The Relationship between Rotational Wind Patterns and Ozone Exceedances in Houston, Texas

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ABSTRACT

Elizabeth Edith Christoph: Relationship between Rotational Wind Patterns and Ozone Exceedances in Houston, Texas
(Under the direction of William Vizuete)

The Houston-Galveston-Beaumont (HGB) area in southeast Texas has been designated as a non-attainment area for 0.08 ppm 8-hour ozone by the EPA. High ozone episodes in Houston have previously been related to circular wind patterns accompanying land-sea breezes. The direction the wind blew from during the day was divided into quadrants, and the number of quadrants the wind blew from was summed daily. The number of quadrants the wind blew from was highly correlated with ozone exceedances. This study found that 95% of all ozone exceedances occur on 3-quadrant or 4-quadrant days, but on 90% of 3-quadrant and 4-quadrant days, there were no ozone exceedances. The average wind speed and temperature of a day vary with the quadrant class of the day, but not significantly enough to dominate ozone production. This method is helpful in predicting high ozone, and selecting days for attainment demonstrations.

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INTRODUCTION

To protect human health, the US Environmental Protection Agency (EPA) created National Ambient Air Quality Standards (NAAQS). The NAAQS set the permissible outdoor air concentrations of 6 criteria pollutants: Ozone, Lead, Particulate Matter, Carbon monoxide, Sulfur dioxide, and Nitrogen oxides. The EPA is required to review the ozone NAAQS every five years, which has resulted in several changes to the ozone NAAQS. The first NAAQS ozone standard was set at an average of 0.12 parts per million (ppm) over one hour. In 2005, the EPA revoked the 1-hour ozone standard for most of the country and replaced it with an 8-hour ozone standard set at 0.08 ppm. In 2008, the EPA set a new 8-hour ozone standard at 0.075 ppm (US EPA, 2009). If a region does not meet the NAAQS, it must submit its plans for attainment to the EPA in a document named the State Implementation Plan (SIP). Since ozone is not directly emitted, SIPs target the emissions of ozone precursors: Nitrogen oxides (NOx) and Volatile Organic Compounds (VOCs). The production of ozone, however, is more complicated than a simple combination of these precursors. In reality, it is dependent on a complex interaction of non-linear chemical and meteorological processes. A reduction of calculated quantities of these precursors does not necessarily produce a similar reduction in ozone. Due to this complexity, air quality managers rely on air quality models (AQMs), to evaluate the effectiveness of emissions reduction strategies outlined in the SIP.

The Houston-Galveston-Beaumont (HGB) area in southeast Texas has been designated as a non-attainment area for 0.08 ppm 8-hour ozone by the EPA. The Texas

Commission on Environmental Quality (TCEQ) is creating a SIP to show attainment of this standard by the year 2018. One challenge facing the TCEQ regarding attainment in the region is the air quality found in Houston. In 2007 the American Lung Association designated the Houston-Baytown-Huntsville metropolitan statistical area as the fifth most ozone-polluted in the nation. (American Lung Association, 2007). Major sources in Houston include oil and petrochemical industries and a significant mobile emission sector. Houston is the unrivaled center of the United States oil industry, and is arguably the energy capital of the world. All aspects of the oil industry – exploration, production, transmission, marketing, service, supply, offshore drilling, and technology are done in Houston. The port of Houston is the tenth largest in the world in total tonnage, and the largest in the United States in international waterborne tonnage. (City of Houston, 2009). According to the Greater Houston Partnership, Houston and the surrounding area has a crude operable capacity of 4.081 million barrels of refined petroleum products per day. This is 85.9% of the Texas total and 23.2% of the U.S. total. (City of Houston Partnership, 2008). Oil refineries emit VOCs, and some of the USA's largest refineries are in Houston. In addition to this, Houston meteorology provides conditions ideal for high ozone concentrations.

Geographic, socioeconomic, and meteorological factors have combined in Houston to produce high ozone concentrations for decades. Because of this long history, considerable resources have been used to study the ozone problem which has resulted in a rich set of observation and modeling data spanning more than ten years. Today, Houston has a network of more than 80 ground level monitors that collect meteorological data and measure concentrations of relevant air pollutants. (TCEQ, 2009). In the summers of 2000 and 2006 Houston was also the focus of two multi-million dollar intensive field campaigns that included state-of-the-art measurement techniques providing a supplemental observational data set. (TCEQ, 2009). These data present a unique opportunity to investigate and understand the conditions that produce the highest ozone violations in Houston. This understanding is essential to the development of an effective SIP. This investigation focused on one influential factor on ozone formation, meteorology.

The relationship of meteorology in Houston to high ozone concentrations has been the focus of several studies. The most common type of study classified days into clusters based on observed meteorological phenomenon. Most studies clustered days on by factors like average daily wind speed, looked at the ozone concentrations in each cluster of days, and examined factors that differed between days, particularly that could be the cause of variation in ozone measurements. Davis et al. (1998) performed single and two-stage clustering techniques - based on two variables, to identify more clearly the meteorological factors that influence ozone production. They concluded that wind speed and direction were most important, and that temperature and solar radiation had significant impacts as well, especially considering meteorological regimes in Houston dominated by anticyclones. Davis and Speckman (1999), determined that the interaction between wind directions, cloud cover, previous day's maximum temperature and morning mixing depth were also important to statistically predicting ozone concentrations using regression. These studies were unable to consistently accurately predict more than around 50% of the variation in ozone concentrations. Their regressions were aided by the fact that they predicted ozone concentrations within clusters, not just daily concentrations, yielding better results than if they had simply tried to predict daily concentrations. Jammalamadaka and Lund (2006) used circular correction and circular regression techniques to describe the ozone concentrations in Houston based on the wind patterns, but were able to explain even less – at most thirty percent of the variation in the ozone concentrations.

Meteorologist John Neilsen-Gammon posited a conceptual model for high ozone development based on the land-sea interaction that is unique to Houston's location (Banta et al., 2005). Since the specific heat of water is higher than land, land both heats and cools faster than water. In the absence of a low pressure system, this results in mornings with relatively calm winds; the breeze blows toward the southeast, out to the ocean where it is warmer. Later in the day, once the land has heated up, the wind reverses direction and starts blowing back toward the land. Because Houston is located in the northern hemisphere, the Coriolis force causes the wind to rotate in a clockwise direction (Banta et al. 2005). This combines with the breeze created by resonance between the inertial and diurnal periods of the earth. The half pendulum day, P, is the inertial period of the earth, as shown below.

$$P = 2\pi \, | f |^{-1} \tag{1}$$

The variable f is the Coriolis parameter, where

$$f = 2\,\omega \sin \varphi \tag{2}$$

where ω is the earth's rotation rate and φ is the latitude. The inertial period of the earth is equal to the diurnal period of the earth's solar heating and cooling cycle (24 hours) at 30° latitude (Holton, 1992). Houston is around 30° and the inertial period and the diurnal periods of the earth are equal, so the breeze is a combination of the thermal land-sea breeze and the breeze of the Coriolis force (large scale gradient wind influenced by the inertial/diurnal periods). When the winds are in the same direction, the strength of the wind is double what just one breeze would cause by itself. Because this breeze combination is so strong, it has a particular role in transporting ozone and the precursors of it when a large-scale flow is not present. (Banta et al. 2005). This rotational wind pattern blows ozone precursors out over the ocean in the morning, over the VOC-rich ship channel area and back into the NOx-rich ozone- producing system over the city in the afternoon. When these emissions mix, there is tremendous potential for ozone creation. Some factors that may reduce the likelihood of ozone formation are high wind speed, dense cloud cover, and precipitation.

In addition to the land-sea breeze and interaction with the cycles of the earth, Neilsen-Gammon calculated that if there were no background wind, the air would rotate in a circular pattern because of the Coriolis force and breezes described above, and shown in Figure 1. For background wind speeds greater than zero, the wind would rotate in a loop and then spin off, with the size of the loop dependent on the speed of the wind. From

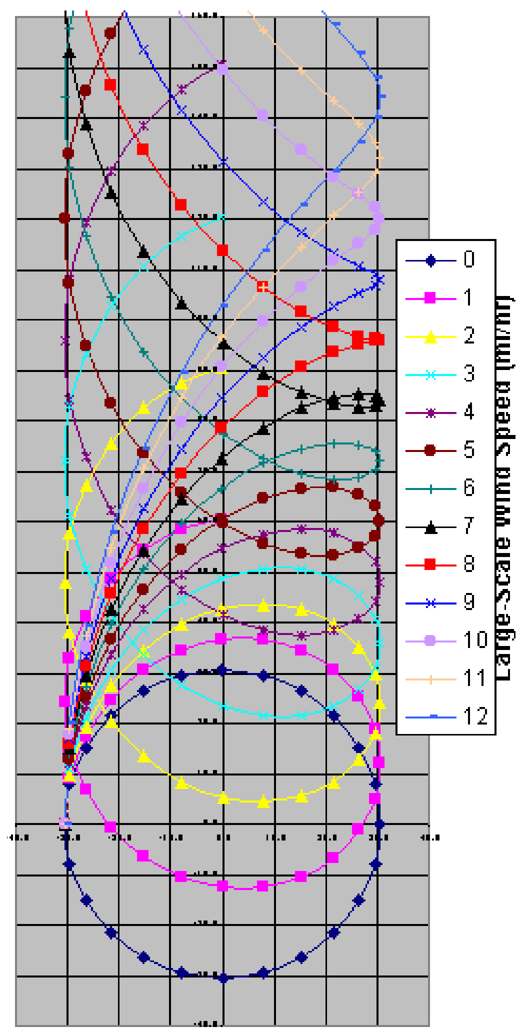


Figure 1. Wind trajectories based on speeds for a monitor in Houston, Texas during a calm day developed by John Nielsen-Gammon (2009).

around 8 kilometers per hours (kph) to 12 kph, the loop is compact enough that the air stays in the same area, and when the flow changes directions, somewhat stagnates. This brief period of stagnation prevents further dilution of ozone and its precursors, and encourages the production of more ozone, potentially leading to high ozone values. Darby (2005) incorporated Neilsen-Gammon's findings into a new cluster analysis of the wind patterns and ozone concentrations in Houston. Darby found that clusters with a least 1 hour of stagnant winds in between a transition from offshore flow to onshore flow usually occurred on days that exceeded the 1-hour ozone standard, supporting Neilsen-Gammon's conceptual model. On other days with high ozone, the peak usually occurred the hour after the wind direction changed by at least 45°.

Charlie Blanchard (2002) conducted further investigation of Neilsen-Gammon's hypothesized rotational wind fields in days with observed high ozone concentrations. Dr. Blanchard tested this hypothesis by using number quadrants as a proxy for rotational wind patterns. He categorized the wind patterns on approximately 20,000 site-days across a three-year time period, and observed the number of ozone exceedances in each category. He found that ozone concentrations only exceeded the 1-hour ozone standard on days when the wind came from more than one quadrant. This study did use 20 monitors, but over only a three-year time period 10 years ago. Since Blanchard's study, the EPA enacted new standards and has also significantly altered its methodology to show attainment. For these reasons, and others, it was important to update Blanchard's valuable analysis and include recent data.

The purpose of this study is to understand the fundamental relationships between meteorology and high ozone events, particularly in a regulatory context. The first part of this study focuses on 1-hour ozone data across a nine year time period at six monitors and investigates correlations with wind speed, direction, and temperature. The second phase of the analysis examines wind patterns and temperature and their correlation with exceedances of the 8-hour standard. Beyond just observing relationships between ozone and wind patterns, this analysis also quantifies the statistical significance of these trends. The final study component analyzes the observational data used by the TCEQ for its current HGB SIP. In the end, this study also examines whether the observational data set used in the attainment demonstration is representative of the meteorological trends observed in our study.

METHODS

The dataset used in this analysis consisted of hourly resultant (average in degrees) wind direction, hourly resultant wind speed, 1-hour daily ozone concentration maximums, and 8-hour daily ozone concentration maximums at six monitors. All data obtained for this analysis can be found at the Hourly Air Pollution and Daily Maximum 8-hour Ozone Averages sections of the Texas Commission on Environmental Quality (TCEQ) website (2009). The monitors analyzed were Bayland Park, Deer Park, Wallisville Road, Clinton, Aldine, and North West Harris County as shown in **Figure 2**. Monitor names and labels are in

Table 1.

Figure 2. Six monitors included in the analysis in the Houston, Texas area.

Table 1. Monitors and labels included in this analysis corresponding to the monitors on the map in Figure 2.

