Synoptic Typing of High Ozone Events

in Arizona (2011-2013)

by

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ABSTRACT

This thesis examines the synoptic characteristics associated with ozone exceedance events in Arizona during the time period of 2011 to 2013. Finding explanations and sources to the ground level ozone in this state is crucial to maintaining the state's adherence to federal air quality regulations. This analysis utilizes ambient ozone concentration data, surface meteorological conditions, upper air analyses, and HYSPLIT modeling to analyze the synoptic characteristics of ozone events. Based on these data and analyses, five categories were determined to be associated with these events. The five categories all exhibit distinct upper air patterns and surface conditions conducive to the formation of ozone, as well as distinct potential transport pathways of ozone from different nearby regions. These findings indicate that ozone events in Arizona can be linked to synoptic-scale patterns and potential regional transport of ozone. These results can be useful in the forecasting of high ozone pollution and influential on the legislative reduction of ozone pollution.

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RESEARCH STATEMENT

1.1 INTRODUCTION

One of the six most common air pollutants in the atmosphere is ground level ozone. Ground level ozone or surface ozone is created from the pollutants released from the burning of gasoline, coal, and oil, and is not beneficial in the lower atmosphere unlike stratospheric ozone (EPA, 2016b). Stratospheric ozone acts as a natural shield against harmful ultraviolet radiation from the sun, but surface ozone does not do the same. Surface ozone is rather a main component in smog in the troposphere (EPA, 2016b). Ground level ozone is created from the photochemical reaction between the sun and the volatile organic compounds (VOCs) and nitrogen oxides (NOx) that are released into the air (EPA, 2016b). Surface ozone has a lifetime of about 22 days, allowing it to be moved around by the atmosphere and travel great distances (EPA, 2016b). This allows for ozone to be created in one area, and be transported to a downwind location, where it will have an effect on an area that did not originally produce it.

The Environmental Protection Agency (EPA) establishes and enforces regulations for monitoring and enforcing air quality standards via the Clean Air Act (CAA) (EPA, 2016b). The CAA sets the National Ambient Air Quality Standards (NAAQS) for each of the six criteria pollutants, including ground level ozone concentrations. The EPA sets these standards based mainly on health and environmental factors. Areas that do not achieve these levels, said to be “nonattainment” areas, are allowed to develop regulatory plans specific to their area to reach the regulated levels.

Most counties in Arizona currently meet these permissible levels of ozone, with a couple of areas in two counties exceeding levels marginally. The EPA has issued new standards recently, in October 2015, specifically on ground level ozone. The prior 2008 standard for surface ozone was 0.075ppm, and the new 2015 standard has been reduced to 0.070ppm (EPA, 2015b). Based on these new regulations and ozone data from 2011-2013, all but two counties in Arizona would exceed the new level of 0.070 ppm (EPA, 2016a). Finding explanations and sources to the ground level ozone in this state is crucial to maintaining our adherence to these regulations.

1.2 RESEARCH OBJECTIVE

This project will focus on identifying meteorological conditions and potential interstate transport pathways associated with ground level ozone exceedances in Arizona. The objective is to establish if past days of ozone exceedances in Arizona coincide with specific large-scale synoptic patterns in the upper atmosphere and transport pathways of ozone from neighboring states and/or countries, and, if so, to classify these synoptic patterns.

The identification of upper air patterns, coupled with potential transport pathways and surface meteorological conditions, will be helpful in being able to forecast for ozone exceedances. This research will hopefully lead to better understanding of how regional ozone transport impacts the Southwest, which then would help to guide regulations on ozone and transport. This research will also be helpful in gaining a better understanding of the regional characteristics of tropospheric ozone and in Arizona and the Southwest.

1.3 ORGANIZATION OF THESIS

My research begins with a review of the problems with tropospheric ozone and the need for analysis of surface ozone and transport pathways in the Southwest United States, particularly in Arizona. Chapter 2 will discuss the necessary information needed to understand what tropospheric ozone is, how it is created, and how it can be transported long distances. In addition to overall information regarding tropospheric ozone, past research conducted on the influence of the atmosphere and transport on surface ozone concentrations will be examined. Gaps are apparent within the previous literature and research into regional transport and the synoptic conditions associated with high ozone events, particularly in Arizona. Prior research using the methods that will be utilized in this research will also be discussed.

The next step in my research was to determine the spatial and temporal scales to be analyzed that would be appropriate and for which sufficient data would be available. This process is explained in detail in Chapter 3. The majority of the considerations for the data selection were taken from ozone measurement guidelines from the Clean Air Act, as well as a transport study done by the EPA. In addition to determining and collecting the ozone data, upper air charts, surface analyses, and surface meteorological data was collected. The sources of these data are discussed in detail in Chapter 3.

Chapter 4 will discuss the methods for manipulating and analyzing the data. In addition to the ozone and meteorological data, the HYSPLIT model was utilized to demonstrate regional transport pathways of tropospheric ozone. The details of the data inputs and selections for the HYSPLIT model are discussed more in detail in Chapter 4. This chapter also frames the process of the synoptic analysis and composite mapping for the ozone exceedance events. Chapter 5 will then present the analysis of the data and the interpretation of the results to determine if high ozone events in Arizona can be categorized by synoptic conditions.

Chapter 6 presents a summary of this thesis. It recaps the literature reviewed in Chapter 2, the data considerations and methods discussed in Chapter 3 and 4, and the results presented in Chapter 5. This final chapter will also discuss the reasons for conducting this research, the significance of the findings, and the need for further research in the future. To begin this research, I will now review some of the past literature, relevant to this area of study, in Chapter 2.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This thesis involves the evaluation of the synoptic conditions and potential regional transport pathways surrounding high ozone events in Arizona. This chapter discusses the science of tropospheric ozone, including its formation and life cycle, as well as the health and environmental impacts of ozone. In addition, this chapter discusses the transport of ozone in the troposphere, and the methods used for modeling and analyzing the transport of ozone in the troposphere.

2.2 TROPOSPHERIC OZONE

The gas ozone (O_3) forms naturally in the stratosphere, and is beneficial to the earth at that level of the atmosphere. But the formation of ozone in the troposphere, particularly at the surface, is detrimental and is considered pollution. The EPA has analyzed numerous studies assessing the impacts of ozone on human health. In their 2006 Air Quality Criteria Document (AQCD) on ozone, the collection of many studies spanning several decades indicates that there is a causal relationship between short-term exposure the ozone and respiratory effects, as well as a likely causal relationship between long-term exposure and respiratory effects (EPA, 2013). The EPA has also assessed studies done on the impacts of tropospheric ozone on the environment. Forty years of research on the effects of ozone exposure on vegetation and ecosystems, indicates that exposure to ozone is causally linked to visible foliar injury, decreased photosynthesis, changes in reproduction, and decreased growth (EPA, 2013). "Recently, studies at larger spatial scales support the results from controlled studies and indicate that ambient O3 exposures can affect ecosystem productivity, crop yield, water cycling, and ecosystem community composition. On a global scale, tropospheric O3 is the third most important greenhouse gas, making it likely to play an important role in climate change" (EPA, 2013).

Ozone is a secondary pollutant in the troposphere, meaning that it is formed from photochemical reactions of precursor gases, and it is not directly emitted from sources on the earth's surface (EPA, 2013). The two main precursor gases, that cause the production of ozone at the surface, are nitrogen oxides (NOx) and volatile organic compounds (VOCs) (EPA, 2013). The main source of these precursor gases is anthropogenic emissions, such as the burning of fossil fuels, with additional sources including biogenic emission, wildfires, lightning, and stratospheric intrusions (EPA, 2013). The photochemical reactions that create ozone are non-linear and have many factors, including atmospheric conditions and the ratio of NOx to VOCs (EPA, 2013). Sunlight is a necessary component in the formation of ozone, as well as other favorable conditions such as high pressure systems, light winds, and clear skies (EPA, 2013). All of this aids in the production of ozone and the buildup of it in the troposphere throughout the day, and over several days.

There have been numerous studies done on the meteorological aspects and effects of air quality, including those done by Logan (1985), Steiner (2010), Lelieveld and Dentener (2000), and Jacob and Winner (2009). Each of these studies examined the trends, behavior, and sources of surface ozone, in addition to looking at the future trends of surface ozone. Logan's (1985) research looked at the overall trends of surface ozone, using existing data that has been collected. She concluded that there is a seasonal trend for surface ozone to reach a maximum in the summer, especially in the northern mid-latitudes where there are more emissions (Logan, 1985). Another study by Steiner (2010) found a statistically significant change in the ozone-temperature slope, showing that under extremely high temperatures ozone concentrations plateau or decrease. Lelieveld and Dentener (2000) used climate models with existing surface ozone data to determine the main sources of ozone, concluding that photochemical processes are the main contributor, over stratospheric exchange, lightning emissions, and soil emissions. Their model was able to accurately represent a 15-year period of data, allowing them to run their model as a future forecast of surface ozone concentrations. Jacob and Winner (2009) conducted a similar study using climate models and circulation models to predict the effects of climate change on surface ozone. Their model showed that urban areas with increased temperatures would have the highest increase in surface ozone, which relates to Lelieveld and Dentener's findings that photochemical processes are the main contributor to surface ozone, and an increase in global temperatures will increase surface ozone.

2.3 LONG-RANGE TRANSPORT

Another aspect of meteorology that is useful in studying air quality, particularly surface ozone, is the movement and circulation of air. The long-range transport of surface ozone is a new and more recently studied topic in air quality research.

There have been several studies done to show that the long-range transport of ozone occurs throughout the atmosphere. A couple of studies performed in northern U.S. cities showed that ozone concentrations over metropolitan areas increase with wind speed, indicating that the transport of ozone and its precursors from upwind areas is important (Schichtel and Husar, 2001; Husar and Renard, 1998). Another study by Comrie (1994) used an air-mass trajectory analysis to analyze the sources of high ozone events in rural, forested Pennsylvania and found that the Ohio River Valley and Texas are the most probable sources of NOx emissions. A study done by Blumenthal (1997) showed that during episodes of high ozone in the eastern U.S. that winds several hundred meters above the ground can transport pollutants from the west, even if surface winds are from another direction. Additional studies established that nocturnal low level jets are able to transport pollutants that have been entrained into the residual boundary layer several hundred kilometers, and can contribute to high levels of ozone overnight and in the early morning (Corsmeier et al., 1997). Even topography is not a hindrance in the transport of ozone, as shown by Langford (2010) demonstrating that orographic lifting resulted in ozone being transported from the Los Angeles area hundreds of kilometers downwind, to areas such as Colorado or Utah. There have numerous other studies done, such as Levy (1985), Lin (2012), and Langford (2010), to show that the transport of surface ozone over long distances is possible, and that previously thought hindrances such as topography and lack of daylight are not as important.

