THE INFLUENCE OF THE CHESAPEAKE BAY BREEZE ON MARYLAND AIR QUALITY

Laura Landry*, Duc Nguyen, and Michael Woodman
Maryland Department of the Environment, Baltimore, MD

1. INTRODUCTION

On March 12, 2008, the U.S. EPA strengthened the National Ambient Air Quality Standard (NAAQS) for 8-hour average ground-level ozone concentrations from 85 parts per billion (ppb) to 75 ppb. The new standard reflects over 1,700 scientific studies that linked adverse health effects at the level of the old standard or below. Maryland has greatly improved its air quality over the past several years. However, one region within the Baltimore Nonattainment Area (BNAA) presents many challenges in meeting this new standard (Fig. 1). The northern Chesapeake Bay region suffers from the highest ozone concentrations throughout the state, largely due to its location downwind of two major metropolitan areas as well as the development of the bay breeze. The formation of this micro-scale circulation has been known to create a sharp gradient of observed ozone concentrations across its boundary.

A climatological study of the Chesapeake Bay breeze is presented, specifically focusing on the northern bay region of the BNAA. The results of this study describe bay breeze frequency during the months of June to August, 2004-2009 with respect to high ozone episodes. In addition, a comparison of ozone concentrations between coastal and inland air monitoring sites will help quantify the ozone load that can be attributed to the bay breeze.

2. METHODOLOGY

To investigate the influence of the Chesapeake Bay breeze on air quality within the BNAA, exceedance days of the 75 ppb NAAQS during the summer months of June through August 2004-2009 were examined. These exceedance days were only those observed by air monitoring sites within the BNAA, which are the Aldino, Davidsonville, Edgewood, Essex, Fort Meade, Furley Recreation Center, Padonia, and South Carroll sites. Through this dataset, a five[†] year climatology was formulated. The results answer the question: How often does the Chesapeake Bay breeze play a significant role in creating a poor air quality day within the BNAA?

The primary method used for determining the answer was to utilize AIRNow-Tech's[‡] Navigator tool which displays state and local agencies' hourly air monitoring and meteorological data in a map format. In addition, the National Weather Service's (NWS) meteorological data can also be displayed on the same platform. Hourly ozone concentrations with both state and NWS wind barbs were generated for each daytime hour during all BNAA exceedance days. These hourly maps were the basis for determining whether each day could be categorized as a bay breeze event, marginal event, or non-bay breeze event.

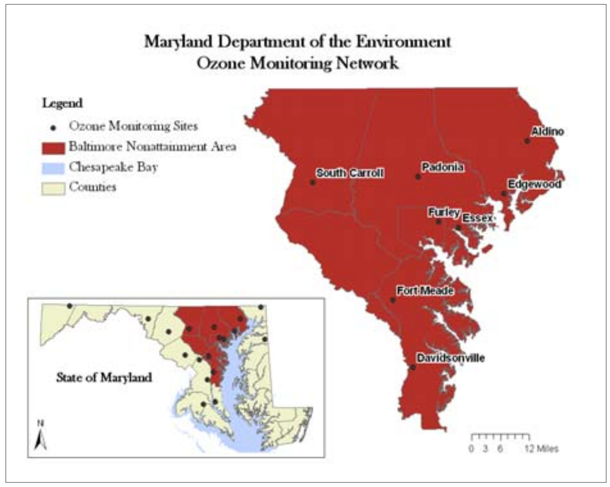

Figure 1. Map of the Maryland Department of the Environment's ozone monitoring network within the BNAA. NOTE: Fort Meade was discontinued in December 2004.

2.1 *Event Identification*

Criteria were developed to systematically classify each exceedance day as an event type. These criteria were an adaptation of criteria used

* *Corresponding author address:* Laura Landry, Maryland Dept. of the Environment, Baltimore, MD 21230-1720; e-mail: llandry@mde.state.md.us

[†] Wind data at the Edgewood site in June-August, 2006 were irregular and inconsistent with surrounding wind data. As a result, no BNAA exceedance days during 2006 were included in this study.

[‡] All data from AIRNow-Tech are preliminary.

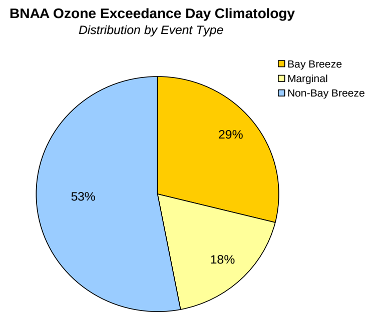

Figure 2. Pie chart of the Northern Chesapeake Bay breeze climatology during days when the 2008 NAAQS were exceeded in June to August, 2004-2009.