Monitor	Label
Northwest Harris County	HNWA
Bayland Park	BAYP
Aldine	HALC
Clinton	C35C
Deer Park	DRPK
Wallisville	WALV

The monitors BAYP, DRPK and WALV were chosen because they represent unique challenges to SIP modeling for showing ozone attainment. The TCEQ has reported that for these monitors to attain the standard, a 28% reduction in NOx (approximately 100 tons per day) is necessary. Reported emissions of NOx in 2007 from industrial point sources in HGB were only about 150 tons per day (tpd), so a reduction of 100 tpd would be the majority of total NOx emissions from these sources (Hendler). This is important because the state government cannot regulate NOx from mobile emissions; therefore, industrial point sources are the largest sources of NOx the state of Texas can regulate. Three additional monitors, C35C, HALC, and HNWA, were added to more fully represent the entire Houston geographic area, and because they showed a large number of complete measurements. Additionally, the HNWA monitor has shown Transient High Ozone Events (THOEs) violations, and is frequently impacted by emissions traveling from the city center.

1-Hour and 8-Hour Ozone Data

All monitors include data from January 1, 2000, to December 31, 2008, except the WALV Road site, where monitoring began June 6, 2003. Due to the potential for rotational winds, it is important to have all the wind directions for an entire day to avoid misclassifying a day because of missing values. Each calendar day had the potential to be six site-days in the dataset – one site-day from each monitor. Days were also required to have ozone measurements from 8:00 a.m. to 6:00 p.m. LST to be included in the 1-hour dataset. If other ozone measurements outside of that time window were unavailable, the day was still used because peak ozone necessarily occurs during daylight hours. Each day had to have a valid daily maximum 8-hour ozone value, as determined by the TCEQ, to be included in the 8-hour dataset.

This analysis covered all days that fit the completeness criteria, a total of 16,179 site-days out of a possible 18,471 site-days; 88% of the total possible site-days during the time period examined fit the completeness criteria described in the paragraph above for

1-hour ozone. For 8-hour ozone, there were 17,053 site-days included in the analysis, or 92% of the total possible. A day was determined to be in violation of the 1-hour ozone standard if the maximum 1-hour average ozone value of the day was greater than or equal to 125 parts per billion (ppb). A day violated the 8-hour standard if the maximum 8-hour average ozone value was greater than 85 ppb. From 2000-2008 there were 169 1-hour ozone exceedances, and 428 8-hour ozone exceedances across the six monitors. The contributions of each site to the datasets are summarized in Table 2Table 2.

Table 2. Summary of available data at each of the six monitoring sites. The total number of days is the sum of the number of days that exceeded the 1-hour (125 ppb) and 8-hour (85 ppb) NAAQS ozone standard for each site.

	1- Hour Dataset			8-Hour Dataset		
Monitor	**Days Total**	**No Exceedance**	**Exceedance**	**Days**	**No Exceedance**	**Exceedance**
DRPK	3,049	3,008	41	3,087	3,001	86
BAYP	3,020	2,984	36	3,076	2,975	101
WALV	973	951	22	1,840	1,793	47
HALC	2,886	2,855	31	2,957	2,874	83
C35C	2,547	2,527	20	3,057	3,012	45
HNWA	2,987	2,968	19	3,036	2,970	66
Total	**16,179**	**16,010**	**169**	**17,053**	**16,625**	**428**

A potential concern with using site-days, instead of simply days, is that each day accounts for 6 observations in the dataset, instead of just one. For example, a single calendar day often had complete ozone and wind measurement at all six monitors. This means that the meteorological and ozone conditions that day are more influential on the results than days where only 5 of the monitors (or less) had complete data. This could potentially cause the meteorology of several high ozone days to dominate the "characteristic ozone producing meteorology," but this was likely not the case in this study. Table 3 shows that in the 1-hour dataset only 35 days out of the 169 total exceedance days (~20%) exceeded the standard at multiple sites. Approximately 50% of the 1-hour exceedance days included in this study had only one monitor exceeding. None of the days had all six monitors exceeding the standard. For the 8-hour dataset, only ~25% of the days showed exceedances at multiple sites; however, only ~30% of the exceedance days were single monitor exceedances. This means that on the majority of ozone exceedance days the ozone concentrations and the meteorology experienced at that monitor are unique.

Table 3. Frequency of the six monitors exceeding the 1-hour and 8-hour ozone standards per day, as well as the total percentage of exceedance days that exceeded the standard at multiple monitors.

1- Hour Dataset			**8-Hour Dataset**		
Number of Monitors Exceeding Standard	**Frequency**	**Percentage of Total Exceedance Days**	**Number of Monitors Exceeding Standard**	**Frequency**	**Percentage of Total Exceedance Days**
1	86	50.89	1	125	29.21
2	26	30.77	2	59	27.57
3	6	10.65	3	29	20.33
4	2	4.73	4	14	13.08
5	1	2.96	5	6	7.01
6	0	0.00	6	2	2.80
Total Days with Multiple Exceedances		**35**	**Total Days with Multiple Exceedances**		**110**

Attainment Demonstration Data

Our investigation also focused on whether this observed meteorological phenomena is present in the observational data used for the HGB SIP. This analysis focused on observed ozone concentrations used to calculate the ozone design value (DV). According to the EPA guidance, “the 8-hour ozone design value is calculated as the 3 year average of the fourth highest monitored daily 8-hour maximum value at each monitoring site” (US EPA, 2007). Three design values are used calculate a baseline design value (DV_B). The DV_B is used along with a relative reduction factor (RRF) based on modeling data to determine if a given monitor is in attainment of the standard for the future. The RRF is the ratio of the episode average predicted future peak 8-hr daily maximum ozone near the given monitor to the episode average predicted peak 8-hr daily maximum ozone near the same monitor. Methods for determining if a monitor is in attainment can be found in the EPA guidance document. The goal of this analysis was to see if the meteorological trends we observed across 9 years of data are represented in the design values. If not, then the attainment demonstration includes meteorological phenomena that may not be representative of the worst ozone conditions in Houston. As described earlier, three monitors BAYP, DRPK, and WALV had showed non-attainment (Karp, 2008).

At each monitor, the first, second, third, and fourth highest maximum daily 8-hour ozone averages were determined. Over a nine-year period and across six monitors, there were a total of 204 days. There were 4 days per monitor per year except for at WALV, which only had seven years of data. From this data set three days had incomplete wind data, but could be classified as 4-quadrant days and were included in the dataset; six days were excluded due to incomplete wind direction data. With these exclusions, the final dataset, referred to as Top 4, was 198 days; the first, second, third, and fourth-highest daily 8-hour ozone concentrations at each of the six monitors for the years 2000-2008; WALV had data from 2003-2008. A separate dataset, the design values dataset considered only the days that determine the attainment status of these monitors, the fourth-highest average (DV) days each year.

Meteorological Classification

The average direction of the wind measurements for each hour was categorized and the number of quadrants in which the hourly wind vectors fell was determined. Figure 3 shows the way the quadrants were broken up. At each site, the monitor was considered to be the origin. If a day contained winds coming from only 1 quadrant, the day was classified as a 1-quadrant day. If the wind came from 2 quadrants, it was a 2-quadrant day, etc. The particular quadrant from which the wind blew was not studied, only the number of different quadrants from which the wind blew throughout the day. Site-days were not included if any of the twenty-four hourly wind direction measurements were unavailable. For example, using Figure 3, if the wind blew from quadrants I, II, and III, it was a 3-quadrant day. If it blew from I, II, and IV it was also a 3-quadrant day. The sequence and location of various wind directions were not considered, just the total number of quadrants per day. Figure 4a-d show example of what the wind rose for a 1, 2,3, and 4-quadrant day (wind from quadrants I, II, III, and IV in Figure 3) could look like. Days when the wind came from 3 or 4 quadrants (Figure 4c and d) in Houston have varying degrees of rotational winds. The quadrant classification is done separately for each monitor on each day, and used in analysis with that site-day ozone. The monitors often experienced winds similar monitors near them, but there were many days when individual monitors experienced different wind patterns than others around Houston.

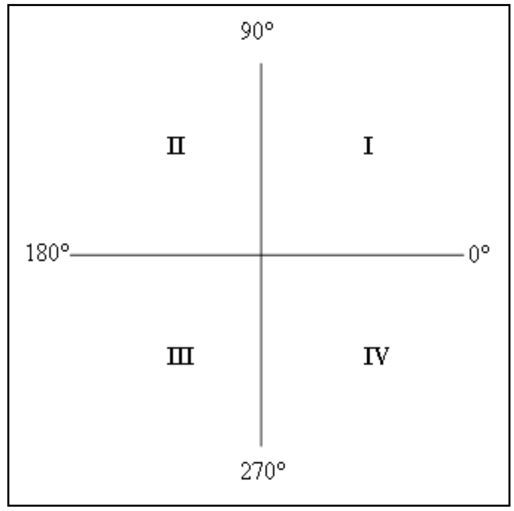


Figure 3. Quadrant breakdown at each monitor. The monitor is at the origin.

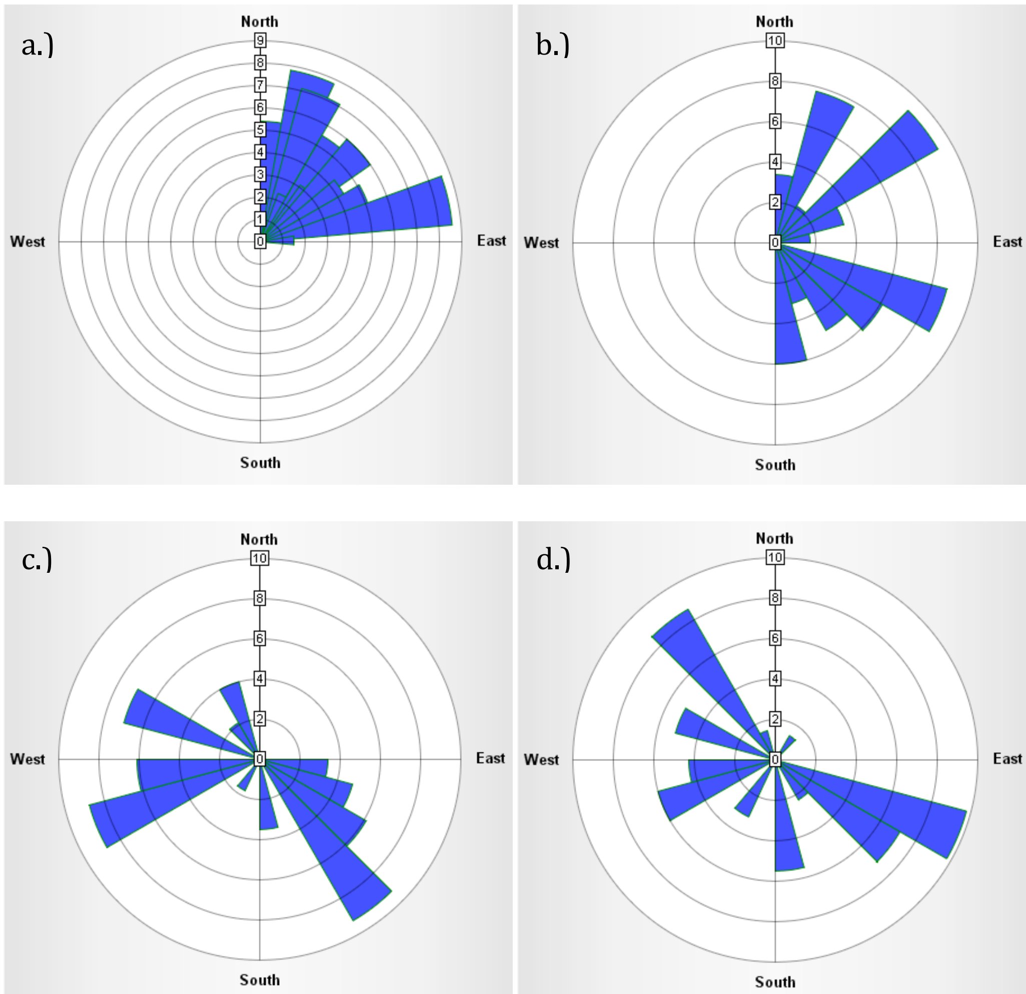


Figure 4a-d. Figure a is an example of a 1-quadrant day with wind from the northeast all day. Figure b is a 2-quadrant day with winds from the northeast to southeast all day. Figure c is a 3-quadrant day, and figure d is a 4-quadrant day. The width of the bar is representative of the frequency of observations that fall into each petal. The length of the petal is related to the wind speed of the observations, although this data is only an example, and was not taken from the Houston dataset.