In addition to the studies reviewed above, there have been several studies performed using chemical modeling to analyze tropospheric ozone transport. The EPA performed chemical modeling to assess the impact of transport on ozone concentrations throughout the country. Their analysis utilized the Comprehensive Air Quality Model with Extensions (CAMx version 6.11). “CAMx is a three-dimensional grid-based Eulerian air quality model designed to simulate the formation and fate of oxidant precursors, primary and secondary particulate matter concentrations, and deposition over regional and urban spatial scales (e.g., the contiguous U.S.). Consideration of the different processes (e.g., transport and deposition) that affect primary (directly emitted) and secondary (formed by atmospheric processes) pollutants at the regional scale in different locations is fundamental to understanding and assessing the effects of emissions on air quality concentrations." (EPA, 2015a, p. 2) This modeling platform utilized a 2011 base year for emissions, meteorology, and other inputs, and was then projected forward to 2017. With future ozone projections, nonattainment areas were identified, as well as maintenance areas in the United States. The EPA used a source apportionment modeling technique to quantify the contribution of emissions from all sources, including all other 49 states, biogenics, tribal lands, Canada and Mexico, fires, offshore sources, and boundary concentrations (EPA, 2015a).

This model projected that by 2017 zero counties in Arizona would be "nonattainment" and only one county, Maricopa County, would be "maintenance" for the 2008 NAAQS. They modeled significant contributions (>1%) from California, Mexico & Canada, initial/boundary conditions, and biogenic emissions. Arizona was modeled to have a largest contribution to a downwind nonattainment site of 1.78 ppb (Imperial County, California), and a largest contribution to a downwind maintenance site of 0.41 ppb (Jefferson County, Colorado) (EPA, 2015a). Arizona only significantly contributed (>1%) to Imperial County and to one monitor in Los Angeles County in California.

The transport of surface ozone and the methods used has been applied in numerous studies, for example in the Mid-Atlantic region (Liao et al., 2014), the New York-Connecticut-Massachusetts region (Cleveland, 1976), in California regarding Asian pollution (Lin et al., 2012), as well as other international locations. While there are numerous studies relating to this topic, there is a lack of research in the Southwest, specifically in Arizona. This project will focus on how interstate transport of ozone influences ground level ozone exceedances in Arizona, with the hopes to verify if past days of ozone exceedances coincide with the transport of ozone from neighboring states. I will be using similar methods to the research described above, including the use climate and forecasting models to try and back trace ground level ozone to determine the source and the significance of contribution.

2.4 HYSPLIT TRAJECTORY MODEL

Studying surface ozone transport uses methods including surface ozone data collection, wind analysis, and various modeling techniques, including climate modeling, circulation modeling, and wind trajectory modeling. One model used in studying the transport of surface ozone is the Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT). The Air Resources Laboratory's (ARL's) model is a tool that helps explain how, when, and where potentially harmful materials are atmospherically transported, dispersed, and deposited (ARL, 2016). "The model calculation method is a hybrid between the Lagrangian approach, using a moving frame of reference for the advection and diffusion calculations as the trajectories or air parcels move from their initial location, and the Eulerian methodology, which uses a fixed three-dimensional grid as a frame of reference to compute pollutant air concentrations" (ARL, 2016, p. 1).

The HYSPLIT model is able to compute back trajectories of air parcels, which is useful in determining the source or where an air mass came from (ARL, 2016). The trajectory features include single or multiple (space or time) simultaneous trajectories, ensemble trajectories, as well as integrated trajectory clusters.

Shan et al. (2009) used this model to study the transport of surface ozone in Jinan, China. They were able to model the back trajectories of several high surface ozone days, and determine that there are six main transport flows of ozone into Jinan (Shan et al., 2009). Due to a lack of detailed data they were not able to determine quantitatively how these flows were impacting the surface ozone in Jinan (Shan et al., 2009).

The HYSPLIT model has similar applications in determining the back trajectories of other meteorological events such as dust storms or “blood” rains. White et al. (2012) used this model in mapping the back trajectories of “blood” rain events in Europe, which are rain events that have a reddish color (White et al. 2012). He was able to map the back trajectories of three specific “blood” rain events in Europe to dust events in Northern Africa (White et al., 2012).

Another example of the use of this model is in the mapping of dust storm back trajectories in China. Yan et al. (2015) used this model to map the back trajectories of several dust storm events in China, and used a cluster analysis to then determine the likelihood of what direction it would have traveled (Yan et al., 2015). They then overlaid these back trajectories onto satellite imagery to see which trajectory overlapped with dust plumes (Yan et al., 2015). The HYSPLIT model is not the only model applicable to studying the transport of surface ozone, but it is one of the more widely used models for investigating pollution transport.

2.5 CATEGORIZATION OF SYNOPTIC CONDITIONS

Maddox's research on characterizing the synoptic conditions of flash flood events over the western region of the United States was demonstrated the use of "synoptic typing" of specific events. The methods Maddox used in categorizing flash flood events will be similar to the methods I will be using to classify ozone events. In his research, he examined a large set of flash flood events that occurred in the western portion of the US (west of 104° longitude) during the period 1973-1978 (Maddox, 1980). He used the data reported during these events in addition to surface charts and standard level analyses from the National Meteorological Center. He employed these data to then categorize flash flood events based on similar 0hPa-500hPa flow patterns, and taking into account additional factors such as the position of old or weak frontal boundaries, unusually moist regions, and trough/ridge axis locations. He then created composite maps for each of the groupings of flash flood events and calculated mean conditions (and standard deviations) for each grouping. These groupings became his four flash flood event categories. One example would be the "Type 1" events, which were associated with a weak 500hPa short-wave trough moving up the western side of a long-wave ridge. He determined that these events were associated with weak surface fronts and 500hPa moisture over the Rockies.

In addition, the synoptic typing methodology has been utilized in several other research studies. One example is by Kalkstein (1996), who used this synoptic typing in identifying the characteristics and frequencies of upper air masses over the United States. Kalkstein developed six air mass types for the United States, beyond the historical four categories (mT, mP, cT, and cP). In developing these six air mass categories, Kalkstein utilized clustering and statistical analysis to categorize days with similar days, using initial “seed day” characteristics. He was able to develop six categories that are based on their characteristics, instead of their source regions. For example, instead of the historical category of continental polar, he developed a similar category, dry polar, that is characterized by the coldest, dry air mass.

Another example of the use of synoptic typing is Kahana’s (2002) research of major floods in the desert of Israel. Kahana analyzed discharge data for the flood events, in addition to upper air data, such as sea-level pressure, 500hPa geopotential height, 850hPa temperature, and 250hPa wind components. Using this data, he was able to group 80% of the flood events into four categories. For example, the most frequent type was associated with a surface low-pressure trough that is accompanied by a pronounced upper level trough. I plan to employ similar synoptic typing methods when categorizing ozone events in Arizona.

2.6 SUMMARY

This chapter has identified numerous studies that have examined various aspects of tropospheric ozone, long-range transport of ozone, and some of the methods that will be used in this research. There is a large body of research explaining the formation of ozone and the meteorological conditions that are favorable to ozone. The EPA has published that in addition to sunlight, being a critical component in the chemical reaction that produces ozone, meteorological conditions such as high pressure systems, light winds, and clear skies aid in this production (EPA, 2013). There is also a great body of research on the transport of tropospheric ozone in many parts of the country, and even around the world. Researchers, including Blumenthal (1997), Corsmeier (1997), and

Langford (2010), have shown that long-range transport of pollutants is possible through various meteorological methods. While the research on ozone transport is widespread, there is a lack of research in the desert southwest, particularly Arizona.

With the lack of studies done in Arizona regarding tropospheric ozone and synoptic meteorology and the increasing regulation on this pollutant, more information needs to be known surrounding tropospheric ozone and transport in this area. This research will utilize the knowledge provided from previous studies, as well as the methods employed, to try and characterize the synoptic meteorology associated with exceeding ozone events in Arizona. The data sources and considerations for this research are given in the next chapter.

CHAPTER 3

DATA CONSIDERATIONS

3.1 INTRODUCTION

This thesis classifies high ozone events in Arizona based on synoptic meteorological conditions and the potential for ozone transport. The preceding chapter discussed how the EPA currently classifies high ozone events, the known meteorological conditions that support the development of high ozone events, and past research regarding ozone transport, as well as classifying meteorological events. This chapter now addresses the various concerns, considerations, and decisions that must be made in compiling and analyzing the data for this research.

3.2 STUDY AREA

The Arizona Department of Environmental Quality (ADEQ) is interested in gaining a better understanding of the meteorological characteristics of high ozone events and the influence of ozone transport from other regions. Based on this consideration, the study area for this research includes all of the ambient air monitoring sites in Arizona that monitor ozone concentrations. These sites include those operated by ADEQ, Maricopa Air Quality Department (MCAQD), Pinal County Air Quality Control District (PCAQCD), and Pima County Department of Environmental Quality (PCDEQ) (Figure 3.1). The only ozone monitoring sites in the state that were not included are the sites operated by tribal governments. Although multiple organizations operate these ozone monitoring sites, all of the ozone monitoring data was submitted to the EPA's Air Quality System (AQS), where the data are quality assured, and were then provided by ADEQ.

Data were received from 36 ambient air monitoring sites across the state of Arizona. These sites span the counties of Coconino, Gila, La Paz, Maricopa, Pima, Pinal, Yavapai, and Yuma. There were no reported exceedances at the individual monitoring sites in Cochise and Navajo counties. Also, there are no current ozone monitoring sites in Apache, Graham, Greenlee, Mohave, and Santa Cruz counties (Figure 3.1).

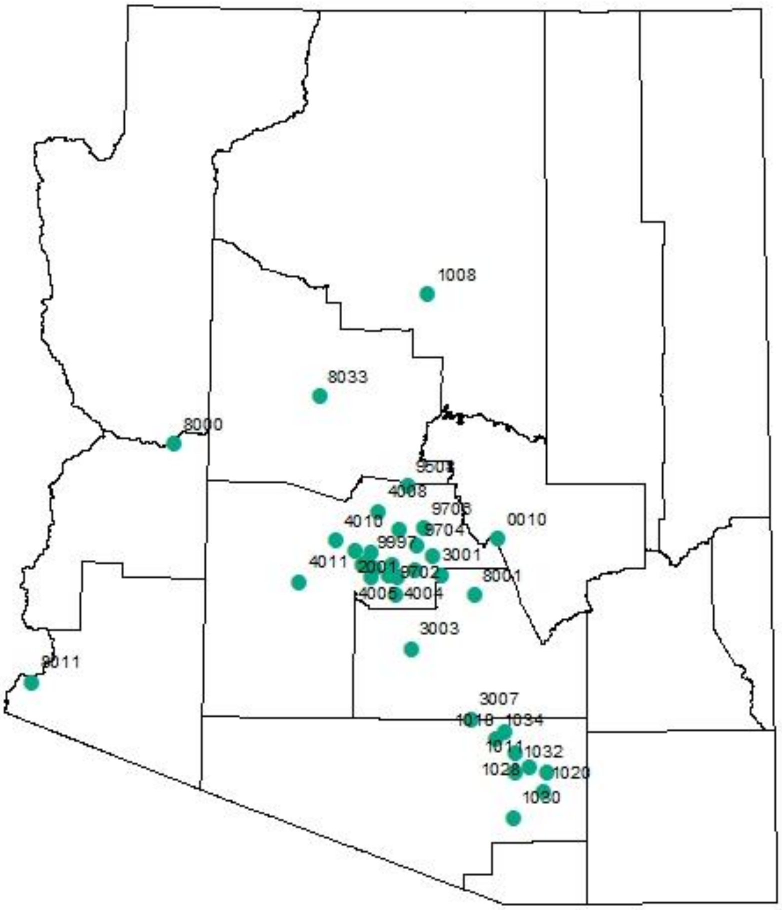


Figure 3.1 The 36 ozone monitoring sites in Arizona, labeled with their site ID number.

