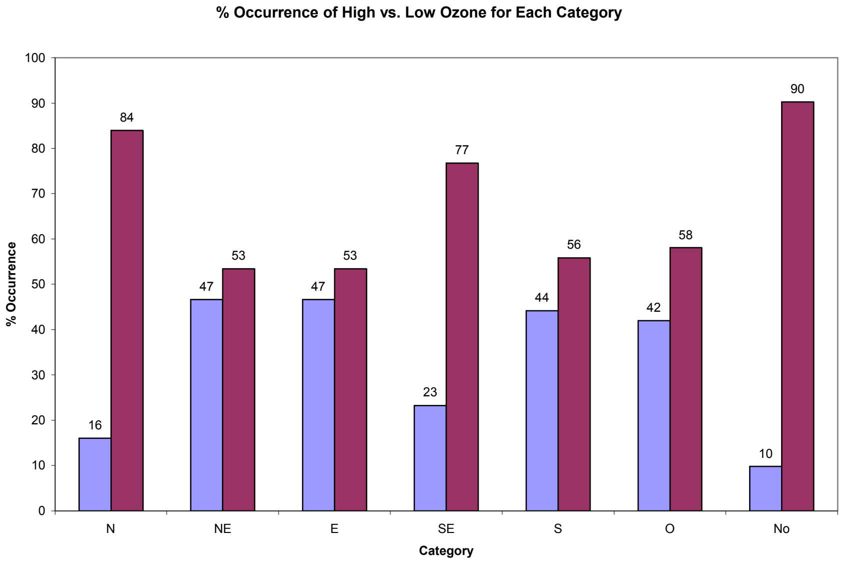

Figure 5.39: Rate of occurrence of high or low ozone concentrations for each surface category for the last five years of the ten year study period. (Blue represents high ozone, Purple represents low ozone)

Chapter 6

Summary and Conclusions

6.1 Summary

The main purpose of this study was to analyze the atmospheric conditions that are associated with high concentrations of ground level ozone in Missouri. This main objective was accomplished in three ways.

- First, an Air Quality Index was created for three major cities in the state of Missouri.
- Second, mixing heights, transport wind speeds, and ventilation rates for the area were analyzed to help determine their contribution to high ozone concentrations in Missouri.
- Third, synoptic weather patterns, which are favorable for the formation of ground level ozone in the state of Missouri, were determined and classified.

The overall data set consisted of a ten-year period of hourly ozone concentrations (in ppm) for the three major in Missouri. For each year, the data set contained the warm season of Missouri from April to September. At least three monitoring stations were used from each city to create a city average ozone concentration. The study area consisted of the three major cities in Missouri. These cities were St. Louis, Kansas City, and Springfield.

The first step of an Air Quality Index involved converting the hourly ozone concentrations into daily values. This was accomplished by using the highest and continuous eight-hour average for each day. These values were then put into Equation 1 based on how they fell into certain breakpoint categories. This helped to create the AQI values for each day of the study period. The AQI values were then placed into the appropriate air quality category following the EPA guidelines.

Mixing heights were found by using the 850mb heights over Springfield, Missouri. Transport wind speeds were found by averaging the wind speeds throughout the mixing layer over Springfield, MO. Both of these variables were found using 12Z temperature soundings from the University of Wyoming. Mixing heights were then placed into categories based on if they fell below or above 1500m. Transport wind speeds were then placed into categories based on if they fell above or below $4ms^{-1}$. Ventilation rates were found by multiplying the mixing heights by the transport wind speeds for each elevated ozone day. They were then placed in their appropriate category based on the ventilation guidelines provided by the National Weather Service at Grand Junction, CO. The ventilation rates, mixing heights, and transport wind speeds were then compared to high ozone days in Missouri.

To place the high pollution days into synoptic flow categories, 12Z surface and 500mb weather maps were observed for each high day. These maps came courtesy of NOAA. At the surface, the categories were chosen and named based on the presence of a high-pressure system around Missouri. At 500mb, the categories were chosen and named based on the presence of a ridge in the overall flow pattern. After the categories were found, they were analyzed to find out how they related to high ozone days in Missouri. Each surface category was analyzed to determine the percentage of time that it caused high or low ozone concentrations for the last five years of the study period.

For the Air Quality Index, a total of 555 days with high ground level ozone concentrations were found in the ten-year study period. Of these 555 days, yellow-levels occurred on 535 days, orange-levels occurred on 58 days, and red-levels occurred on two days. During the ten-year study period, St. Louis experienced high ozone concentrations on 395 days, while Kansas City experienced high ozone concentrations on 335 days. The city of Springfield experienced high ozone concentrations on 200 days. St. Louis experienced orange-levels on 42 days, while Kansas City experienced orange-levels on 20 days. Springfield experienced orange-levels on just six days. St. Louis was the only city that experienced red-level ozone concentrations.

Overall, for the ten-year period, the average mixing height and transport wind for high ozone days were found to be 1550m and $7ms^{-1}$ respectively. Over Missouri, the mixing height seemed to be fairly constant with little variability in its height. On the other hand, transport winds seemed highly variable on the average and seemed to be linked to poor and fair ventilation rates. Overall, for the ten-year period, the average ventilation rate for elevated ozone days was found to be $10000m^2s^{-1}$. The ventilation rates for each year seemed to be highly variable due to it being highly dependent on the transport wind speed in the mixing layer.