After each day had been classified according to wind direction and maximum ozone values, statistical analysis revealed patterns in this dataset. Statistical analysis of this dataset included a 1-way Analysis Of Variance (ANOVA). The ANOVA procedure compares the means of the quadrant classes (proportions of each quadrant that are exceedances) with the variance of each quadrant class, which yields an F-value. A high F-value signifies that the variance in the means is unexpected considering the degree of variance within each quadrant, and the variance in the means is significantly different. Once the F-value has been determined, based on the size of the dataset and number of groups (in this case there are four quadrants), and the statistical F-distribution, a p-value is calculated. The p-value is the probability of obtaining an F-value as large as was determined, if there are no significant differences between the proportions of exceedance days in each quadrant class.

RESULTS

1-Hour Ozone Dataset

The first part of these results will focus on 1-hour data for 6 monitors from 2000-2008. Preliminary analyses of the observational data set reveal that ozone exceedances are influenced by season. Ozone exceedances occur more frequently during the spring and summer months, as shown in Figure 5. This figure shows the distributions of 1-hour ozone violations by month. There was only one exceedance in January, February, and December during the 2000-2008 time period. These results show that nearly all of the ozone violations occurred March through November. In addition, ~70% of the 1-hour standard exceedances were in June through September.

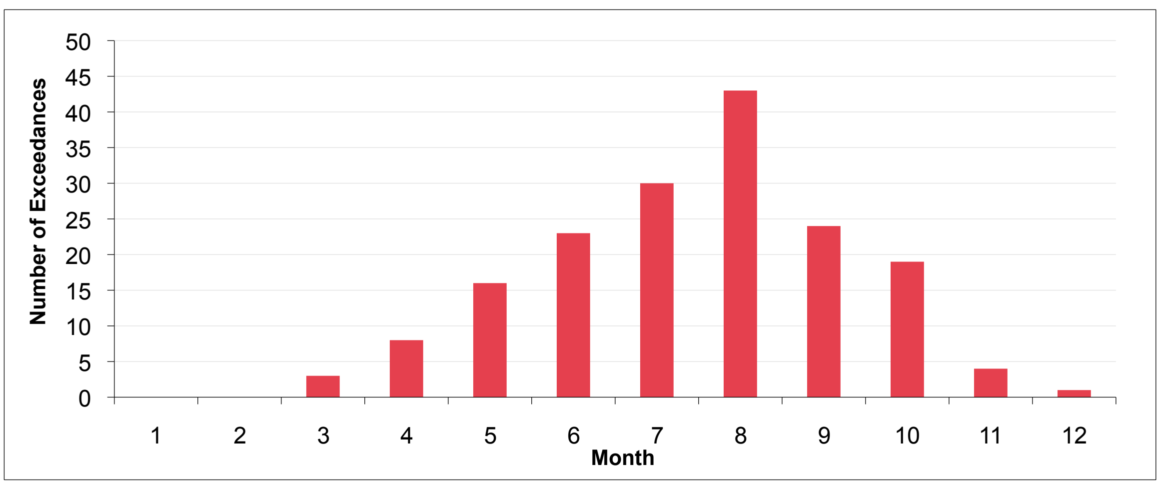


Figure 5. 1-Hour Ozone Violations at 6 surface monitors by month. The time period covered is January 1, 2000 to December 31, 2008.

The distribution shown in Figure 5 suggests an analysis of 3 time periods: January 1, 2000-December 31, 2008; March-November, 2000-2008; and June-September, 2000-2008. Breaking the data up this way allowed a focus on the meteorology of Houston year-round, the times when the majority of ozone exceedances occur, and on the peak ozone season. Using these time periods we then aggregated measurement data from all six sites into a single dataset. This facilitated a picture of ozone behavior across several monitors, and a direct comparison with Blanchard's results.

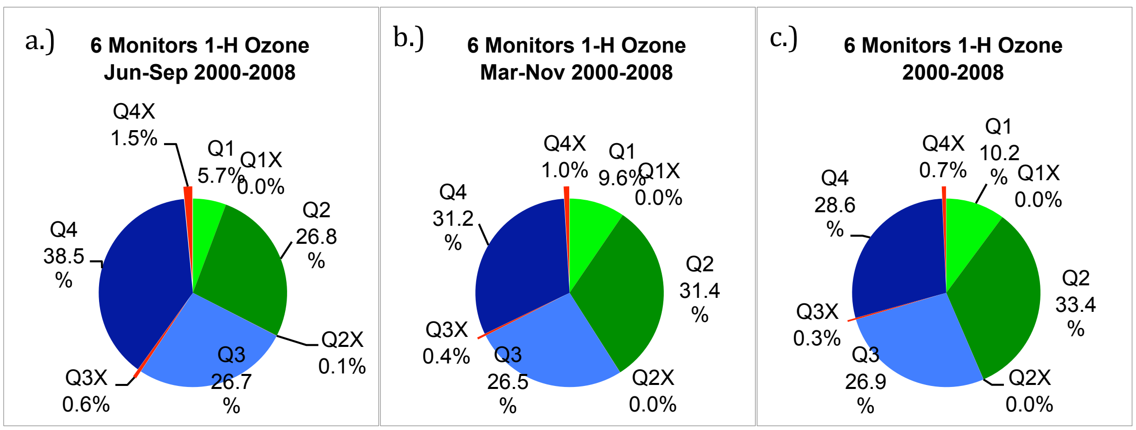


Figure 6a-c. 1-H Ozone exceedances by quadrant across all 6 monitors. The three time periods are June-September 2000-2008, March – November 2000-2008 and January – December 2000-2008. The "X" on the end of the quadrant number denotes exceeding days. For example, Q4 are 4-quadrant non-exceeding days, and Q4X are 4-quadrant days that exceeded the 1-hour standard.

Figure 6a-c show 1-hour ozone violations by quadrant class and a trend is evident. Regardless of the time period considered, there are never any 1-quadrant exceedance days. Table 4 shows that there were only five 2-quadrant exceedance days in nine years. Similarly to what Blanchard found, the majority of exceedances were on 4-quadrant days, and a smaller, but significant portion were on 3-quadrant days. The three different time periods reveal different things about the data. They show how the proportions of exceedance days vary throughout the year, and allow focused analysis on the time period with the most exceedances (June through September). In Figure 6a, exceedances made up a greater percentage of the total days considered than in Figure 6c.

Table 4. Summary data of 1-hour exceedances at the 6 monitors studied from January 2000-December 2008.

Quadrant Class	Days per quadrant	Percentage of total days	Exceedance days	Percentage of exceedance days
1	1,640	10.2%	0	0.0%
2	5,385	33.4%	5	2.9%
3	4,389	27.2%	49	28.5%
4	4,726	29.3%	118	68.6%
Total	16,140	100%	172	100%

The dataset was then classified by monitor, and the same calculations were made. Figure 7a-c shows the 1-hour ozone exceedances by quadrant, as well as the percentage of days in each quadrant without ozone exceedances. The data are from the BAYP site, but are representative of all six monitors, which had similar results. The distribution of exceedance days is very similar to the distribution of all six monitors in Figure 6. In general, about 5-10% of the days are 1-quadrant (with no exceedances), about 30-35% are 2-quadrant (with no exceedances), about 25% are 3-quadrant days (with about a fourth of the total exceedances), and 30-40% are 4-quadrant days (with about three quarters of the total exceedances). This was true for not just the BAYP monitor, but all six monitoring sites (shown in Figure 6 and Appendix A).

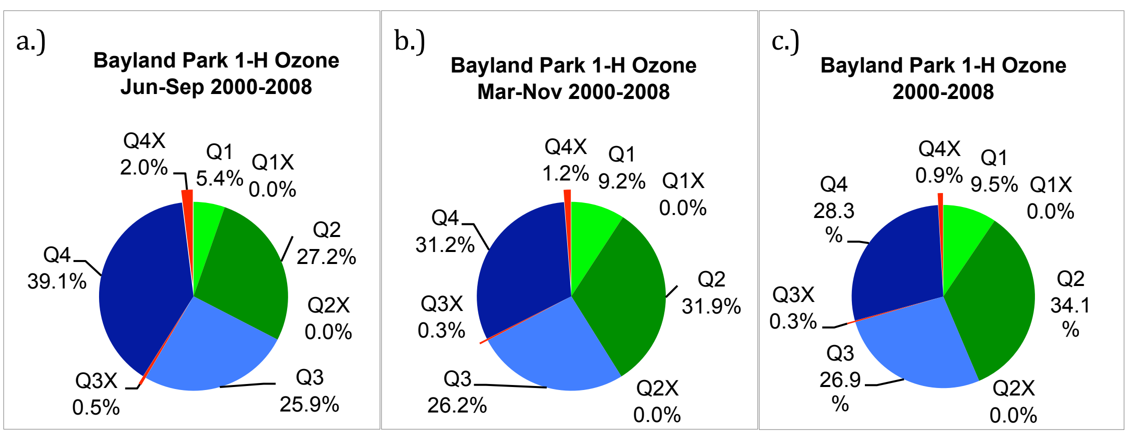


Figure 7a-c. 1-H Ozone exceedances by quadrant at BAYP. Figure 7a covers only June – September. Figure 7b spans March – November, and Figure 7c spans January 1, 2000 to December 31, 2008. The "X" on the end of the quadrant number denotes exceeding days. For example, Q4 are 4-quadrant non-exceeding days, and Q4X are 4-quadrant days that exceeded the 1-hour standard. In Figure 7a, 39.1% of the total numbers of days from June to September were 4-quadrant days. In addition to this, 2.0% of the days were 4-quadrant days that also exceeded the 1-H ozone standard.

If wind quadrant class is not correlated with high ozone, the percentage of ozone exceedances in each quadrant class should simply be proportional to the size of the quadrant class. For example, a quadrant class containing 50% of the days should contain 50% of the ozone exceedances also. There seems to be a disproportionate number of 1-hour ozone exceedances in the 3 and 4-quadrant classes, and virtually none in the 1 and 2-quadrant classes. To make conclusions about this data however, it is important to consider the total number of days in each quadrant class. In June through September only 5.4% of the days were 1-quadrant. This percentage rises to 9.5% when the whole time period is considered. When the whole time period is considered, there is about a 10% increase in the proportion of 4-quadrant days. These trends mean that 1-quadrant days occur more frequently in January, February, and December than in June through September. Also, 4-quadrant days occur more often in the summer months, when temperatures are higher.

Table 5 displays the number and percentage of days that fall into each quadrant class, as well as the number and percentage of exceedance days in each quadrant class. From this table it is clear that the number of exceedance days in each quadrant class is not proportional to the total number of days in that quadrant class.

Table 5. Summary data of 1-hour exceedances and non-exceedances at the BAYP monitor from January 2000-December 2008. Columns two and three show the number and percentage of days that were classified as 1, 2, 3, and 4-quadrant days. The fourth and fifth columns show the number and percentage of the total number of exceedance days that each quadrant class contained.

Quadrant Class	Days per quadrant	Percentage of Total days	Exceedance days per quadrant	Percentage of exceedance days
1	286	9.5%	0	0.0%
2	1,031	34.1%	0	0.0%
3	820	27.2%	8	22.2%
4	883	29.2%	28	77.8%
Total	**3,020**	**100%**	**36**	**100%**

Figure 6 and Figure 6, as well as Table 4 and Table 5 seem to indicate a correlation between quadrant classification and peak ozone concentration. If there were no interaction between the number of quadrants and the peak ozone value, ozone exceedance days should be randomly distributed throughout the dataset, and throughout the classes of quadrant days. The total proportion of days in each quadrant class should be roughly equal to the total proportion of exceedance days in each quadrant class. For example, at the BAYP monitor, 3-quadrant days comprised 27% of the total days and 22% of the total exceedance days observed at that monitor – the proportion of total days and proportion of exceedances in the 3-quadrant class were relatively close. In contrast, at BAYP, 4-quadrant days account for 29% of the total site-days, and 78% of the total 1-hour NAAQS violating days at that monitor. There is more than double the number of 4-quadrant exceedance days than would be expected if violations of the NAAQS were randomly distributed throughout all four quadrants.