The Environmental Protection Agency has published ozone transport modeling that examines the significance of the regional transport of ozone throughout the country (EPA, 2015a). This modeling was initialized using a base year of 2011 for meteorological data and emissions data (EPA, 2015a). Using this model, this study examines ozone exceedance events from 2011 to 2013. The year 2011 is used as the initial year of ozone exceedances in order to remain consistent with research the EPA has done. This range of years allows for a good sample size of ozone exceedance events to use in characterizing the meteorological conditions. At the time of the study these were also the most recent complete years' of data available.

3.3 OZONE DATA

Each of the ozone monitoring locations that fit the description above was considered in this research. Most of these monitoring locations monitor ozone from April through October (the peak ozone season in Arizona), with a few sites monitoring ozone year round. The ozone concentration data were provided at the hourly level, as well as the 8-hour running average interval level. The 8-hour running average is the concentration value that is used by EPA to determine an exceedance over the National Ambient Air Quality Standards (NAAQS) for ozone. The highest 8-hour average value for each day is used to determine if an exceedance occurred at that site on that day (Table 3.1). These dates and time were extracted for each site where an 8-hour average exceeded the 2008 NAAQS for ozone of 75ppb. All of the exceeding dates for each site were compiled and sorted by year and date.

Figure 3.2 The photo above to the left is of the ADEQ JLG Supersite monitoring site in downtown Phoenix, and the photos above to the right show the stainless steel inlets where ambient air is drawn in and then analyzed in the ozone instrument below. While not all monitoring stations are set up in the same fashion, they all use the same equipment and adhere to certain siting regulations. (Photos courtesy of ADEQ).

There were many days that have multiple sites exceeding ozone concentrations. For these the dates, I analyzed all sites, but only the specific site with the highest 8-hour average ozone concentration was used as a representative for that date. This is similar to the procedure used by EPA when determining if an area is in nonattainment, in that only the site with the highest exceeding concentration is used as a the “design monitor” when determining the classification of an area or county.

Table 3.1 Example of raw max 8-hour ozone concentrations for one ozone monitoring site.

AQS ID			**Ozone Parameter Code**	**Date**	**Ozone Sample Value (ppm)**
State Code	**County Code**	**Site ID**			
YEAR : 2011					
04	027	8011	44201	20110401	.052
04	027	8011	44201	20110402	.048
04	027	8011	44201	20110403	.047
04	027	8011	44201	20110404	.057
04	027	8011	44201	20110405	.060
04	027	8011	44201	20110406	.048
04	027	8011	44201	20110407	.055
04	027	8011	44201	20110408	.047
04	027	8011	44201	20110409	.054
04	027	8011	44201	20110410	.058
04	027	8011	44201	20110411	.054
04	027	8011	44201	20110412	.071
04	027	8011	44201	20110413	.063
04	027	8011	44201	20110414	.062
04	027	8011	44201	20110415	.058
…	…	…	…	…	…

When available, the meteorological data for each ozone monitoring site were also received. These data typically included wind speed, wind direction, ambient temperature, and occasionally relative humidity, at an hourly scale. Not all of the monitoring sites have the equipment to monitor meteorological conditions, but a significant amount do (Table 3.2). When possible, I incorporated sites with available meteorological data as the “representative” exceedance value if they also had the highest ozone concentration. For days where the highest ozone exceedance was at a site that did not measure meteorological data, then the next highest site was used for surrogate meteorological data. For days where there was only one exceeding site, which did not monitor meteorological data, then the next closest site was used for surrogate meteorological data.

Finally, for days where the only exceeding site did not measure meteorological conditions, and there was no other nearby sites, meteorological conditions at the site were not considered; this was only applicable to the monitor in Yuma county, AZ and La Paz county, AZ which are significantly far away from any other ozone monitors.

Table 3.2 Example of raw hourly ozone concentration and meteorological data for one ozone monitoring site.

AQS ID			**Date**	**Start Time**	**Ozone Sample Value (PPM)**	**Wind speed (m/s)**	**Wind Direction (degrees)**	**Temp (ºC)**	**RH (%)**	**Max. Wind speed (m/s)**
State Code	**County Code**	**Site ID**								
04	013	9997	20110401	0:00	0.001	.7	54	20.7	37.8	1.588
04	013	9997	20110401	1:00	0.001	.7	47	19.7	41	1.764
04	013	9997	20110401	2:00	0.001	.5	202	18.6	45	1.49
04	013	9997	20110401	3:00	0.001	.8	33	18	46.9	1.921
04	013	9997	20110401	4:00	0.001	.7	165	17	51	1.764
04	013	9997	20110401	5:00	0.001	.6	64	16.6	51.8	2.117
04	013	9997	20110401	6:00	0.001	.5	351	16	54.8	1.49
04	013	9997	20110401	7:00	0.004	.5	28	19.6	44.5	1.47
04	013	9997	20110401	8:00	0.009	.5	356	24.5	30.8	1.627
04	013	9997	20110401	9:00	0.017	.9	190	28.4	21.8	2.215
04	013	9997	20110401	10:00	0.03	.8	101	31.1	16.8	2.626
04	013	9997	20110401	11:00	0.042	1.4	129	33.4	11.8	4.9
…	…	…	…	…	…	…	…	…	…	…

3.4 SYNOPTIC METEOROLOGICAL DATA

In addition to the meteorological data monitored at certain ozone monitoring sites, synoptic analyses of the atmosphere were acquired for each of the ozone exceedance dates, as well as the two days leading up to the events. DIFAX upper air analyses from the National Weather Service were received from Colorado State University Department of Atmospheric Science online archives (CSU, 2016). The North American surface analyses from the National Weather Service were also received from the Colorado State

University Department of Atmospheric Science online archives (CSU, 2016). In addition to these analyses, satellite images of cloud cover were received from the National Climatic Data Center (NECI, 2016). Vorticity charts, from the National Weather Service via the Colorado State University Department of Atmospheric Science online archives, were examined initially, but I decided that vorticity did not contribute significantly in the synoptic analysis and such charts were not considered further (CSU, 2016).

For the upper air analysis, I analyzed DIFAX charts for the 0hPa-200hPa level, 0hPa-500hPa level, 0hPa-700hPa level, and the 0hPa-850hPa level. These upper air analyses were performed by the National Weather Service for North America valid 12 UTC on each day. Charts were looked at for each day of an ozone exceedance event, as well as the two days leading up to each event. The 12 UTC analysis was chosen, instead of the 00 UTC analysis, to get an impression of the synoptic patterns leading up to each event; whereas the 00 UTZ analysis would be representative of several hours after the max ozone concentration of most events.

For the surface analysis, completed National Weather Service surface charts from the Colorado State University Department of Atmospheric Science online archives were employed (CSU, 2016). The 12 UTC surface analysis charts were chosen for consistency with the upper air analysis; as well as to see the surface conditions leading up to the ozone exceedance. Also, I did have access to surface weather conditions at the time of the event from the ozone monitoring sites in most cases.

Cloud cover was determined by using satellite images in the visible spectrum from the National Center for Environmental Information (NCEI, 2016a). These images were provided by the GOES 11 satellite for 2011 dates and then by the GOES 15 satellite for 2012 and 2013 dates. Images at 18 UTC and 21 UTC on the day of the ozone exceedance, and also at 00 UTC on the next day, were examined at to arrive at a general impression of cloud cover throughout the daytime hours during the ozone exceedance.

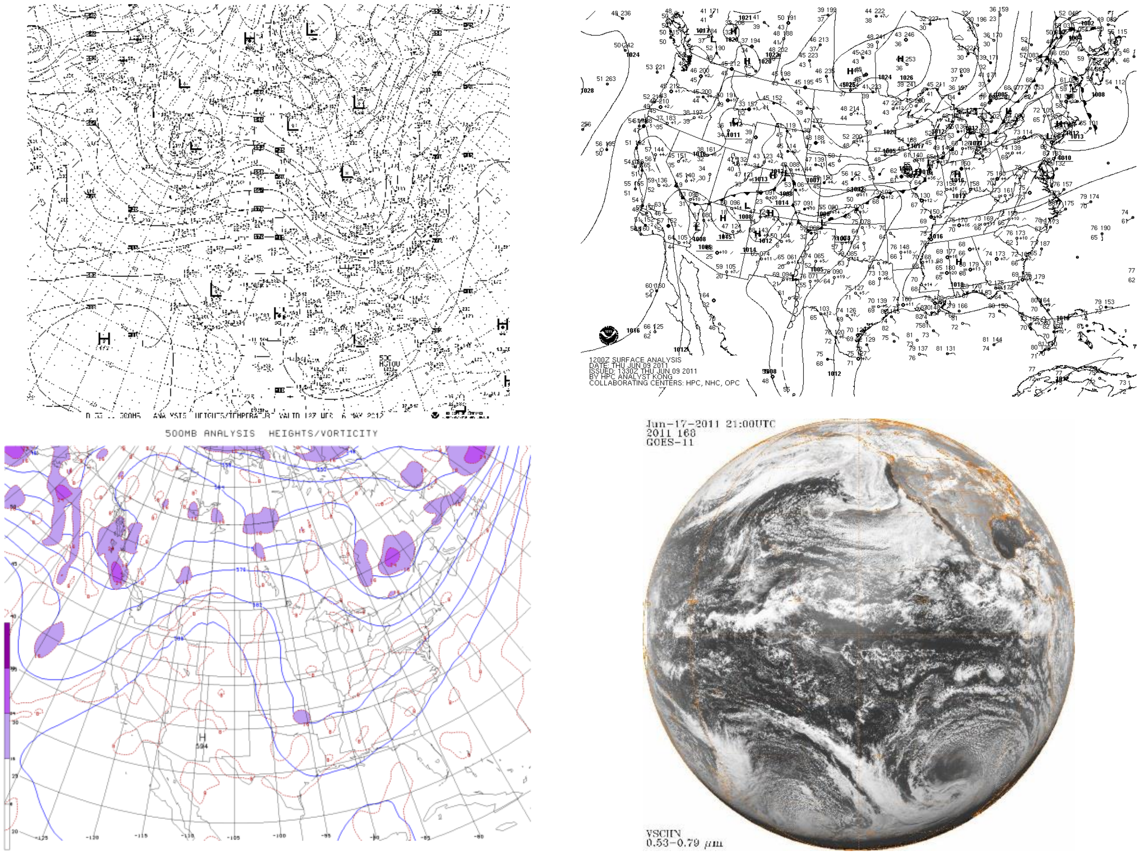


Figure 3.3 Examples of an upper air chart, a surface analysis, a vorticity chart, and a visible satellite image.