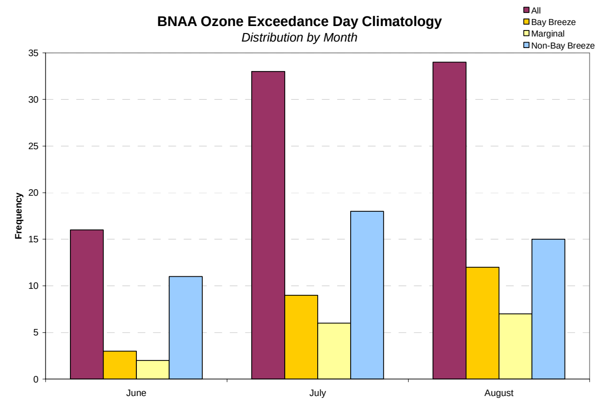

Figure 3. The bar chart displays each type of event and all events distributed by month.

by Miller and Keim (2003) in which a sea breeze climatology was created for the New England coast. In this study, a bay breeze event was defined as a non-onshore wind flow switching to onshore flow in the wind direction range of south-southwesterly to east-southeasterly. This range was chosen due to the contour of the bay's coast. Wind direction signifying onshore wind flow must be observed from the coastal air monitoring sites of Edgewood and/or Essex (Fig. 1). When data was not available at these sites, the NWS sites of Martin State Airport (KMTN) and Aberdeen Proving Grounds, MD (KAPG) became their substitutes. During the time of onshore flow, wind direction at the inland sites of Aldino and/or Padonia must be parallel, antiparallel, or perpendicular to the shoreline to indicate the bay breeze boundary. In addition, wind speeds associated with the bay breeze must be three knots or greater, although one hour of lighter wind speed was allowable due to the calm wind nature of the bay breeze. As with Miller and Keim (2003), these criteria must continue for a duration of three hours or more.

Sky cover was an additional parameter used to confirm that a wind shift thought to be a bay breeze was not synoptically driven. On each ozone exceedance day, the average cloud cover at KMTN between 1200-1800 UTC (800-1400 EDT) must observe less than “BKN”, or 5/8 sky cover or more, at less than 18,000 ft. As further confirmation that bay breeze events were categorized correctly, wind roses were generated during the afternoon hours of 1500-2100 UTC (1100-1700 EDT) for the air monitoring sites of Aldino, Edgewood, Essex, and Padonia. Each coastal site was paired with its closest inland site and prominent wind directions, as indicated by the wind roses, were compared. The sites of Edgewood and Aldino were paired together while Essex was assigned Padonia. On occasion, bay breezes in this area have been known to progress further inland passed the Padonia and Aldino sites. This behavior should be noted when looking at the results as some marginal events may include these types of occurrences. Marginal events simply followed the bay breeze definition but only last two hours or less. Non-bay breeze events were defined as any day in which the bay breeze and marginal criteria were not met.

Miller and Keim (2003) also separated their events into synoptic classes. In general, their research showed there were six common types of synoptic scale setup of pressure patterns with special focus on geostrophic wind direction. Classes 1-3 include northwesterly varying wind flows, classes 4 and 5 were southwesterly, and class 6 was northeasterly. Those that were of a southeasterly synoptic flow pattern were not included in the Miller and Keim (2003) study because of the difficulty that would arise in determining whether a sea breeze or synoptic forcing were the cause of a wind shift.

3. RESULTS

There were a total of 83 events that were analyzed. Of these 83, there were 24 bay breeze events, 15 marginal events, and 44 non-bay breeze events. This means that just over 50% of the events were non-bay breeze events, while about 30% were bay breeze events (Fig. 2). All event types separated by month show that the general trend they follow is an increase from June through July while July and August are relatively consistent with each other (Fig. 3). This trend is mirrored in the marginal events category. Though the differences were relatively minimal the bay breeze and non-bay breeze events did not show this trend as readily. In June, there were three bay

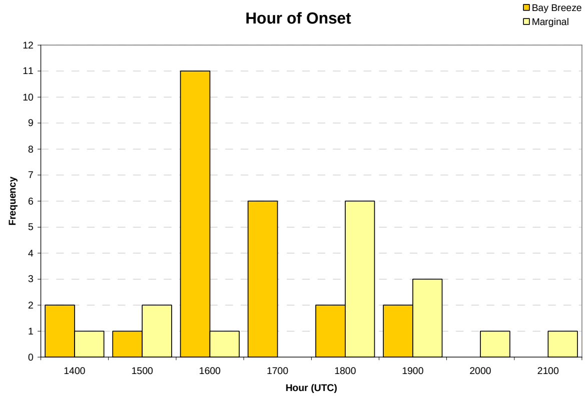

Figure 4. The bar chart displays bay breeze and marginal events distributed by hour of onset.