It is important to note, however that 78% of exceedance days represents only 28 days. If over the nine-year time period there had been two less 4-quadrant exceedance days each year (for a total of eighteen 4-quadrant exceedance days less total), 4-quadrant exceedance days would only be 28% of the total exceedance days. Twenty-eight percent is extremely close to the 29% of total site-days that are 4-quadrant days. If there were double or triple the exceedances in the dataset, it would be easier to be certain of trends. This scenario demonstrates the issue of how sharply different the proportions of total site-days in each quadrant and total exceedance days in each quadrant must be before significant conclusions can be reached.

Besides the limited number of exceedances in the data set, another factor that needs investigation is the distribution of 1, 2, 3, and 4-quadrant days per month. If each category of quadrant day is distributed randomly throughout the year, then expecting exceedances to be randomly distributed through each category is valid. As Figure 8 shows, however, the categories of quadrant days are not evenly distributed throughout the year. The number of 4-quadrant days jumps about 25 days in June through August, and the number of 1-quadrant days drops about 10 days during the same time period. This means that 4-quadrant days occur more frequently during peak ozone season, so one would expect that there would be more 4-quadrant exceedance days than otherwise expected. Inversely, because there are fewer 1-quadrant days during the peak ozone seasons, one would expect to see fewer 1-quadrant exceedance days.

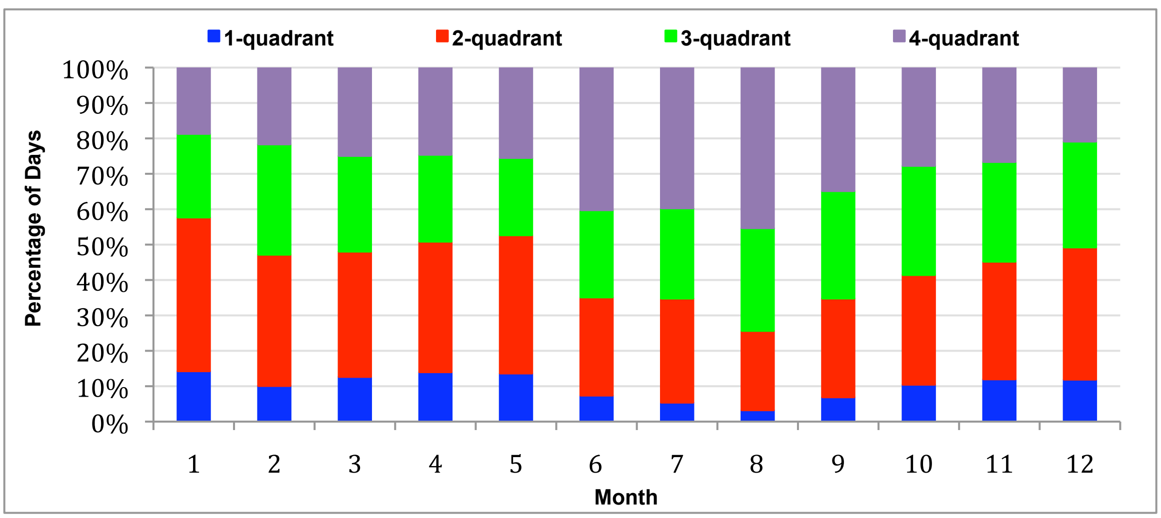


Figure 8. Percentage of days per wind quadrant classification and month of the year for the 1-Hour dataset at all sites from 2000-2008.

This unequal distribution of quadrant days throughout the year made it necessary to determine how significant the proportions of exceedances in each quadrant were not only year round, but also in just June through September. To determine the importance of the quadrant class of a day, an ANOVA was performed. Table 6 displays for all 6 monitors the p-values, or the probability of obtaining a distribution of exceedances among quadrants like the one observed if exceedances are randomly distributed among the quadrants. A p-value less than or equal to 0.05 is considered statistically significant.

Table 6. P-values for the 1-hour dataset at each of the 6 monitors. For example, at the HALC monitor, in January through December there is a 0.07% chance of the distribution of exceedances in quadrants as extreme or more extreme as was observed. When the p-value is less than 0.0001, the probability of the exceedances being randomly distributed throughout the quadrants and obtaining the observed patterns of exceedances is less than 0.01%

Monitor	June through September p-value	March through November p-value	January through December p-value
HALC	0.067	0.0025	0.0007
BAYP	0.0007	<.0001	<0.0001
C35C	0.0084	<.0001	<0.0001
DRPK	0.0003	<.0001	<0.0001
HNWA	0.0362	0.0008	0.0002
WALV	0.4214	0.0596	0.0334

The ANOVA results suggest that over the entire time period, the probability of finding a significant proportion of exceedance days in each quadrant class is less than five percent. When March through November is considered, all of the monitors have statistically significant differences between the proportions of exceedance days in each quadrant class, and the proportions of total days in each quadrant class, except WALV. This does not mean that WALV does not have differences; it means that given the size of the data set and magnitude of the difference in proportions, there isn't a clear enough difference to be certain it is not random. The p-values for the WALV monitor are always higher than the p-values for the other monitors. This is because WALV only had about one-third as many days as the other monitoring sites. With a smaller number of site-days it is more difficult to make definite conclusions about patterns in the data. In June through September only, the p-values are larger (and therefore less significant) than for the other time periods, although all except HALC and WALV are still statistically significant. HALC is almost significant, and it is likely with more data it would be more significant.

A reason for the increase in p-values is the smaller dataset (only 5 months), which makes it harder to separate trends from noise.

Statistically significant differences between the proportions of total days and exceedance days between quadrants do not mean that there is a causal relationship between wind direction and the peak ozone value. Other meteorological factors, including wind speed and temperature, could be an important part of the process. Table 7 displays wind speed data for the six monitoring sites in kph. The wind speeds calculated in Table 7 are the averages for three different time periods (all day, daytime, and night) based on the entire dataset of all days at all monitors. The entire day was all 24 hours, the daytime was 8:00 a.m. to 6:00 p.m. LST, and the night was midnight to 8:00 a.m. and 6:00 p.m. LST to midnight.

Table 7. Wind speeds (kph) by quadrant class and time of day. The 24-Hour Average resultant wind speed is the average of all hourly measurements taken in a day. The Daytime average wind speed is the average of the hourly resultant wind speeds from 8:00 a.m. to 6:00 p.m. LST. The Night average wind speed is the average of all hours in the day not included in the Day average.

Quadrant Class	Type of Day	24-hour Average Resultant Wind Speed (kph)	Daytime Average Wind Speed (kph)	Night Average Wind Speed (kph)	Number of Days
1	All	12.3	14.8	10.2	1,638
	Non-Exceedance	12.3	14.8	10.2	1,638
	Exceedance				0
2	All	10.6	12.9	8.7	5,387
	Non-Exceedance	10.6	12.9	8.7	5,382
	Exceedance	6.4	6.6	6.1	5
3	All	8.3	10.6	6.4	4,383
	Non-Exceedance	8.3	10.6	6.4	4,335
	Exceedance	6.0	7.3	4.9	48
	All	6.8	8.8	5.1	4,732

4	Non-Exceedance	6.8	8.8	5.1	4,614
	Exceedance	5.4	6.6	4.3	118

From Table 7 it is evident that there is a slight difference in average wind speed per quadrant class. The range of average wind speeds for the entire day across the four quadrant classes is 5.5 kph, and the difference from one quadrant to another is never more than 2.3 kph., Figure 1, at the beginning of this document, showed the wind trajectories based on wind speed in mph. The range of wind speeds represented across the quadrants, about 5.5 kph is around 3.4 mph, and it is evident from examining Figure 1 that a difference in wind speed of 3.4 mph between two days will not cause extreme differences in wind trajectories. When comparing the exceedance days and non-exceedance days within a quadrant class, it is important to consider the number of days that went into the average wind speed. If the number of days is small, differences in wind speeds are not as significant. This means that while the 24-hour average wind speed for 2-quadrant days that exceeded the standard is 6.4, while the average for non-exceeding days is 10.6 kph , there were only 5 days that exceeded the standard, so 6.4 kph is the average of only five days of data while 10.6 kph is the average of 5,382 days. Examining the distributions of wind speeds on exceedance and non-exceedance days in each quadrant would look closer into this idea. There are differences in average wind speeds between exceedance and non-exceedance days within a quadrant class, but they are likely not the factor dominating the ozone production.

The daily temperature (in degrees Fahrenheit) data has similar trends to the wind speed, as shown in Table 8. The lowest average temperature is for 1-quadrant days, and increases slightly when moving up to the next quadrant classification each time, and is highest for the 4-quadrant days. Wind speed and temperature data for the 8-hour ozone dataset is in Appendix B.

Table 8. Daily Temperatures by quadrant class and time of day. The Daytime average temperature is the average of the hourly temperatures from 8:00 a.m. to 6:00 p.m. LST in degrees Fahrenheit.

Quadrant Class	Type of Day	24-hour Average Temperature (°F)	Number of Days
1	All	67.98	1,638
	Non-Exceedance	67.98	1,638
	Exceedance		0
2	All	69.40	5,387
	Non-Exceedance	69.39	5,382
	Exceedance	83.43	5
3	All	70.46	4,383
	Non-Exceedance	70.36	4,335
	Exceedance	79.44	48
4	All	72.62	4,732
	Non-Exceedance	72.42	4,614
	Exceedance	80.21	118

The temperature increases across the quadrant classes. Temperatures are also higher in the same quadrant class for exceedance days than non-exceedance days. This is due in part to the seasonal variation of the quadrant classes each year. For example, 2-quadrant days are more frequent in the colder months, so it is more likely that the majority of 2-quadrant days are colder than 3-quadrant days. Of particular interest is the difference between non-exceeding and exceeding 3-quadrant and 4-quadrant days. There is at least a 7°F difference between the exceeding and non-exceeding days in both categories. Further investigation is needed to determine how significant this is in the production of ozone, but again, it is likely not the dominating factor.

If the wind pattern was the most significant variable in the production of ozone, years with more 3 and 4-quadrant days should have more ozone standard exceedances. Figure 9 shows the number of ozone exceedances for each year studied.

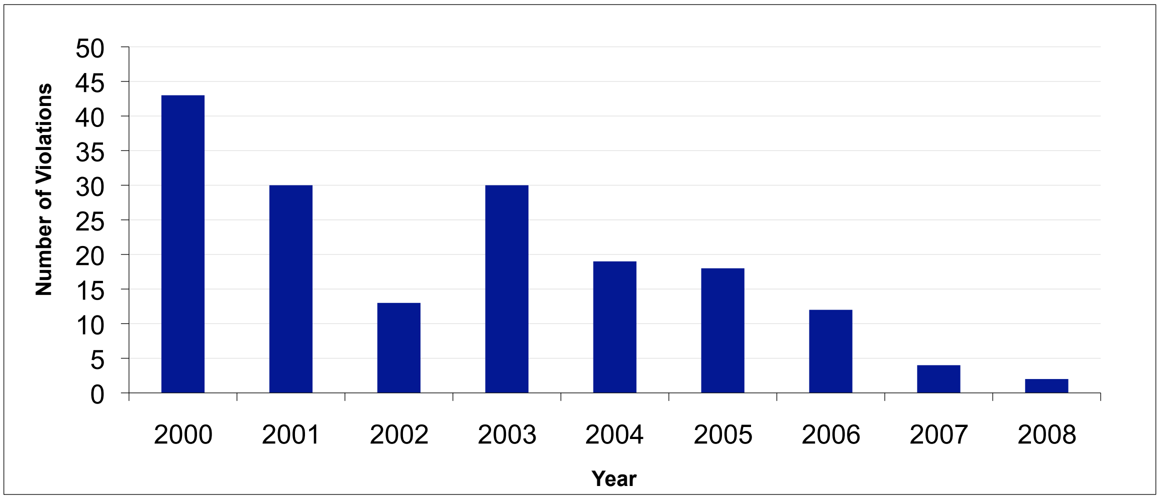


Figure 9. 1-Hour Ozone exceedances per year at all 6 sites for 2000-2008 time period.

Figure 10 shows the number of 3-quadrant, 4-quadrant, and the sum of 3 and 4-quadrant days per year. If the wind quadrant pattern was the only cause of high ozone, Figure 9 should have a similar trend to Figure 10.