3.5 SUMMARY

This project employs two distinct types of data. First, I am accessing ozone data from the Arizona Department of Environmental Quality. Second, I am employing synoptic meteorological observations, including upper air charts, surface analyses, and surface monitor data. These data will provide the necessary initial data into my ozone synoptic classification scheme as detailed in the next chapter.

CHAPTER 4

METHODS

4.1 INTRODUCTION

My research analysis is comprised of four parts: (a) the synthesis of the ozone data, (b) the HYSPLIT backward trajectory analysis, (c) the synoptic meteorological analysis, and (d) the categorization methods. I will discuss each of these parts individually in this chapter and then the overall synthesis of these parts into an operational scheme from which results will be discussed in the next chapter.

4.2 OZONE DATA

The ozone data collected for this research needed to be initially grouped together by the monitor location to identify clearer patterns. Due to the location of ozone monitoring sites throughout Arizona, some sites were immediately grouped together. I aggregated all sites in Maricopa County, the one site in Gila County, and three sites in Pinal County due to their close proximity to the Phoenix metropolitan area (Figure 4.1). Similarly, all eight sites in Pima County and one site in the southern part of Pinal County were grouped together due to their close proximity to the Tucson area (Figure 4.1). The remaining sites were all individual monitoring sites in Yuma County, La Paz County, Yavapai County, and Coconino County, and they were all analyzed individually (Figure 4.1).

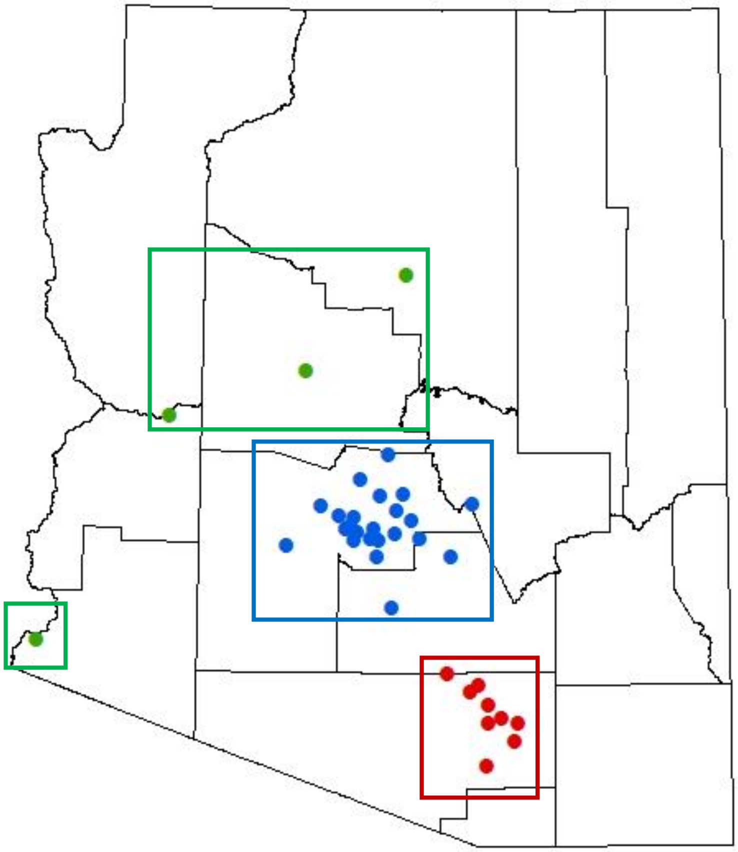


Figure 4.1 All ozone monitoring sites grouped together by area. The blue rectangle includes all sites in or near the Phoenix metropolitan area, the red rectangle includes all sites in the Tucson area, and the two green rectangles include all other sites.

4.3 HYSPLIT ANALYSIS

I employed the HYSPLIT model to analyze the backwards trajectory of a parcel of air from the monitoring sites at the time of each exceedance event. The HYSPLIT model, as discussed in Chapter 2, is a trajectory and dispersion model that is useful in modeling the path or dispersion of an air parcel. The HYSPLIT trajectories provide visual representations of the origin of the air mass at the time of the ozone exceedance. The model was run for each date with an ozone exceedance from 2011 to 2013, and at each exceeding site on dates with multiple exceedances.

The HYSPLIT model was run using initial meteorological conditions modeled from the North American Mesoscale 12km (NAM) meteorological model at the date and time of each ozone exceedance event. The NAM meteorological model is one of the major weather models run by the National Centers for Environmental Prediction (NCEP) for producing weather forecasts and is a high resolution numerical model (NCEI, 2016b). I selected this meteorological model as the input conditions because of its high resolution and because it was the same model used to initialize the EPA's ozone transport study (EPA, 2015a). I selected an ensemble trajectory model to establish the confidence of the back trajectory.

Each ensemble trajectory was initiated with slightly different initial meteorological conditions, so as to ensure confidence in the model's path of the trajectory. I modeled the ensemble trajectory 48 hours backward from the time of the ozone exceedance. The recommended method to compute vertical motion in the model uses the vertical velocity field from the meteorological data (ARL, 2016). The model was run at a starting height of 250m above ground level (AGL) to best capture surface level conditions associated with the exceedance origin site; if the starting height were any lower, the model would have difficulty accounting for topography, while a higher starting position would not render consideration of initial surface conditions (ARL, 2016).

The final result of the HYSPLIT model was a plot of the 48-hour back trajectory, originating from the exceeding site at the time of the 8-hour exceedance. These images were used to establish where the air mass originated, and where the potential for ozone transport occurred (Figure 4.2).

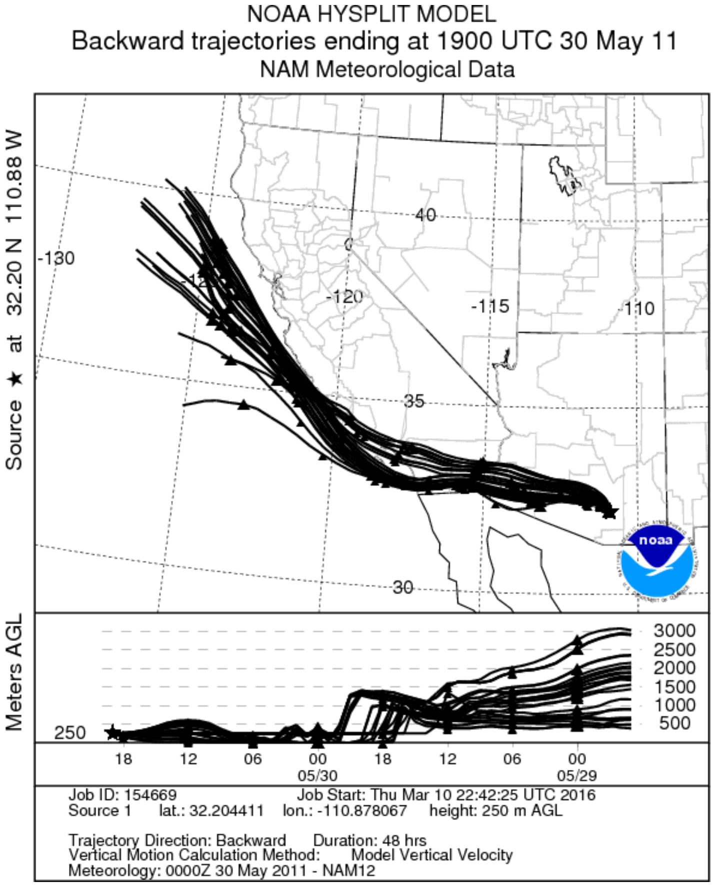


Figure 4.2 Example HYSPLIT 48-hour back trajectory for an ozone exceedance event in Arizona.

4.4 SYNOPTIC METEOROLOGICAL ANALYSIS

I performed a synoptic analysis for each event, grouping coinciding days together as one exceedance event. The synoptic analysis included multiple levels of the atmosphere and involved the two days leading up to the exceedance event to establish a temporal sequence of the exceedance weather. I selected five different pressure levels to examine, specifically the 200hPa level, 500hPa level, 700hPa level, 850hPa level, and the surface. At each level I recorded the height of the pressure level, as well as the general pattern (e.g., trough, ridge). Also I noted the location of high and low pressure centers and shortwaves. The wind speeds and wind direction are noted for each level, as well as temperature and dew point depression. I gave particular emphasis to the low level (850hPa) moisture, or lack thereof. Also, following studies, such as Maddox (1980), the 500hPa general pattern is a key point in the analysis.

In addition to the upper air analysis, I also examined the NWS surface analysis. With regard to the surface analysis, I selected for consideration the wind speed and direction, temperature, dew point, and the pressure height, as well as the general pattern and location of surface lows and highs. In addition to the surface analysis chart, the surface meteorological conditions monitored at each sites, when available, were also considered. I examined the surface analysis chart for 12z on the day of the event, to remain consistent with the upper air charts, though the monitoring sites surface conditions were taken from the time of the 8-hour ozone exceedance. The cloud cover on the day of the exceedance event was also noted, looking at satellite images of the area around the average time of ozone exceedances (midday to late afternoon). If cloud cover was present during this period, “some” cloud cover was noted, if none was visible in the satellite images, then “no” cloud cover was noted.

4.5 CATEGORY ANALYSIS

After all of the ozone data and synoptic charts were analyzed for each exceedance event, categories were determined based on patterns and similar conditions. Looking at just exceedance events in Maricopa County, Gila County, and three sites in Pinal County together, I began by grouping exceedance events together by back trajectory origin and 500hPa pattern. Exceedance events in the rest of the state were then analyzed to determine if they matched the groupings initially determined from the Phoenix metropolitan exceedances. Some exceedance dates had multiple exceeding sites that originated from different locations, so the events were categorized using the 500hPa pattern. I then analyzed synoptic conditions at all levels of the atmosphere, including wind patterns, low level moisture, surface conditions, and cloud cover, for each of the initial categories. At this point, any outlying events in the categories were removed or reassigned to a more appropriate category. After the synoptic analysis of each category, I created composite maps to represent the average conditions of each category. Finally average conditions for each category were calculated.