The average number of high ozone days for the three El Nino years was 62, while the average number of high ozone days for the two La Nina years was 61. For the five Neutral years in the data set, the average number of high ozone days was 59. El Nino to La Nina transitions showed a relatively constant number of high ozone days. During a transition from a La Nina year to a Neutral year, the number of high ozone days slightly increased. Neutral to El Nino transitions showed a slight decrease in the number of high ozone days. During a transition from an El Nino year to a Neutral year, the number of high ozone days showed a large decrease in the number of high ozone days. Finally Neutral El Nino year transitions showed a slight decrease in the number of high ozone days.

At the surface, seven categories were found to exhibit an association with high ground level ozone days. The seven surface categories included: high-pressure system to the north of Missouri, high-pressure system to the northeast of Missouri, high-pressure system to the east of Missouri, high-pressure system to the southeast of Missouri, high-pressure system to the south of Missouri, high-pressure system over Missouri, and miscellaneous weather patterns when no high is present. When analyzed, the miscellaneous category was linked to the highest percentage of low ozone days, while the other categories seemed to have a 50% chance of being linked to a high ozone day. At the 500mb, four categories were found: a ridge axis to the west of Missouri, a ridge axis to the east of Missouri, ridge axes to the east and west of Missouri, and zonal flow.

6.2 Conclusions

Based on the results discussed above, several general conclusions can be made. These conclusions are listed below.

- Overall, Missouri has good air quality. When an AQI was created, there were only a few days that fall into the orange-level category for the whole ten-year period. There were even fewer days that reached the red-level. In the beginning, this study intended on using just using days that fell into the orange-level, however, there were not enough of them to make any determinations. The threshold was then lowered to the yellow-level to incorporate a larger data set into the study. Most of the days used in this study are high ozone days, but they are not considered high enough to cause health problems.
- Another conclusion that can be made is the fact that the synoptic flow patterns that are associated with high ozone concentrations can be put into categories using an environment to circulation approach. This process offers a viable way to determine which type of surface features and 500mb flow patterns are associated with high ozone days in Missouri. This process may be a viable option for determining the atmospheric features that are associated with high ozone concentrations in other areas around the world.
- The miscellaneous surface category was found to have a high rate of being associated with low ozone days, 90%. This is primarily due to the fact that this type of situation contains conditions that are not favorable for the formation of ground level ozone, such as high winds, high mixing heights, and high ventilation rates. For the five-year period analyzed, most categories had a 50% chance of

being associated with a high or low ozone day. This means that most of these surface categories have a good chance of causing a high ozone concentration somewhere in Missouri when they occur. A larger data set may need to be analyzed in order to give a more accurate percentage of how often each surface category causes a high ozone concentration.

- Over Missouri, mixing heights are relatively constant. This can be seen when looking at the standard deviation, which is relative small. So, on the synoptic scale using a mixing height from one city in Missouri offers a good estimation of the mixing height at other cities in Missouri. This also means that the boundary layer establishes itself during the day and remains fairly constant over the state of Missouri. This also means that this variable can be held constant in the ventilation rate calculation. In the ten-year period, there were very few days that fell below the 1500m line and these days did not always match up with high ozone days. Often, mixing heights are above the 1500m line and also cause high ozone days. For these reasons, solely looking at mixing heights as a determinant factor for high ozone days falls short of a reasonable option.
- Transport wind speeds were found to be highly variable. This means that the transport wind speed cannot be held constant across the state of Missouri. Its high variability means that it should be found locally instead of using one city and assuming it is the same everywhere in the state. For this reason, the transport wind speed may be the major variable that needs to be known in order to predict high ozone concentrations for the state of Missouri. Also, transport wind speeds seem to be the determining factor for ventilation rates. If the wind speed is slow,

then the ventilation rate will be low. If the wind speed is high, then the ventilation rate will be high. This means that the ventilation rate is highly dependent on the transport wind speed in the mixing layer.

- Ventilation rates are highly variable and mainly dependent on transport wind speeds in the mixing layer, which was confirmed by this study. At both the synoptic and local scale, high ozone concentrations did not always match up with poor or fair ventilation rates. This may be due to its dependence on the transport wind speed in the mixing layer, which has been found to be highly variable across large spatial distances. On the synoptic scale, Springfield mixing heights and transport wind speeds were used as representations for the entire state. There may some problems with this due to the fact that the transport wind speeds may be different for each city. This assumption may be the main reason for the high pollution days not always matching up with poor or fair ventilation rates on the synoptic scale. At the local level, ventilation rates seem to be slightly better at predicting high ozone days in Missouri. For this reason, ventilation rates may need to be calculated using local wind conditions in order to get an accurate number for determining high ozone days. Also, ventilation rate predictions may not have been perfect due to the fact that it only takes into account two atmospheric variables when more play a role in determining the dispersion of pollutants.
- No real conclusions can be made about the effects of the ENSO phases on the number of elevated ozone days in Missouri. One main reason for this is the fact that the data set may be too short. A much larger data set would incorporate

more ENSO phases into it and would offer a better representation of its effect on elevated ozone days in Missouri. Another reason for the inability to draw conclusions is the fact that during the Pacific Decadal Phase #2 there is little ENSO variability. This may mask the overall of effects of each ENSO phase on elevated ozone days in Missouri. One final reason for the inability to draw conclusions deals with the fact that ENSO has little influence during the summer season. This may also hide the overall effects of each ENSO phase on elevate ozone days in Missouri.

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