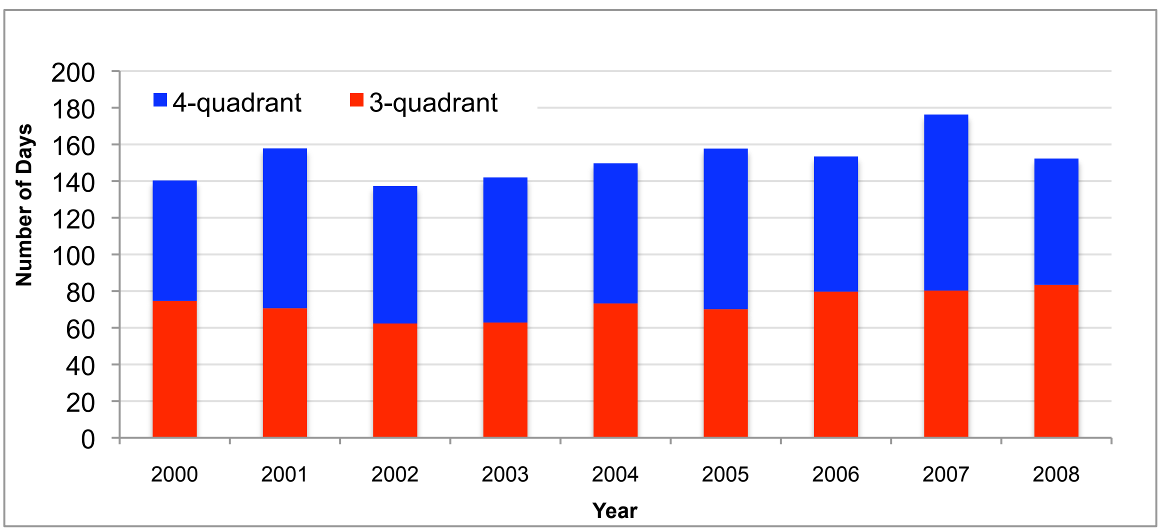


Figure 10. Number of 3 and 4-Quadrant Days per year for 1-Hour Dataset at all sites from 2000-2008.

The trends in Figure 9 and Figure 10 are different, thus there are more factors than wind quadrant pattern affecting ozone exceedances. Temperature and wind speed are also not likely strongly influencing ozone production; it is more likely other factors, such as changes in the emissions of NOx and VOCs are dominant factors.

8-Hour Ozone Dataset

In 2005, the ozone standard was changed to an 8-hour average and all attainment demonstrations are now based on this metric. Therefore, this analysis was also updated to investigate the effect of metrological factors on the 8-hour standard of 85 ppb. The current 75 ppb level was not used because the TCEQ is still in development of their SIP plans to attain the 85 ppb standard. Figure 11 shows the monthly distribution of 8-hour ozone exceedances. Although this is similar to Figure 5, there is an interesting difference. The 8-hour exceedances peak in June, August, and September, while the 1-hour exceedances clearly peaked just in August. This may be because 8-hour ozone is strongly influenced by background ozone conditions, which are high all summer, while 1-hour ozone is not. There are no 8-hour standard exceedances in January, February, and December during the 2000-2008 time period.

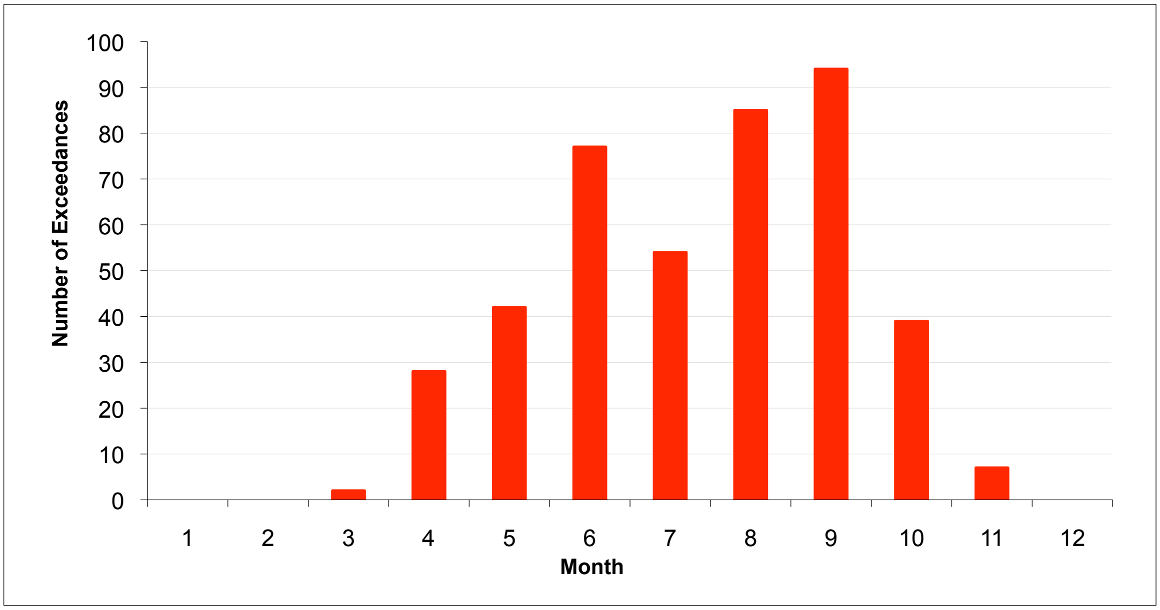


Figure 11. 8-H Ozone exceedances across all 6 monitoring sites by month. The time period covered is January 1, 2000 to December 31, 2008.

The wind quadrant patterns for 8-hour ozone were the same as 1-hour ozone, and included about 1,000 additional days of data that had been excluded from the 1-hour ozone dataset because of incomplete ozone measurements. There were about double the number of 8-hour ozone exceedances over the nine year time period as there were 1-hour, which makes the exceedance proportion a larger part of the dataset. Figure 12a-c shows the 8-hour ozone violations by quadrant, as well as the percentage of days in each quadrant without ozone exceedances, corresponding to Figure 6a-c for 1-hour violations. Table 9 numerically summarizes these results.

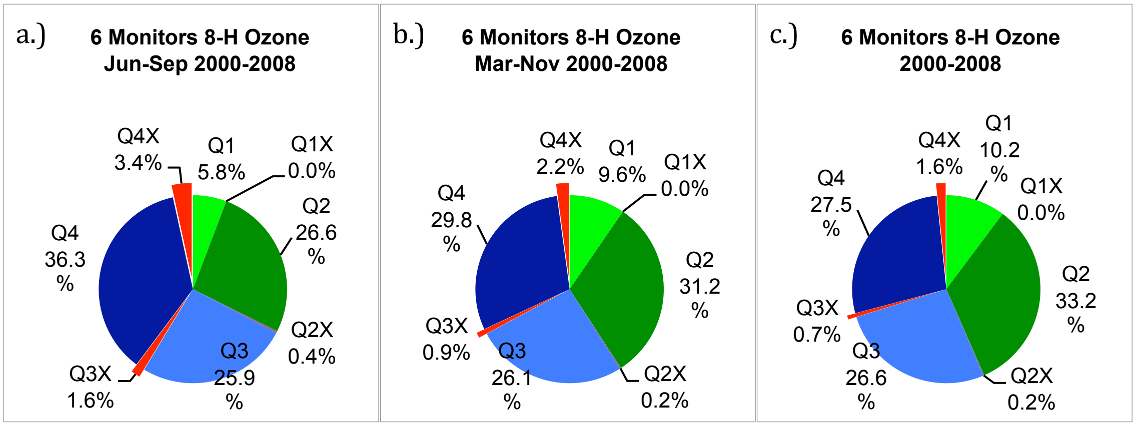


Figure 12a-c. 8-H Ozone exceedances by quadrant across all 6 monitors. The three time periods are June-September 2000-2008, March – November 2000-2008 and January – December 2000-2008. The "X" on the end of the quadrant number denotes exceeding days. For example, Q4 are 4-quadrant non-exceeding days, and Q4X are 4-quadrant days that exceeded the 1-hour standard.

Table 9. Summary data of 8-hour exceedances and non-exceedances at the BAYP monitor from January 2000-December 2008.

Quad-rant Class	Total Number of Days	Percentage of Total Days	Exceed-ance days	Percentage of total days	Non- Exceedance days in quadrant	Percentage of total days
1	291	9.5%	0.0	0.00%	291	9.5%
2	1,053	34.2%	3.0	0.1%	1,050	34.1%
3	833	27.1%	28	0.9%	805	26.2%
4	899	29.2%	70	2.3%	829	27.0%
Total	**3,076**	**100%**	**101**	**3.3%**	**2,975**	**96.7%**

Focusing on an individual monitor, BAYP in Figure 13, the results are very similar to the 1-hour results as shown in Figure 13a-c.

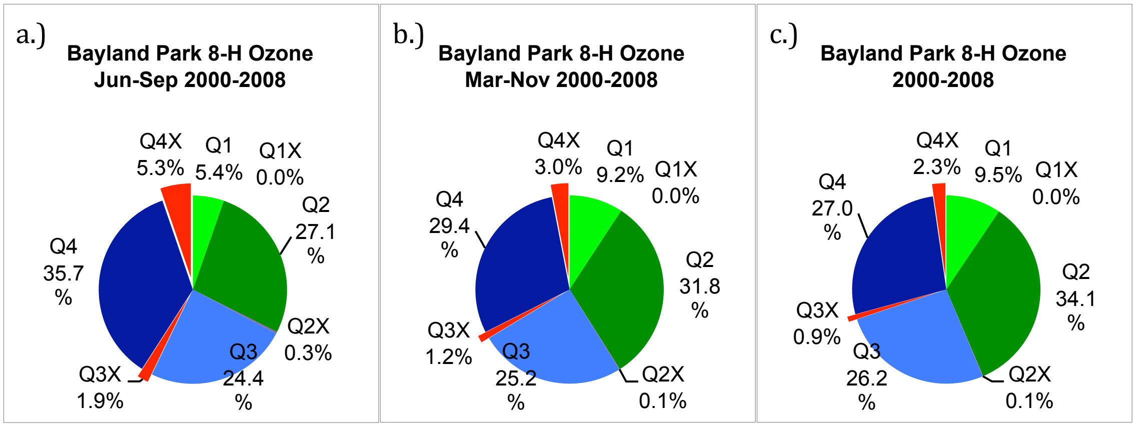


Figure 13a-c. 8-H Ozone exceedances by quadrant at BAYP. The three time periods are June-September 2000-2008, March – November 2000-2008 and January – December 2000-2008. The "X" on the end of the quadrant number denotes exceeding days. For example, Q4 are 4-quadrant non-exceeding days, and Q4X are 4-quadrant days that exceeded the 1-hour standard.