4.6 SUMMARY

This project employs four distinct methods for analyzing the data. First, I synthesized the ozone data from the Arizona Department of Environmental Quality. Second, I modeled back trajectories of the ozone exceedance events utilizing the HYSPLIT model. I then analyzed synoptic meteorological observations, including upper air charts, surface analyses, and surface monitor data for each event. Finally, utilizing the three previous methods results I categorized the ozone events. These methods will result in my ozone synoptic classification scheme as detailed in the next chapter.

CHAPTER 5

RESULTS

5.1 INTRODUCTION

This study allowed me to identify patterns or similarities in the synoptic weather pattern that coincide with high ozone events, and potential inter-state transport pathways. These patterns can be used when forecasting for ozone, and aid in informing when an exceedance is likely to occur and make decisions about how to lessen the impact. From the analysis, five categories were determined from the synoptic patterns, meteorological conditions, and Hysplit analyses. This chapter will discuss each of these categories in detail, outlining the general pattern, average surface conditions, and ozone concentrations.

5.2 “NORTHWEST INFLUENCE” CATEGORY

I named the first category identified the “Northwest Influence” category, or the Type 1 category, and it accounted for 7% of all of the high ozone events from 2011 to 2013. This category is associated with Arizona being located between a trough (over the plains states) and a ridge (over California and Nevada). The composite map (Figure 5.1) shows the typical synoptic conditions that occur for this category. It shows the location of the typical trough/ridge pattern, with Arizona located at the front of the ridge, or along the front downslope. The composite synoptic map shows that in addition to the 500hPa trough/ridge pattern, there is a dry tongue at 700hPa and 850hPa over the Southwest, specifically Arizona. There is no 200hPa jet present during this type of event. At the surface there is a low pressure center over the Arizona and California border, with a surface trough extending through these two states. Additionally, there is some surface moisture along the coast of California. The dry air aloft and high pressure moving in are both conducive to the formation of ozone.

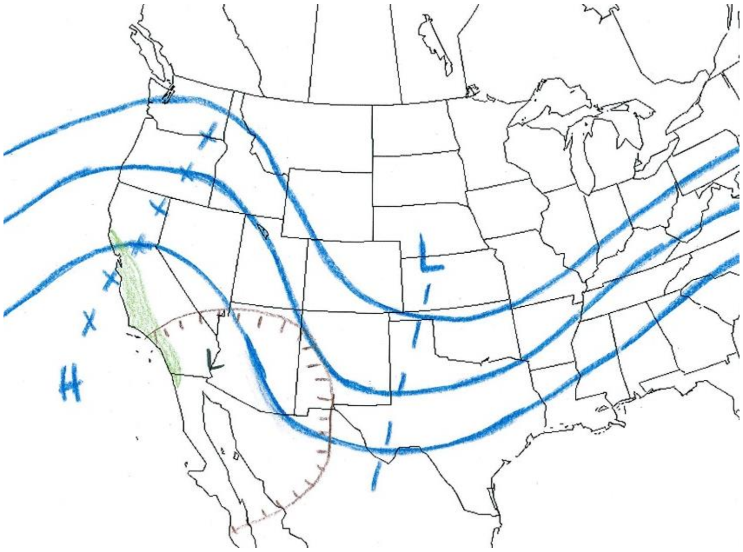


Figure 5.1 Composite map of "Northwest Influence" (Type I) category. The 500hPa flow is shown in blue and the 500hPa trough (dashed line) and ridge positions (x-line). The dry region ($t_{dd}>20^{o}C$) at 700hPa is shown by the brown hatched area, and the area of surface moisture ($t_{d}>50^{o}F$) is shown by the green shaded in area.

Each of the events in this category are also associated with Hysplit back trajectories that originate from the north/northwest, in the Utah, Nevada, and northern California region (Figure 5.2). This fits with the general 500hPa pattern, with Arizona sitting on the front downslope of the ridge.

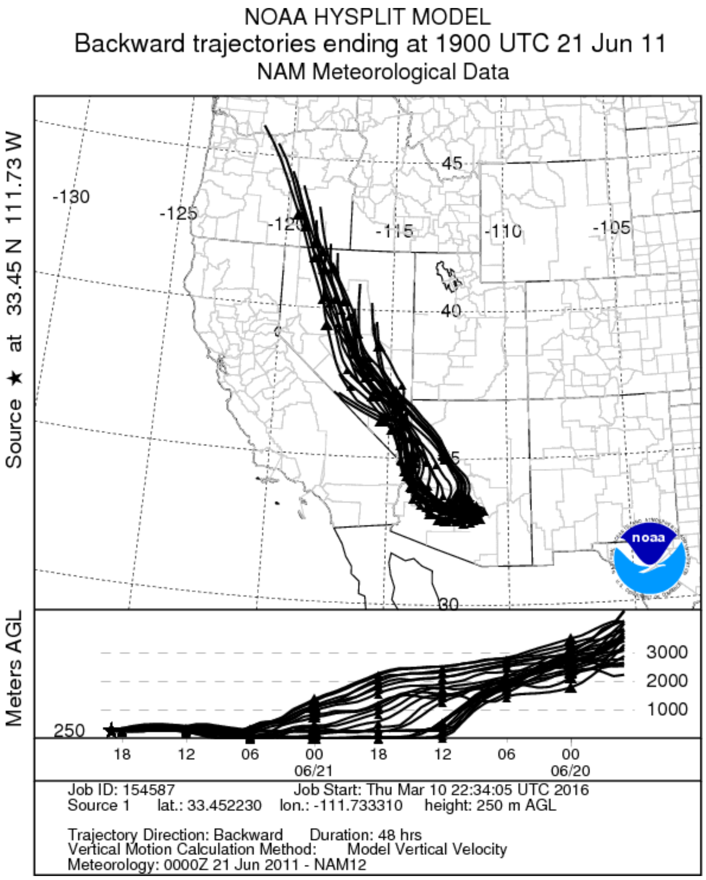


Figure 5.2 Example back trajectory for "Northwest Influence" category.

In addition to the Hysplit trajectories and general pattern, most of these events had winds from the northwest throughout all levels of the atmosphere, with average wind speeds at each level (Table 5.1).

Table 5.1 The average and standard deviation for wind speed and direction at each pressure level for Type I events.

	Wind Speed (kt)		Wind Direction (degrees)	
	Avg.	Std. Dev.	Avg.	Std. Dev.
200HPA	36	17	315	0
500HPA	26	11	333	25
700HPA	10	5	180	191
850HPA	7	3	338	32
MONITOR	6	2	196	73

Based on satellite images, there was no cloud cover during the daylight portion of the day on any of the exceedance days in this category. This is beneficial to the formation of ozone because sunlight is a necessary component in the chemical reactions that occur to create ozone.

There were a total of 5 events out of 73 events total (7%), with all of these events occurring in April, May, and June. The average ozone concentration on days of this category is 81 ppb, and these exceedances occur on average at 12:00 local time.

5.3 “CALIFORNIA INFLUENCE” CATEGORY

The next category accounts for 25% of the ozone exceedance events during this time period, and is associated with a wide, deep trough upper air pattern. This category, the “California Influence” or Type 2 category, typically sees Arizona positioned at the bottom of a wide trough that extends from the Midwest. The composite map (Figure 5.3) shows this 500hPa pattern, as well as the other typical features of this category. This category is associated with a 200hPa jet positioned over Arizona. There is also a low level dry tongue over Arizona extending from Mexico at 700hPa and 850hPa, as well as a shortwave at 700hPa. At the surface, there is a low pressure center over Las Vegas, NV with either a cold or occluded front extending to the north or west of Arizona. There is also a surface trough extending along the Arizona and California border. The dry air aloft allows for better production of ozone, along with the upper level jet being conducive to long-range transport.

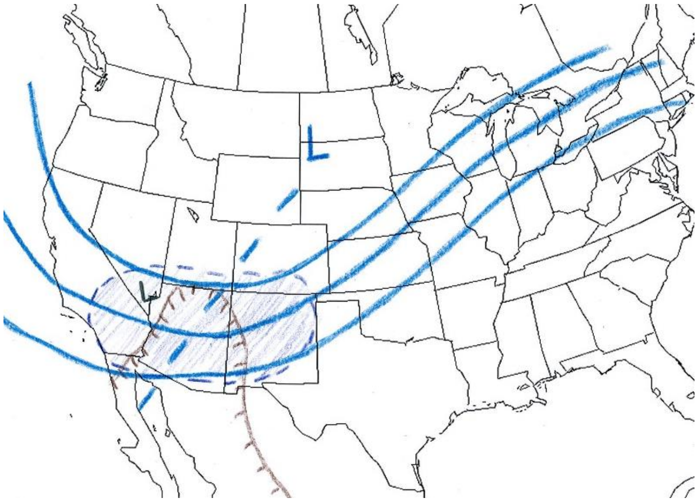


Figure 5.3 Composite map of the "California Influence" (Type 2) category. The 500hPa flow is shown in blue and the 500hPa trough (dashed line) and ridge positions (x-line). The dry region (t_{dd}>20ºC) at 700hPa is shown by the brown hatched area, and the 200hPa jet (>55kt) is shown by the purple dashed area.

The events in this category all have Hysplit back trajectories originating from southern California (Figure 5.4). This matches well with the upper air trough over the region at 500hPa. In addition to the Hysplit trajectories and general pattern, there are westerly winds throughout all levels of the atmosphere and a mid-range wind speeds (Table 5.2).

Table 5.2 The average and standard deviation for wind speed and direction at each pressure level for Type 2 events.

	Wind Speed (kt)		**Wind Direction (degrees)**	
	Avg.	Std. Dev.	Avg.	Std. Dev.
200HPA	62	22	273	29
500HPA	33	17	275	36
700HPA	19	11	246	46
850HPA	8	4	279	54
MONITOR	4	2	229	56

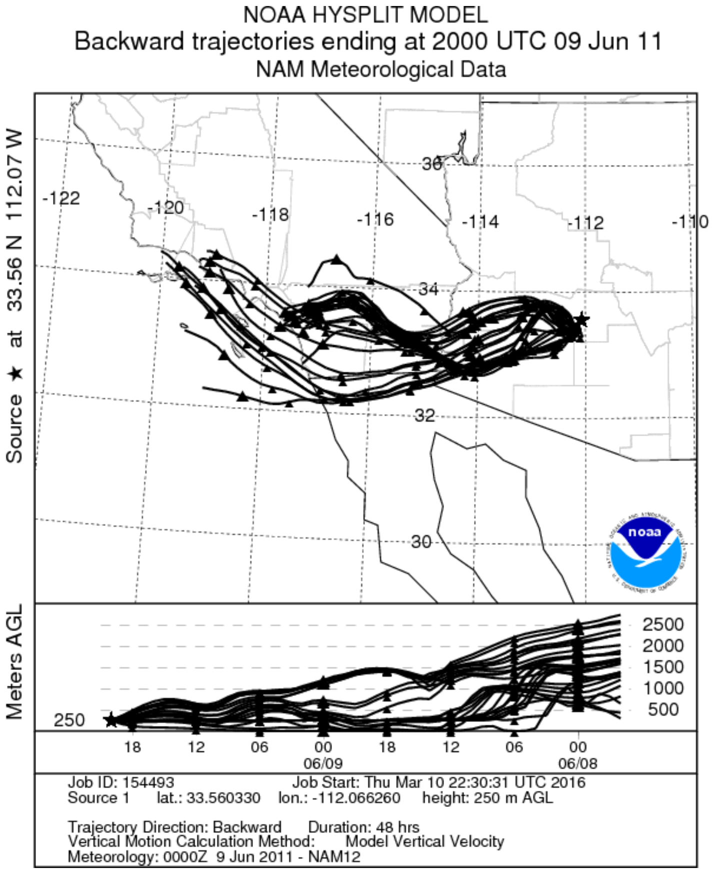


Figure 5.4 Example back trajectory for "California Influence" category.

From satellite images of the area there is no cloud cover during the day of any of the exceedance events in this category, which is beneficial for the production of ozone in the atmosphere.

There were a total of 18 events in this category, and all occurred in early summer, May and June, with only one event occurring in late April. The average ozone concentration for this category is 79ppb and the exceedances occurred on average at 12:00 local time.

5.4 “GULF OF MEXICO INFLUENCE” CATEGORY

The monsoonal subtropical ridge pattern is most closely associated with the “Gulf of Mexico Influence” category, or Type 3 category. This category accounts for 23% of the ozone exceedance events. The composite map shows the typical monsoonal subtropical ridge that forms over the area in late summer (Figure 5.5). This pattern has a high pressure center over the Four Corners area and the ridge takes up much of the country, with influence from the subtropical flow. The composite map also shows that no upper level jet is associated with this category. There is a dry tongue over California and southwestern Arizona at 700hPa and 850hPa, with a significant area of moisture below. At the surface there are two moisture tongues, one extending into Arizona from Baja California and one extending from the Gulf of Mexico. There is also a surface low over Las Vegas, NV and a surface trough extending through California and Arizona. The surface Four Corners high-pressure, as well as the upper level dryness helps aid the formation of ozone.

The Hysplit back trajectories for this category show an air transport pathway from the Gulf of Mexico region. Most of the trajectories in this category originate from New Mexico, Texas, or eastern Mexico. These Hysplit trajectories help to illustrate the subtropical influence over the area (Figure 5.6). The winds are from various directions and low wind speeds at all levels of the atmosphere, with Southeast winds at 850hPa (Table 5.3).

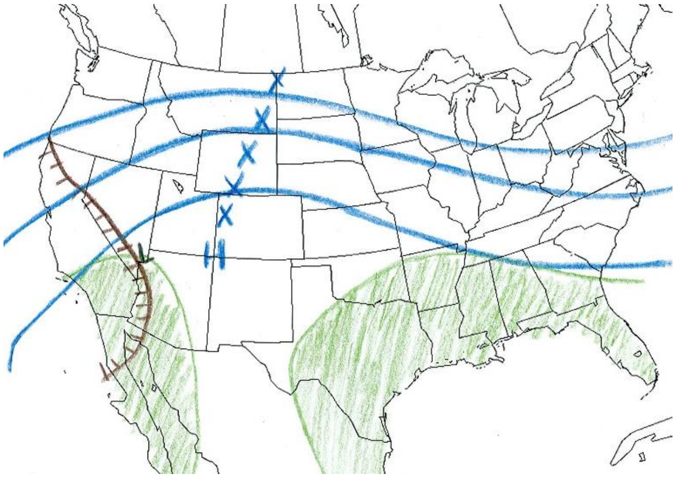


Figure 5.5 Composite map of the "Gulf of Mexico Influence" (Type 3) category. The 500hPa flow is shown in blue and the 500hPa trough (dashed line) and ridge positions (x-line). The dry region (t_{dd}>20°C) at 700hPa is shown by the brown hatched area, and the area of surface moisture (t_d>50°F) is shown by the green shaded in area.

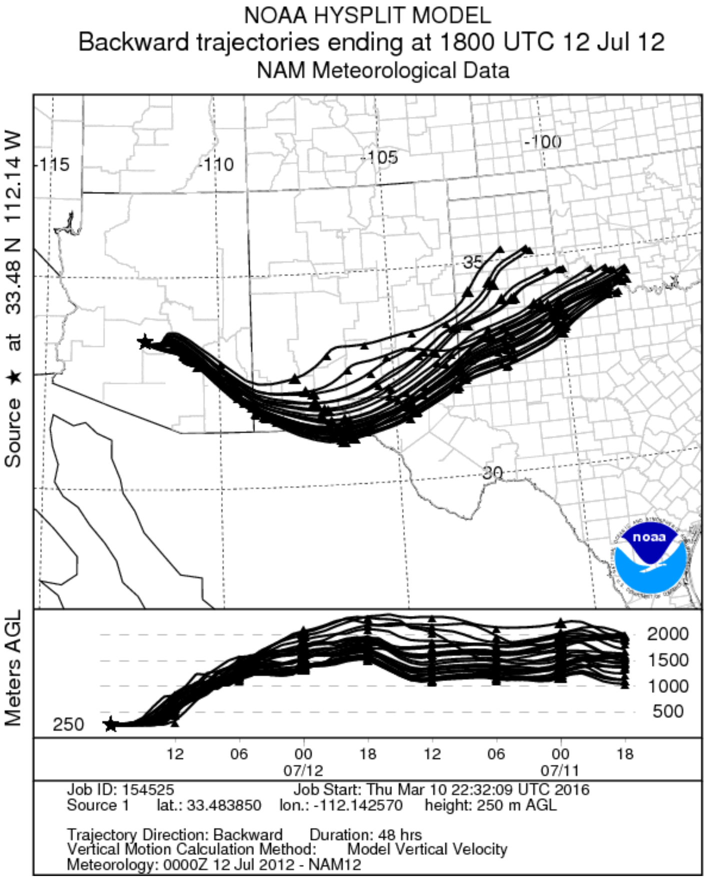


Figure 5.6 Example back trajectory for "Gulf of Mexico Influence" category.

From satellite images of the area there is none to some cloud cover during the day of any of the exceedance events in this category, with the majority of cloud cover occurring in the late afternoon. While no cloud cover is more beneficial for the production of ozone in the atmosphere, since the cloud cover that is visible in the area occurs later in day and is minimal, enough sunlight is still available to allow the production of ozone.

Table 5.3 The average and standard deviation for wind speed and direction at each pressure level for Type 3 events.

	Wind Speed (kt)		**Wind Direction (degrees)**	
	Avg.	Std. Dev.	Avg.	Std. Dev.
200HPA	21	14	197	113
500HPA	12	6	141	94
700HPA	8	3	207	99
850HPA	8	3	185	88
MONITOR	4	2	186	62

There were 17 events in this category, comprising 23% of all events. All of the events in this category occurred in the mid to late summer, July and August. The average ozone concentration was 80 ppb, and occurred at 11:00 local time.

5.5 “MEXICO INFLUENCE” CATEGORY

This category is similar to the previous category, but is characterized by a couple of distinctions. Similar to the “Gulf of Mexico” category, the “Mexico Influence” (or Type 4) category is also associated with a large ridge over the area, but unlike the “Gulf” category, there are two distinct troughs, one on either side of the ridge. Because of the trough positions, and the amplitude of this pattern, there is no sub-tropical influence on this category. The composite map shows this 500hPa trough-ridge pattern, in addition to the areas of dryness and moisture (Figure 5.7). There are also mid-range winds aloft at 200hPa, though they are not quite fast enough to be considered a jet. The areas of dryness at 700hPa and 850hPa are similar to the previous category, but with the addition of an area of dryness over the Rockies. The surface moisture tongues are in the same areas as the previous category, but are further away from Arizona. The surface low is still centered over Las Vegas, NV. The high pressure, low level dryness, and fairly slow winds help aid the production of ozone.

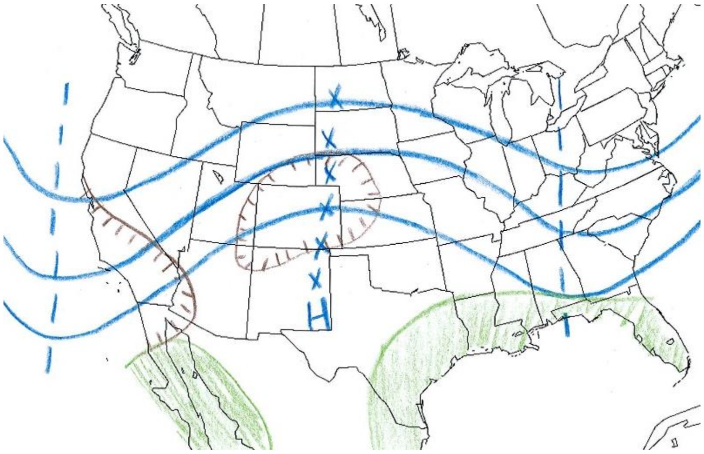


Figure 5.7 Composite map of the "Mexico Influence" (Type 4) category. The 500hPa flow is shown in blue and the 500hPa trough (dashed line) and ridge positions (x-line). The dry region (t_{dd}>20°C) at 700hPa is shown by the brown hatched area, and the area of surface moisture (t_d>50°F) is shown by the green shaded in area.

Table 5.4 The average and standard deviation for wind speed and direction at each pressure level for Type 4 events.

	Wind Speed (kt)		**Wind Direction (degrees)**	
	Avg.	Std. Dev.	Avg.	Std. Dev.
200HPA	34	18	256	67
500HPA	17	9	213	60
700HPA	10	6	225	64
850HPA	7	3	288	80
MONITOR	4	2	205	58

The events in this category were all associated with Hysplit back trajectories originating in Mexico, mainly from the northwestern region. These Hysplit trajectories agree with the upper air pattern over Arizona, since a ridge over Arizona without any sub-tropical influence would allow for winds to flow from the south and not the southeast (Figure 5.8). The upper air winds support this as well, with the winds aloft blowing from the west to southwest to south at 200hPa-500hPa-700hPa respectively (Table 5.4).