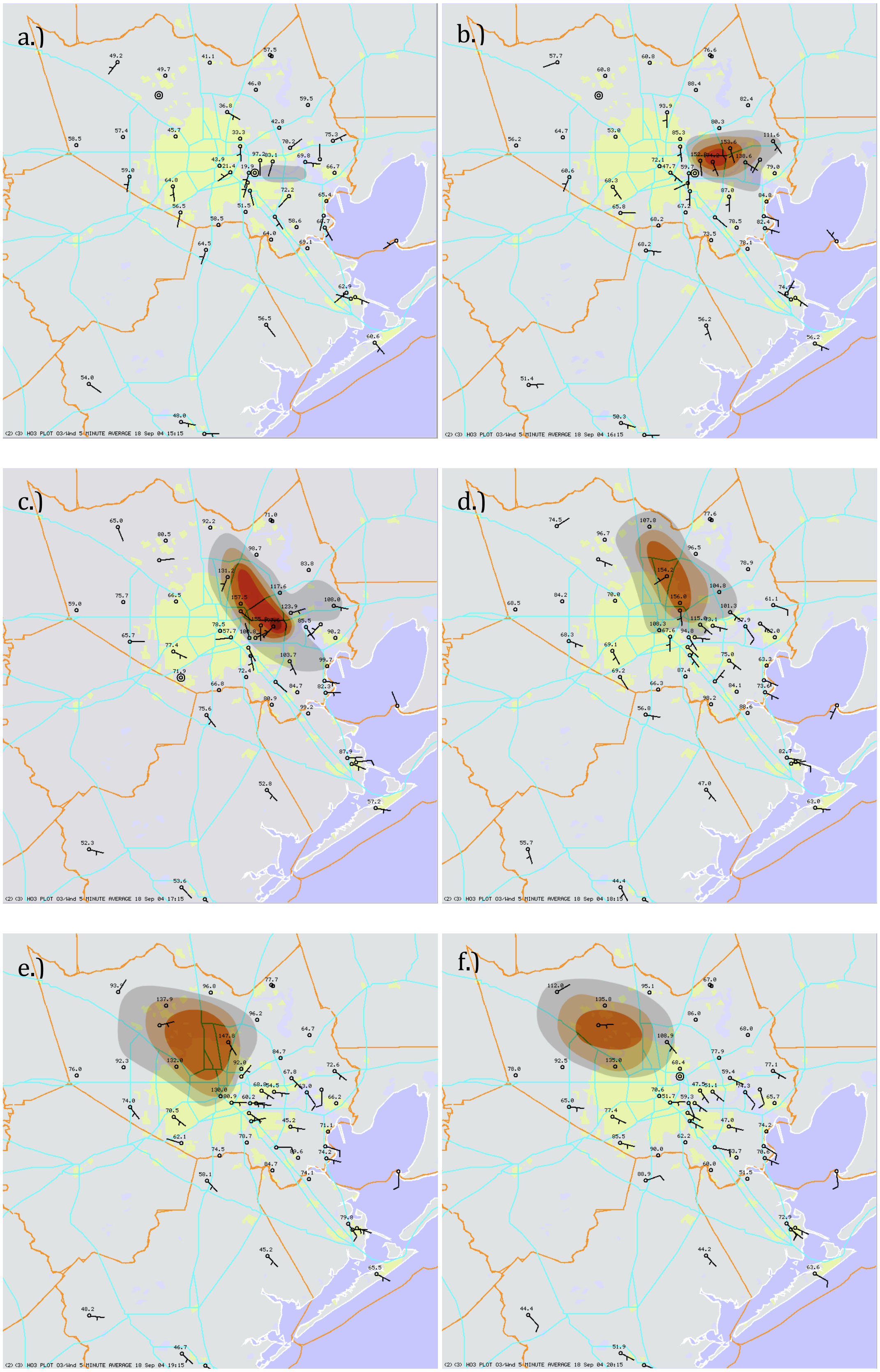
The distribution of each quadrant class each month for the 8-hour dataset was nearly identical to that of the 1-hour dataset (Figure 6, Appendix B). To look more closely at the significance of the distribution of the exceedances among the quadrants, an ANOVA was performed for the 8-hour dataset as well. Table 10 displays the p-values (probability of obtaining a distribution of exceedances among quadrants like the one observed if exceedances are randomly distributed among the quadrants) at each of the six monitoring sites.

Table 10. P-values for 8-hour datasets at each of the 6 monitors. For example, at the HALC monitor, there is a 0.35% chance of the distribution of exceedances in quadrants as extreme or more extreme as was observed during June through September. When the p-value is less than 0.0001, the probability of the exceedances being randomly distributed throughout the quadrants and obtaining the observed patterns of exceedances is less than 0.01%

Monitor	June through September p-value	March through November p-value	January through December p-value
HALC	0.0035	<.0001	<0.0001
BAYP	<.0001	<.0001	<0.0001
C35C	<.0001	<.0001	<0.0001
DRPK	<.0001	<.0001	<0.0001
HNWA	0.0003	<.0001	<0.0001
WALV	0.0243	0.0009	0.0003

The distribution of exceedance days in the 8-hour dataset is even more significant than in the 1-hour dataset. This is partially because of the additional thousand days included in the eight –hour dataset, but primarily because there are so many more exceedances. There is a less than 5% chance of the exceedances being distributed the way they are throughout the quadrants unless there is a correlation between quadrant classification and ozone concentration. This is true even in the summer months. Wind speed, temperature, and yearly trends of both exceedances and quadrant categories were similar to those described in the 1-hour results. This means that although there are statistically significant differences in the distribution of ozone exceedances, they are not due to wind pattern, wind speed, or temperature alone. Differences in emissions could be dominating ozone production on days with conducive meteorology.

To look at the impact emissions make, it is important to compare ozone concentrations at two monitors that experienced almost identical wind patterns, but had different ozone concentrations. As was mentioned in the methods section, some of the days with 8-hour ozone exceedances experienced exceedances at multiple sites. One example of this was September 18, 2004. On this day, all six monitors were classified as 3 or 4-quadrant days, but only two sites, HALC and HNWA exceeded the 8-hour ozone standard. This means that all of the sites experienced the same type of meteorology, a rotational wind pattern, but only two actually exceeded the standard. From the TCEQ's website, Figure 14a-h shows the ozone concentrations over Houston from September 18, 2004, 10:15 a.m. to 5:15 p.m. LST in one hour increments.


a.)
b.)
c.)
d.)
e.)
f.)

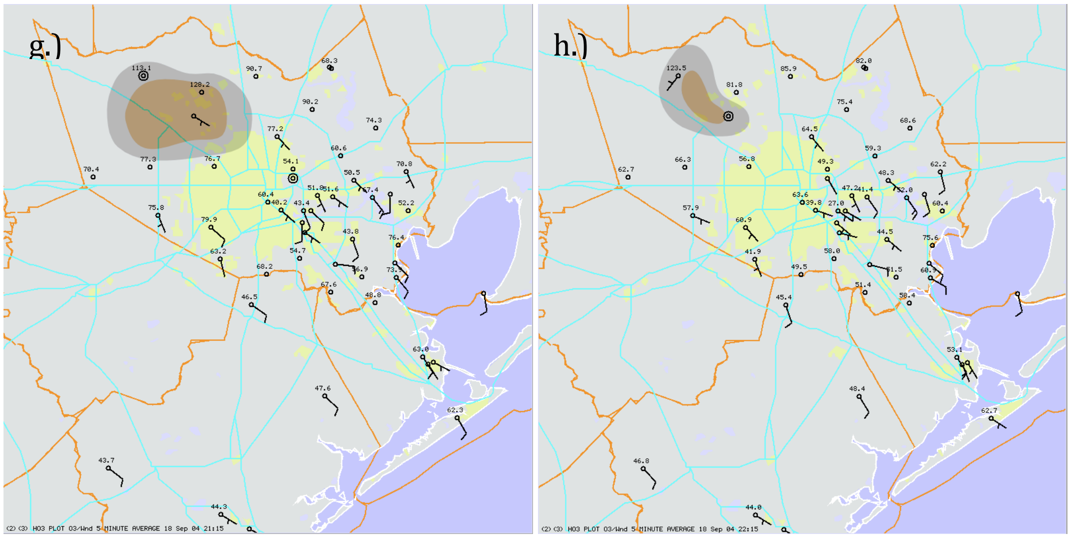


Figure 14a-h. Observed ozone concentrations (ppb) from the TCEQ over Houston, Texas on September 17, 2004 from 10:15 a.m. to 5:15 p.m. LST. The figures are at 1-hour intervals. Each figure shows the ozone concentration at that time, not the previous hour's average. The ozone forms when the onshore breeze from the ship channel reaches the urban area of Houston, and continues moving towards the northwest, where it reaches the HNWA monitor and causes it to exceed (TCEQ, 2009).

September 18, 2004 had an offshore breeze in the morning, and then an onshore breeze in the afternoon, which meant that the monitors experienced some rotational winds. Even though all monitors experience the same wind patterns, some monitors violated the standard. These were the monitors that were in the path of the plume of high ozone – which did not cover the entire city at all. The presence of days in the study where multiple sites undergo the same meteorological conditions, but some exceed the standard and some do not, such as September 18, 2004, point to the importance of including other factors besides meteorology in studying ozone formation, particularly plumes such as the one shown in Figure 14.

Attainment Demonstration Data

Houston is in non-attainment of the 85ppb 8-hour ozone standard and is required to write a SIP. The SIP shows attainment based on a metric called the design value, which is derived from observational data. In light of this, a dataset that exclusively used days involved in the calculation of the design value was analyzed for similar meteorological phenomena. The Design Values are based on the fourth highest ozone value. The top 4 dataset includes 198 days, the four highest 8-hour daily ozone values per year at each monitor. Out of the 198 days, 11, or 5.6% were 2-quadrant days, 51, about 25.8% were 3-quadrant days, and the remaining 136 days, 68.69% were 4-quadrant days. There were no 1-quadrant design value days. This quadrant breakdown is roughly the same distribution as the exceedance days in the complete datasets. The percentage of design value days in each quadrant class and 8-hour exceedance days in each quadrant class is shown in Figure 15. Although the Top 4 days follow the distribution of exceedance days in Houston roughly, they do not represent the distribution of all days in Houston.

Using just the fourth highest measurement reduced the dataset to 48 days. The quadrant classification trends in this dataset were roughly the same for the design value days, aside from a slightly larger percentage of 2-quadrant days, and slightly less 3-quadrant days than would be expected (Figure 15). It is unclear how significant the seemingly slight differences between the DV dataset and the 8-hour exceedance dataset are. If the design values are biased and have more than a proportionate number of 2-quadrant days, then it is likely that 2-quadrant days have some other dominating factor, probably emissions, that is causing the high ozone. This would mean that the ozone concentration on the very highest days, was caused by emissions, not meteorological variability, as the EPA guidance assumes.

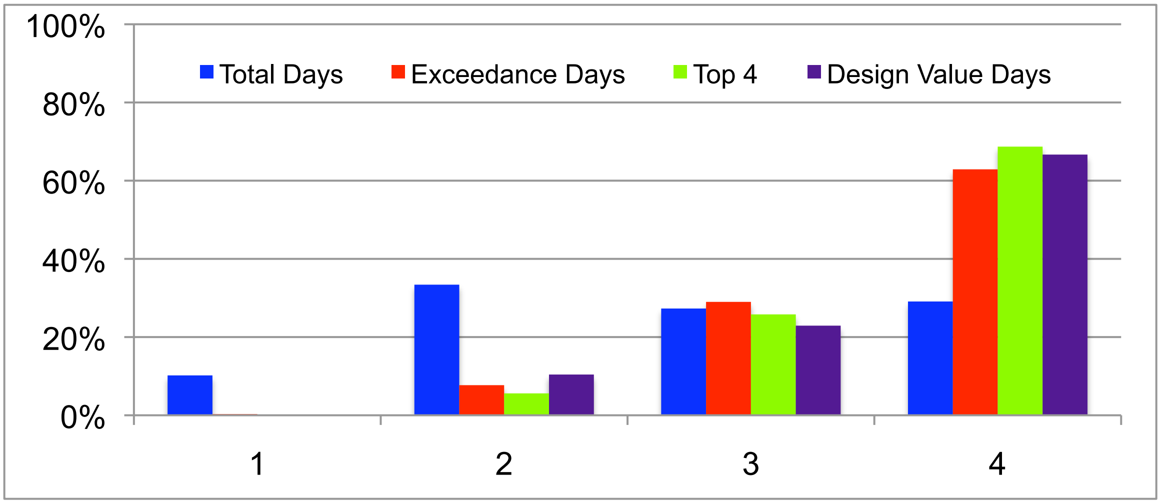


Figure 15. Percentage of the total of days, 8-hour exceedance days, Top 4 dataset days, and design value days that fall into each quadrant class. Proportions in each quadrant class of Top 4 days and exceedance days are never more than 6% different.

CONCLUSION

The number of quadrants from which wind blew from was highly correlated with ozone exceedances. This study showed that wind pattern plays a significant role in the production of ozone, but is not the only factor promoting high ozone. There cannot be high ozone without conducive meteorological conditions, but the presence of conducive meteorological conditions alone does not create high ozone. This study found that 95% of all ozone exceedances occur on 3-quadrant or 4-quadrant days, but on approximately 90% of 3-quadrant and 4-quadrant days, there were no ozone exceedances. The average wind speed, ozone concentration, and temperature of a day vary depending on the quadrant class of the day, but this variation is not the dominating factor in ozone production. Days with rotational wind patterns occur more often in the summer months, when peak ozone also occurs.

The ozone attainment guidance provided by the EPA, and followed in Houston described the use of observational and modeling data for demonstrating future attainment. This guidance recommends that all modeling scenarios used in the attainment demonstration use a fictional baseline inventory that exhibits minimal variability in emission rates. The meteorology, however, is assumed to represent reality and is used with the baseline emission inventory to make model predictions of ozone concentrations. Therefore, this procedure assumes that all high ozone concentrations are due to variability in the meteorology, not the emissions. Previous studies have shown an emission driven physical phenomenon that is unique to Houston: Transient High Ozone Events (THOEs). This is defined by the TCEQ when a measured ozone concentration at a monitor increases by 40 ppb in one hour and then declines. Extensive work in Houston has shown that THOES are the result of a large release of emissions of highly reactive VOCs. This could be a possibility as to the reason why wind patterns, specifically quadrant classification, do not show a greater influence on the total number of exceedance days because of emissions (Allen et al., 2001). Characteristic ozone-producing meteorology and both average and variable emissions are responsible for high ozone in Houston (Berkowitz et al, 2004). Therefore, the unique ozone-conducive meteorology in Houston in conjunction with high emissions are needed to make high ozone.