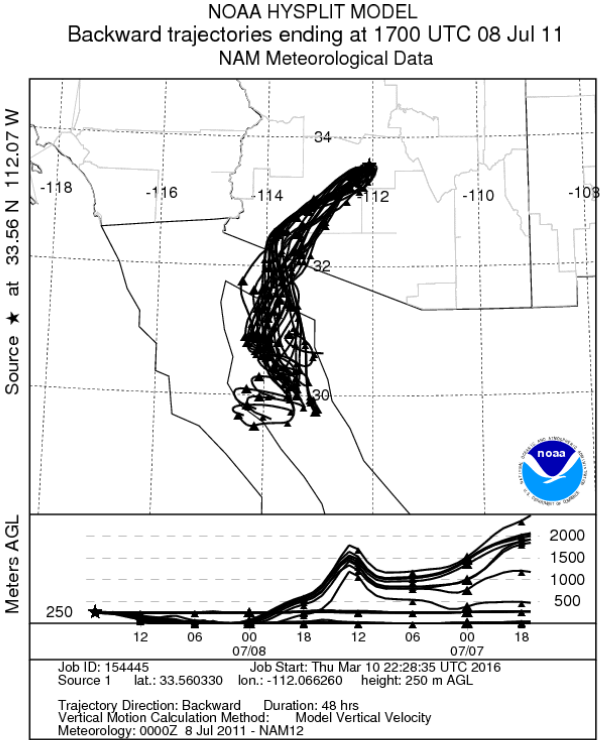


Figure 5.8 Example back trajectory for “Mexico Influence” category.

From the satellite images in the visible spectrum, the same kind of cloud cover as the previous category occurs. There is late afternoon cloud cover on about half of the events, which would still allow for enough sunlight to not prevent the formation of ozone.

This category accounts for the most events, 21 events, or 29% of all events. These events occur throughout the middle of summer, with events from May through September. The average ozone concentration is 78ppb occurring at 11:00 local time.

5.6 “ARIZONA INFLUENCE” CATEGORY

This last category is not entirely a distinct category on its own, but is more of a degradation of category 3 or category 4. The events in this category usually follow events in either Category 3 or 4. This category, that I have termed “Arizona Influence” or Type 5, is associated with a relatively wide and flat 500hPa ridge over the area, or the widening of the ridge in category 3 or 4. The composite map for the category illustrates this wide, flat ridge over Arizona, with almost being zonal (Figure 5.9). There is no 200hPa level jet associated with this category. There is a small dry tongue over Southern California at 700hPa and 850hPa, and the surface moisture tongues are even further to the south. There is also a surface low pressure center over Las Vegas, NV. The breakdown of the ridge, and somewhat stagnant air flow allows for ozone to build up in Arizona.

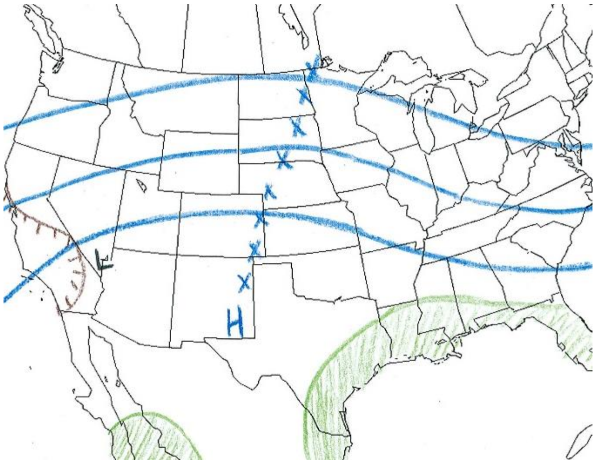
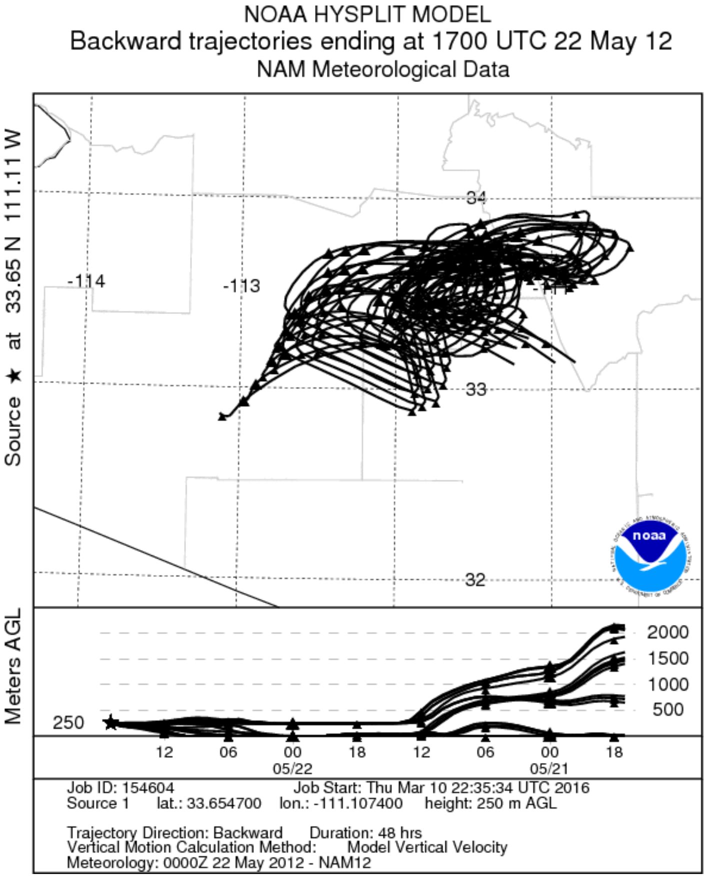


Figure 5.9 Composite map of the “Arizona Influence” category (Type 5) . The 500hPa flow is shown in blue and the 500hPa trough (dashed line) and ridge positions (x-line). The dry region ($t_{dd}>20^{\circ}C$) at 700hPa is shown by the brown hatched area, and the area of surface moisture ($t_{d}>50^{\circ}F$) is shown by the green shaded in area.

The Hysplit back trajectories in this category originate in Arizona, mostly in the Phoenix-metropolitan area (Figure 5.10). These events don’t have a strong 500hPa pattern, and typically follow either a category 3 or category 4 event. Without a strong upper level pattern, the air in the valley lingers, leaving with it the ozone that has yet to scatter, from prior days. This lingering ozone and stagnant conditions allows ozone to build back up, and leads to a transport influence from Arizona. There are fairly low wind speeds at all levels of the atmosphere and from varying directions (Table 5.5).



Job ID: 154604 Job Start: Thu Mar 10 22:35:34 UTC 2016
Source 1 lat.: 33.654700 lon.: -111.107400 height: 250 m AGL

Trajectory Direction: Backward Duration: 48 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 22 May 2012 - NAM12

Figure 5.10 Example back trajectory for “Arizona Influence” category.

Similar to category 3 and 4, satellite images show none or some late afternoon cloud cover over the region, which again is not enough to deter the formation of ozone. There were only seven events in this category, making it only 10% of all of the events. The events in this category occurred at the beginning or end of the ozone season, in either April/May or August/September. The average ozone concentration for this category is 79ppb and on average the exceedances occur at 11:00 local time.

Table 5.5 The average and standard deviation for wind speed and direction at each pressure level for Type 5 events.

	Wind Speed (kt)		**Wind Direction (degrees)**	
	Avg.	Std. Dev.	Avg.	Std. Dev.
200HPA	28	10	240	68
500HPA	11	6	234	59
700HPA	7	4	203	39
850HPA	6	2	135	0
MONITOR	4	2	163	110

5.7 OVERALL RESULTS

There were a few additional high ozone events that did not follow a pattern. These events either had a different pattern of their own or had conflicting data. The events with the pattern of their own were mostly exceedances in Yuma, where Yuma had an influence from somewhere differently than Phoenix. This was mainly due to Yuma being located in a different position of the 500hPa flow, and thus receiving influence from different locations. There were also a couple of events where the upper air pattern did not match the Hysplit, and these events were excluded.

Overall, the majority of the events (94%) agreed with one of the categories detailed above. Figure 5.11 shows the breakdown of the number events in each category.

Ozone season in Arizona is from March to October, and this is the time period monitored each year. From 2011 to 2013 all of the exceedance events in Arizona occurred between April and September, allowing the ozone season of March to October to give some monitoring buffer time. Figure 5.12 shows the number of exceedance events by month during these three years, with the majority of events occurring from May to August. Figure 5.13 shows the number of ozone events by month, labeled by category, showing that certain categories correlate with seasonal atmospheric patterns, such as “Gulf of Mexico” and “Mexico” categories occurring more often in July and August when an upper air ridge sets up. Figure 5.14 shows the distribution of ozone concentration values among the events in each of the five categories. Overall this graph shows that concentrations closer to the 0.076 ppm standard more frequently occur. It also shows that higher concentrations of ozone are more likely to occur during Category 3 or 4 events.

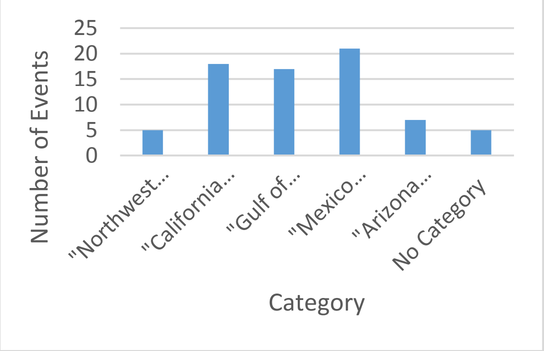


Figure 5.11 Graph of the total number of events in each category.

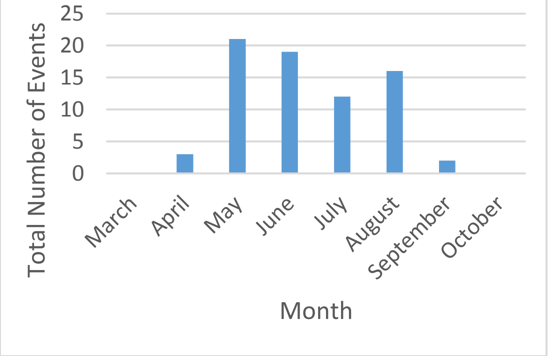


Figure 5.12 Graph of the number of ozone events in each month during the ozone season.

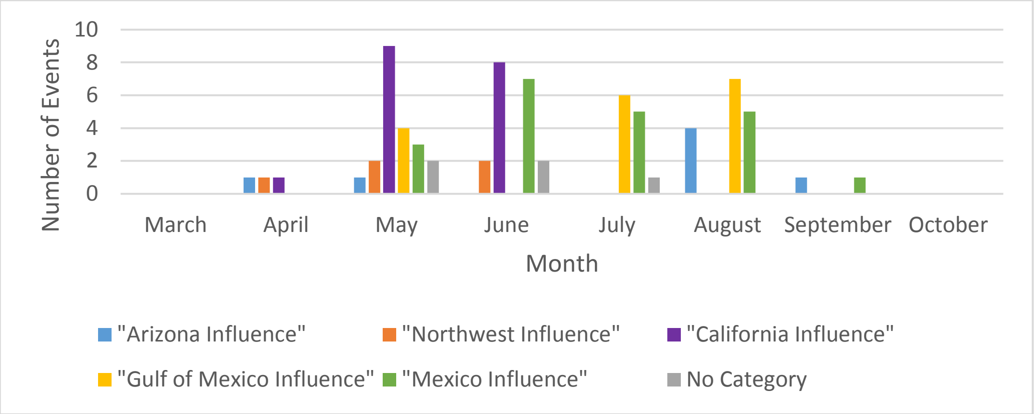


Figure 5.13 Graph of the total number of events in each month and split up by category.