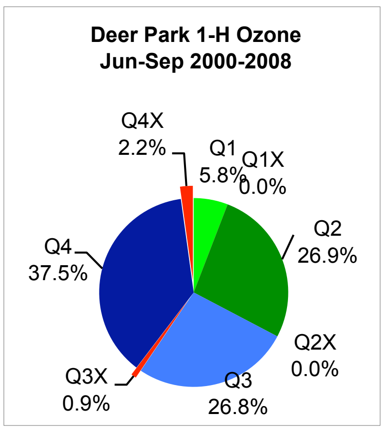
This analysis focused only on the number of quadrants the wind blew from throughout the day; further study could examine the interaction between the number of quadrants and a direction that the wind blew from. This type of study could yield interesting results. Future work on this project could also include expanding the dataset not only to include additional meteorological variables, but also to all of the ground level monitors in Houston. An important future component of this project is to examine the modeling data from Houston and see if the wind patterns and ozone concentrations in the model are correlated in the same way as the observations. The AQMs are used to predict future concentrations of ozone and demonstrate attainment of the EPA's NAAQS, so it is important that they capture the same phenomena as is see in the observations.

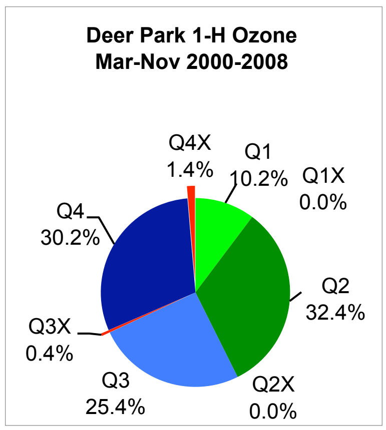
Using wind a quadrant classification system for wind directions as a proxy for detecting rotational wind patterns could be useful in other cities with high ozone concentrations and rotational winds. Several cities, such as Los Angeles, California, Athens (Lu and Turco 1994), Greece (Flocas et al. 2003), the central coast of Taiwan (Cheng 2002), Chicago, Illinois (Lyons and Olsoson 1973), and the gulf coast of Florida all have a land-sea breeze; however due to the different geography and longitudes of these cities, the technique may not be as useful. Houston has a flat coastal plain which allows the wind to completely rotate around, where other cities have geographic features like mountains that get in the way of the circulation (Day et al. 2009).

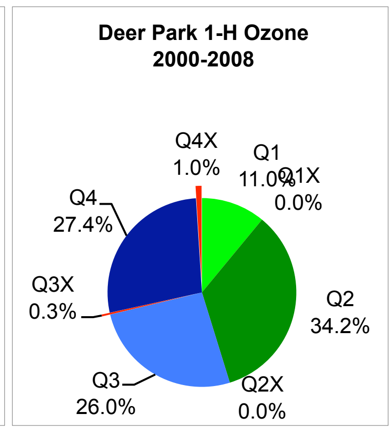
APPENDIX

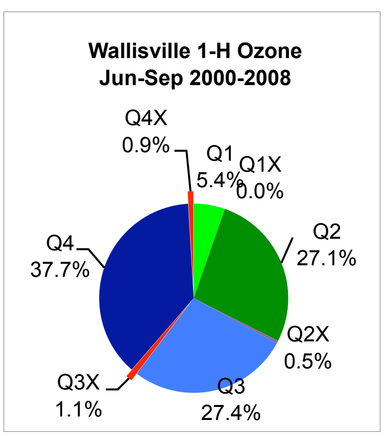
Appendix A

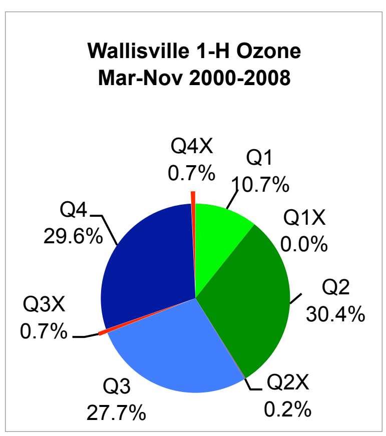
Summary of 1-Hour Data from DRPK, WALV, HALC, HNWA, C35C 1-H Ozone exceedances by quadrant at all sites except BAYP. The first figure in each series of 3 covers only June – September. The second figure spans March – November, and the third spans January 1, 2000 to December 31, 2008. The "X" on the end of the quadrant number denotes exceeding days.

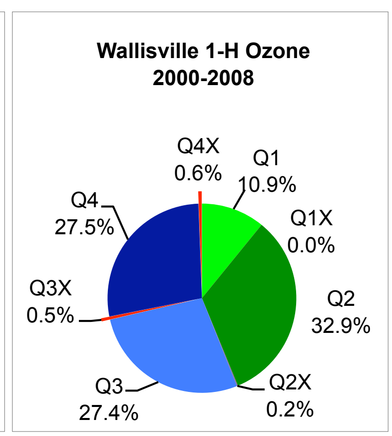


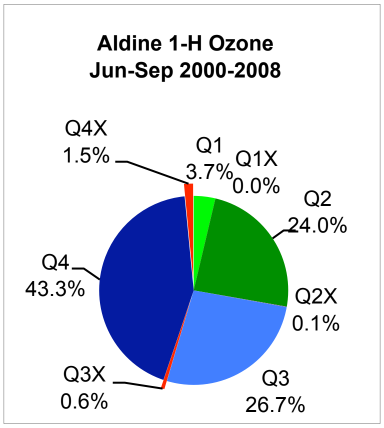


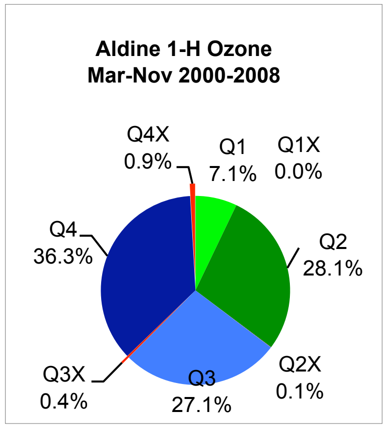


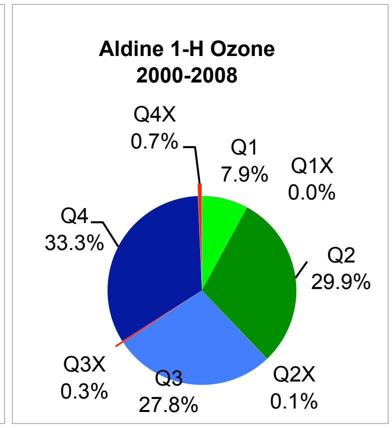


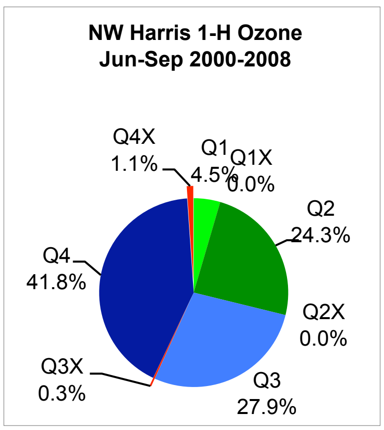


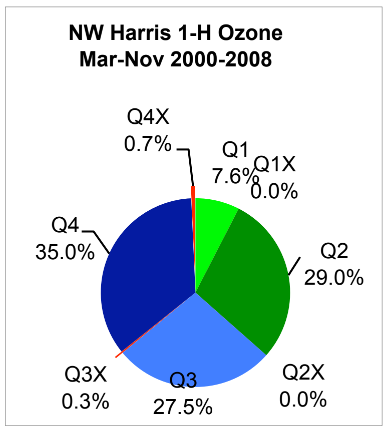


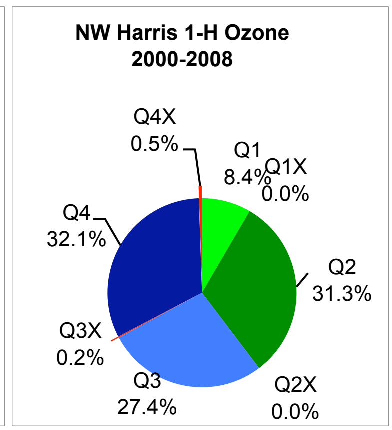

Aldine 1-H Ozone
Jun-Sep 2000-2008
Q4X
1.5%
Q1
3.7%
Q1X
0.0%
Q2
24.0%
Q4
43.3%
Q2X
0.1%
Q3X
0.6%
Q3
26.7%

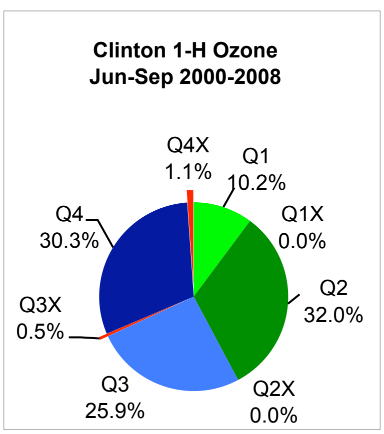

Aldine 1-H Ozone
Mar-Nov 2000-2008
Q4X
0.9%
Q1
7.1%
Q1X
0.0%
Q4
36.3%
Q2
28.1%
Q3X
0.4%
Q3
27.1%
Q2X
0.1%

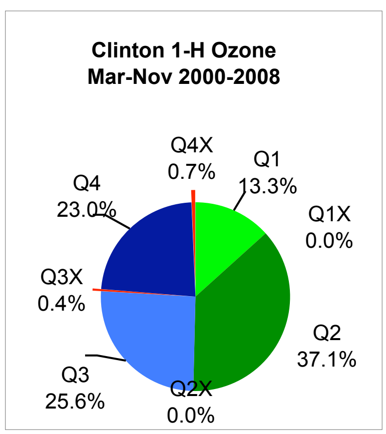

Aldine 1-H Ozone
2000-2008
Q4X
0.7%
Q1
7.9%
Q1X
0.0%
Q4
33.3%
Q2
29.9%
Q3X
0.3%
Q3
27.8%
Q2X
0.1%

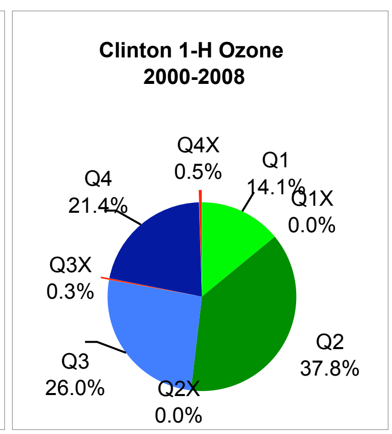

NW Harris 1-H Ozone
Jun-Sep 2000-2008
Q4X
1.1%
Q1
4.5%
Q1X
0.0%
Q2
24.3%
Q4
41.8%
Q2X
0.0%
Q3X
0.3%
Q3
27.9%


NW Harris 1-H Ozone
Mar-Nov 2000-2008
Q4X
0.7%
Q1
7.6%
Q1X
0.0%
Q4
35.0%
Q2
29.0%
Q3X
0.3%
Q3
27.5%
Q2X
0.0%


NW Harris 1-H Ozone
2000-2008
Q4X
0.5%
Q1
8.4%
Q1X
0.0%
Q4
32.1%
Q2
31.3%
Q3X
0.2%
Q3
27.4%
Q2X
0.0%

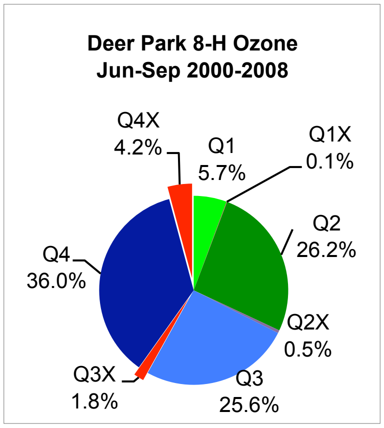

Clinton 1-H Ozone
Jun-Sep 2000-2008
Q4X
1.1%
Q1
10.2%
Q1X
0.0%
Q4
30.3%
Q2
32.0%
Q3X
0.5%
Q3
25.9%
Q2X
0.0%