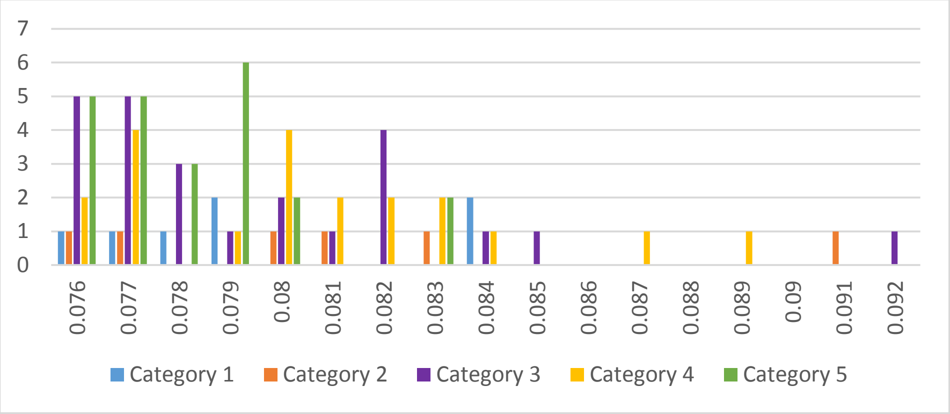


Figure 5.14 Distribution of ozone concentrations among the five categories.

5.8 SUMMARY

Five categories of synoptic conditions were identified in this research in association with high ozone events in Arizona. The categories were identified from the synoptic patterns, meteorological conditions, and Hysplit analyses. The categories included three categories accounting for the majority of the ozone events, and two additional categories that accounted for 17% of the events, with a remaining five events not fitting into any category. The next chapter will review this entire thesis and research project, and discuss the next steps to be taken.

CHAPTER 6

CONCLUSIONS

6.1 RESEARCH DESIGN SUMMARY

One of the six most common air pollutants in the atmosphere is ground level ozone. The Environmental Protection Agency (EPA) establishes and enforces regulations for monitoring and enforcing air quality standards via the Clean Air Act (CAA) (EPA, 2016b). Most counties in Arizona currently meet these permissible levels of ozone, with a couple of areas in two counties exceeding levels marginally. The EPA has issued new standards recently, in October 2015, specifically on ground level ozone. Based on these new regulations and ozone data from 2011-2013, all but two counties in Arizona would exceed the new level of 0.070 ppm (EPA, 2016a). Finding explanations and sources to the ground level ozone in this state is crucial to maintaining our adherence to these regulations.

Consequently, this thesis has categorized high ozone events during the period from 2011 to 2013 in Arizona based on the meteorological conditions and potential transport pathways. This research focusses on tropospheric ozone, which is one of the six main air pollutants regulated by the EPA and which has recently reduced the ozone NAAQS (EPA, 2016b). Ozone is a secondary pollutant in the atmosphere, with its main precursors being emitted though various natural and anthropogenic sources (EPA, 2013). Ozone, and its precursors, have been shown to last in the atmosphere long enough to be transported significant distances, reaching and polluting areas that are far away from the initial sources of emissions (EPA, 2013). This research has helped to identify the patterns associated with high ozone concentrations and transport in the southwest, particularly Arizona.

The data used in this research were comprised of ambient ozone concentration data, surface meteorological data, and upper air synoptic meteorological data. The ambient ozone concentration data, as well as some of the surface meteorological data, were provided by the Arizona Department of Environmental Quality. The upper air analyses, surface analyses, and satellite imagery were received from the National Oceanic and Atmospheric Administration and their various sub-organizations (CSU, 2016 and NCEI, 2016a). These data were then analyzed using several methods to determine the overall meteorological patterns associated with high ozone events.

The methods utilized in this research were drawn from several studies analyzed previously in the literature review (Maddox, 1980, Kalkstein, 1996, and Kahana, 2002). The first step in analyzing the data was to compile the ozone concentration data from all of the ozone monitors in the state and to organize and synthesize this data. Then a synoptic meteorological analysis was performed on all of the ozone events, analyzing the 200hPa, 500hPa, 700hPa, 850hPa, and surface levels of the atmosphere. In addition to the synoptic analysis, several other factors were looked at including surface meteorological data, cloud cover, and vorticity. Then in order to represent the potential transport pathway into Arizona of ozone, the HYSPLIT model was utilized to run back trajectory analyses for the ozone events. Finally, the events were categorized based of the results of the three previous methods.

6.2 SUMMARY OF RESULTS

Overall five categories associated with ozone exceedances in Phoenix were determined, with distinct patterns, to be associated with high ozone events in Arizona during the period analyzed. The categories that were identified all possessed distinct upper air patterns and were associated with a potential transport pathway (Table 6.1).

Table 6.1 Summary Table of Five Ozone Exceedance Categories

Type	**Name**	**Ave. Ozone (ppb)**	**Number of Events**	**Daily Timing**	**Seasonal Timing**	**Description**
1	Northwest Influence	81	7% (5/73)	12 LST	April-June	Threat to Lee of Ridge
2	California Influence	79	25% (18/73)	12 LST	May-June	Threat in Bottom of Trough
3	Gulf of Mexico Influence	80	23% (17/73)	11 LST	July-August	Threat in Monsoonal Subtropical Ridge; no jet
4	Mexico Influence	78	29% (21/73)	11 LST	May-September	Monsoonal Ridge with 2 distinct troughs
5	Arizona Influence	79	10% (7/73)	11 LST	April/May & August/September	Very Broad Ridge

One of the categories identified was the “Northwestern Influence” category that is associated with the front downslope of a ridge. Arizona is located between a trough and ridge, allowing for potential ozone transport form the northwest, Utah, Nevada, and northern California. This category is also associated with dry air aloft and northwest winds throughout the atmosphere, and accounts for 7% of the events, occurring in the early summer.

The “California Influence” category accounts for 25% of the ozone events during the time period analyzed. This category is associated with a deep, wide upper air trough with Arizona positioned at the bottom of the trough. This category is also associated with a 200hPa jet, dry air aloft, westerly winds throughout the atmosphere, and a surface front.

The potential transport pathway for this category is from southern California, and these events typically occur in May and June.

The next category identified was the “Gulf of Mexico” category that is associated with a monsoonal subtropical ridge. During these events there is an upper air dry tongue over the area, along with surface moisture and a Four Corners high pressure center. This category coincides with a transport pathway from the New Mexico, Texas, and eastern Mexico region. The “Gulf of Mexico” category accounts for 23% of the ozone exceedance events, which mostly occur in July and August.

The “Mexico Influence” category was also identified, and is linked to an upper air trough/ridge pattern, where there is a ridge located over Arizona with a trough positioned close by to the east and to the west. This category exhibits a dry tongue aloft and south to southwest winds throughout the atmosphere. This category comprises 29% of the events analyzed, and they occur throughout the ozone season.

The final category identified is associated with the breakdown of the ridge patterns associated with category 3 and 4. This category coincides with Arizona or local transport pathways, and is called the “Arizona Influence” category. This category exhibits a wide zonal 500hPa ridges, with slow, varying winds aloft. This category accounts for 10% of the events, and typically follows a category 3 or 4 event.

There were some additional events (6%) that did not fit into one of these five categories. The majority of these ozone exceedances occurred in Yuma and had influence from an area that did not match the upper air pattern, typically because Yuma was located below the main 500hPa flow.

Further analysis of the categories led to average conditions being identified, as well as patterns in the timing of their occurrences. This categorical analysis of high ozone events will be very beneficial to the understanding of ozone exceedances in the southwest, as well as inform the policies and procedures required by the clean air act, such as forecasting for ozone.

6.3 IMPLICATIONS AND SUGGESTIONS FOR FUTURE RESEARCH

This research will help further the understanding of interstate transport of ozone, particularly in the West, where there is a lack of previous research and different dynamics and politics at play. The western half of the country lacks the political cooperation that the east has, such as with the use of Cross-State Air Pollution Rule (CSAPR) that only includes eastern states (EPA, 2015b). There is a lack of cooperation among the western states in providing data and research on surface ozone movement, but progress is being made with the WESTAR (Western States Air Resources Council) group in trying to improve communication and cooperation, and hopefully this research will be the start to many some interstate projects in the region (EPA, 2015b). More knowledge and studies need to be done in the West to help improve our understanding of surface ozone movement, which can be implemented in improving air quality and policies in the region.

This research is crucial not only to the understanding of surface ozone movement and air quality, but is also useful in forecasting ozone for local agencies. Air quality impacts several factors of life, from human health impacts, to environmental impacts, to political and economic impacts. Being able to better forecast high ozone events will allow for public warning for health risks, as well as being able to prevent additional emissions being contributed to the area.

Long-range transport of surface ozone is an important research topic because of its importance in the field and relating to EPA regulations. The downwind transport of ozone and its precursor emissions can have huge impacts on areas that have no control over emitting these pollutants. This issue can span from localized downwind transport to the global transport of pollutants. This creates a huge issue that leaves very little local ability to regulate.

The transport of ozone and the regulatory impacts it poses opens up a vast array of future research needs and recommendations. There are many studies currently being done, focusing on the use of chemical modeling to analyze the amount of contribution certain sources and locations have to downwind areas, with a notable example being the research conducted by Li et al. (2015). Chemical modeling would be a great expansion on this research, modeling the percent of contribution from the identified transport pathways, but was beyond the scope of this research and my knowledge. My recommendation for future expansion on the research discussed in this thesis would be to first consider more years and to include events that are between the 2008 NAAQS (the standard used for this research) and the updated 2015 NAAQS. In addition, the use of HYSPLIT modeling to model density maps of trajectory source locations or a cluster analysis of back trajectories would further the analysis performed in this thesis. Beyond the scope of this research, further analysis into the impacts of El Nino and La Nina variations on summer ozone concentrations could be immensely helpful in the Southwest

United States, particularly Arizona, who has a significant ozone issue, as well as sees significant impacts from El Nino/La Nina cycles.

Ozone is a dangerous pollutant for any living thing to breathe in, including plant life, and is particularly dangerous for people with respiratory diseases. High levels of ozone are dangerous to human health, can damage plants and crops, and create poor visibility especially in urban environments, all of which lead to political and economic complications. This research, and additional research in the field of air quality, will help further our understanding and provide solutions for how to reduce ozone and pollution, improve the environment, reduce human health aggravators, and improve the efficiency of politics and economics.

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