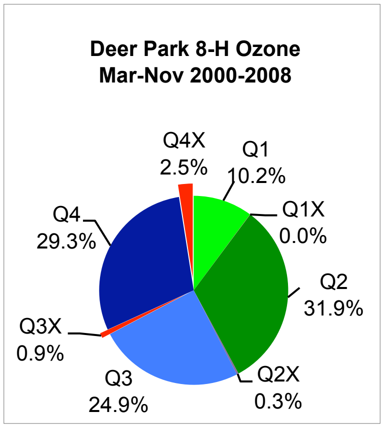

Clinton 1-H Ozone
Mar-Nov 2000-2008
Q4X
0.7%
Q1
13.3%
Q4
23.0%
Q1X
0.0%
Q3X
0.4%
Q2
37.1%
Q3
25.6%
Q2X
0.0%

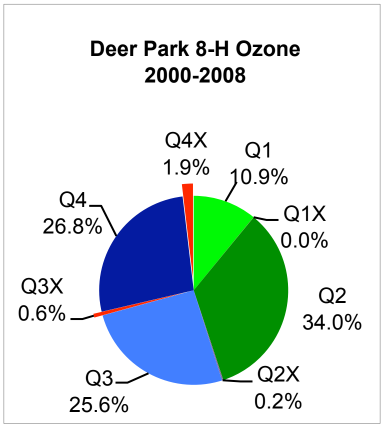

Clinton 1-H Ozone
2000-2008
Q4X
0.5%
Q1
14.1%
Q4
21.4%
Q1X
0.0%
Q3X
0.3%
Q2
37.8%
Q3
26.0%
Q2X
0.0%

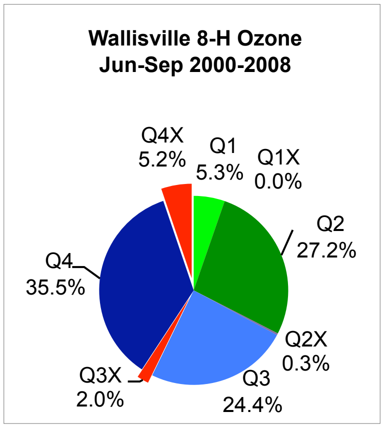
Appendix B

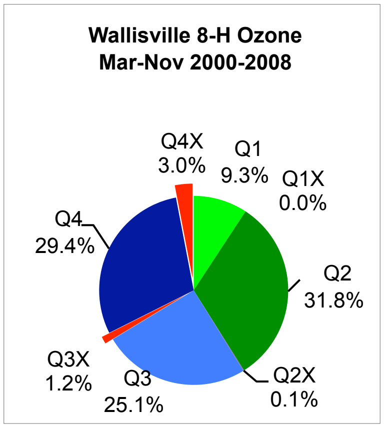
Summary of 8-Hour Data from DRPK, WALV, HALC, HNWA, C35C 8-H Ozone exceedances by quadrant at all sites except BAYP. The first figure in each series of 3 covers only June – September. The second figure spans March – November, and the third spans January 1, 2000 to December 31, 2008. The "X" on the end of the quadrant number denotes exceeding days.

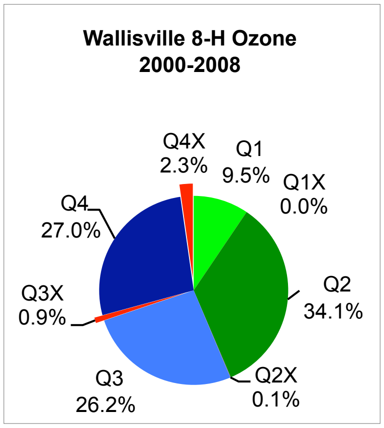


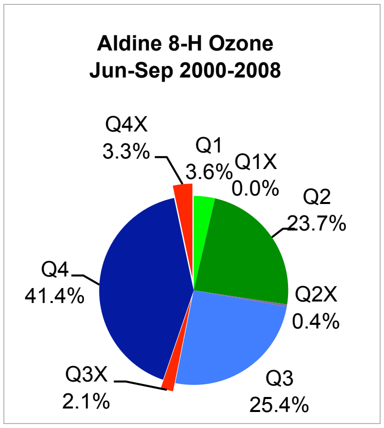


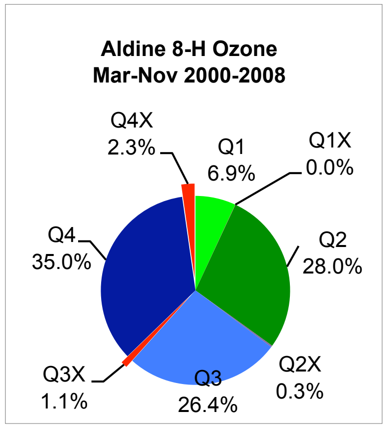


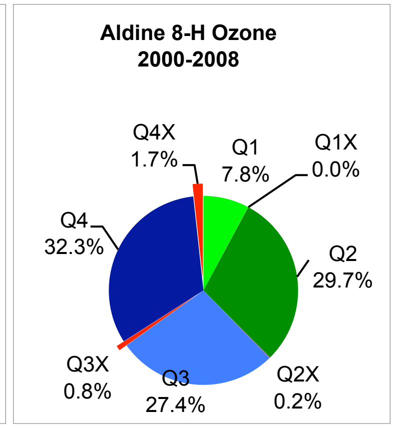


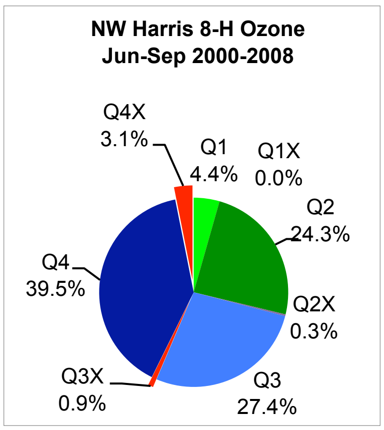


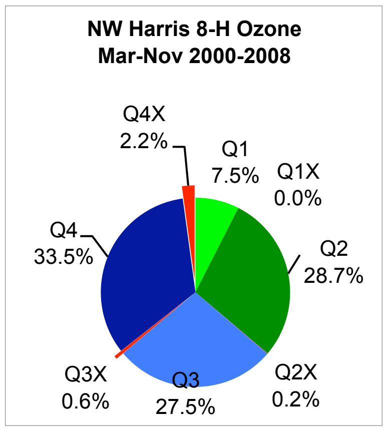


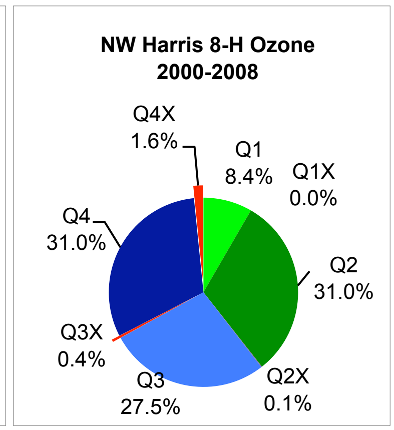

Aldine 8-H Ozone
Jun-Sep 2000-2008
Q4X 3.3%
Q1 3.6%
Q1X 0.0%
Q2 23.7%
Q2X 0.4%
Q3 25.4%
Q3X 2.1%
Q4 41.4%

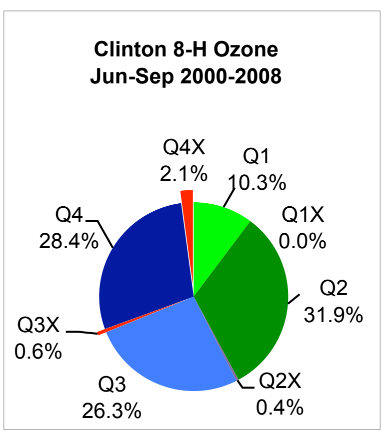

Aldine 8-H Ozone
Mar-Nov 2000-2008
Q4X 2.3%
Q1 6.9%
Q1X 0.0%
Q2 28.0%
Q2X 0.3%
Q3 26.4%
Q3X 1.1%
Q4 35.0%

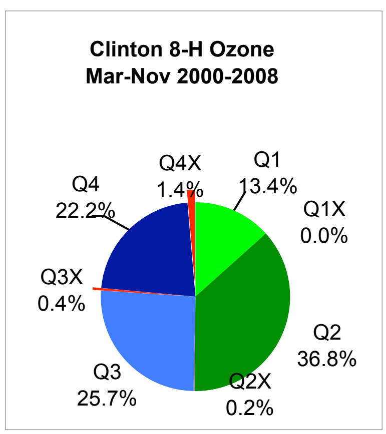

Aldine 8-H Ozone
2000-2008
Q4X 1.7%
Q1 7.8%
Q1X 0.0%
Q2 29.7%
Q2X 0.2%
Q3 27.4%
Q3X 0.8%
Q4 32.3%

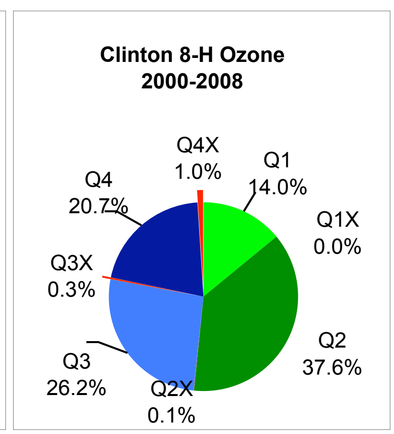

NW Harris 8-H Ozone
Jun-Sep 2000-2008
Q4X 3.1%
Q1 4.4%
Q1X 0.0%
Q2 24.3%
Q2X 0.3%
Q3 27.4%
Q3X 0.9%
Q4 39.5%


NW Harris 8-H Ozone
Mar-Nov 2000-2008
Q4X 2.2%
Q1 7.5%
Q1X 0.0%
Q2 28.7%
Q2X 0.2%
Q3 27.5%
Q3X 0.6%
Q4 33.5%


NW Harris 8-H Ozone
2000-2008
Q4X 1.6%
Q1 8.4%
Q1X 0.0%
Q2 31.0%
Q2X 0.1%
Q3 27.5%
Q3X 0.4%
Q4 31.0%


Clinton 8-H Ozone
Jun-Sep 2000-2008
Q4X 2.1%
Q1 10.3%
Q1X 0.0%
Q2 31.9%
Q2X 0.4%
Q3 26.3%
Q3X 0.6%
Q4 28.4%


Clinton 8-H Ozone
Mar-Nov 2000-2008
Q4X 1.4%
Q1 13.4%
Q1X 0.0%
Q2 36.8%
Q2X 0.2%
Q3 25.7%
Q3X 0.4%
Q4 22.2%


Clinton 8-H Ozone
2000-2008
Q4X 1.0%
Q1 14.0%
Q1X 0.0%
Q2 37.6%
Q2X 0.1%
Q3 26.2%
Q3X 0.3%
Q4 20.7%

Appendix C

8-Hour Wind Speed and Temperature Data

8-Hour Wind Speed Data

Quadrant Class	Type of Day	24-Hour Average Resultant Wind Speed (kph)	Daytime Average Wind Speed (kph)	Night Average Wind Speed (kph)	Number of Days
1	All	12.3	14.8	10.2	1,738
	Non-Exceedance	12.3	14.8	10.2	1,736
	Exceedance	8.8	9.2	8.5	2
2	All	10.6	12.9	8.7	5,693
	Non-Exceedance	10.6	12.9	8.7	5,663
	Exceedance	6.6	7.4	5.8	30
3	All	8.3	10.6	6.4	4,648
	Non-Exceedance	8.4	10.7	6.4	4,531
	Exceedance	5.9	7.1	4.8	117
4	All	6.8	8.8	5.1	4,974
	Non-Exceedance	6.8	8.9	5.1	4,695
	Exceedance	5.3	6.8	4.1	279

8-Hour Temperature Data

Quadrant Class	Type of Day	24-hour Average Temperature (°F)	Number of Days
1	All	67.98	1,400
	Non-Exceedance	67.96	1,399
	Exceedance	87.48	1
2	All	69.40	4,637
	Non-Exceedance	69.32	4,614
	Exceedance	83.92	23
3	All	70.45	3,839
	Non-Exceedance	70.18	3,742
	Exceedance	80.66	97
4	All	72.63	4,090
	Non-Exceedance	72.23	3,869
	Exceedance	79.37	221

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