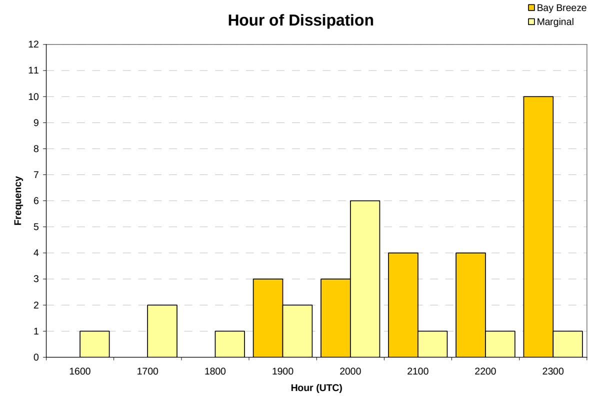

Figure 5. The bar chart displays bay breeze and marginal events distributed by hour of dissipation.

breeze events. However, in July and August there were nine and 12, respectively, indicating a slight increase from July to August. Non-bay breeze events expressed the same increase from June to July, but a slight decrease from July to August with 18 to 15 days, respectively.

The hour of onset was defined as the hour that the wind flow shifted onshore. The hour of dissipation was the first hour that onshore wind flow was absent. For bay breeze events, the most common hour of onset was 1600 UTC, with the earliest hour of onset observed to be 1400 UTC while the latest was 1900 UTC (Fig. 4). The most common hour of dissipation was 2300 UTC (Fig. 5). The earliest and latest hours of dissipation were 1900 and 2300 UTC, respectively. The results of the most common hour of onset and dissipation indicate that bay breeze events generally maintain the boundary for a duration of about seven hours. However, the mean duration for all bay breeze events was actually closer to five hours. Furthermore, the distribution of these events by duration proved that the bay breeze's duration is not consistent, rather the results were scattered somewhat evenly between three and seven hours (Fig. 6).

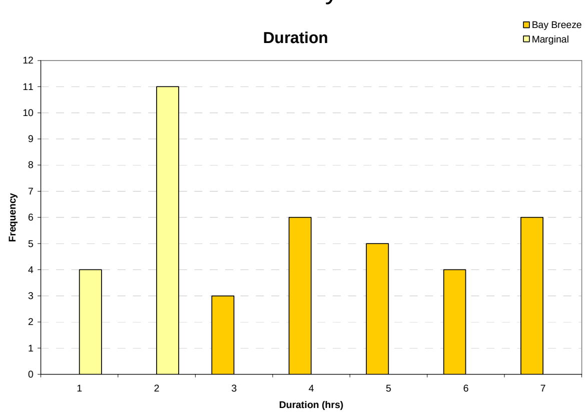

Figure 6. The bar chart displays bay breeze and marginal events distributed by duration.

For marginal events, the results seem to show most events had an hour of onset at 1800 UTC while the hour of dissipation was 2000 UTC (Fig. 4 & 5). About 73% of marginal events show the bay breeze holds for two hours rather than one (Fig. 6). On the other hand, with only 24 bay breeze and 15 marginal cases, it is hard to say whether these distributions are statistically significant.

3.1 *Maximum Ozone Gradient*

To measure and quantify the ozone load caused by the bay breeze formation, coastal air monitoring sites' ozone data were compared with inland sites' data. This comparison, called the maximum ozone gradient, was determined by taking a coastal site's ozone concentration and subtracting an inland site's ozone concentration at a given hour during which the bay breeze or marginal bay breeze was active. For non-bay breezes, these calculations were made for all hours between 1500-2100 UTC. Following these calculations, the largest positive number was declared the maximum ozone gradient. In this case, positive numbers would indicate higher ozone concentrations at coastal sites, while negative numbers represent higher concentrations at inland sites. The same pairing of coastal and inland sites used for the wind rose analysis was used for these computations.

Overall, the mean maximum ozone gradient for bay breeze events was 39.4 ppb with the highest measured maximum ozone gradient of 62 ppb. For marginal events, these numbers showed a large decrease to 17.3 ppb and 38 ppb, respectively. The non-bay breeze mean maximum ozone gradient was approximately 14.7 ppb, while its highest was 41 ppb, similar to marginal events. These results show that the hypothesized

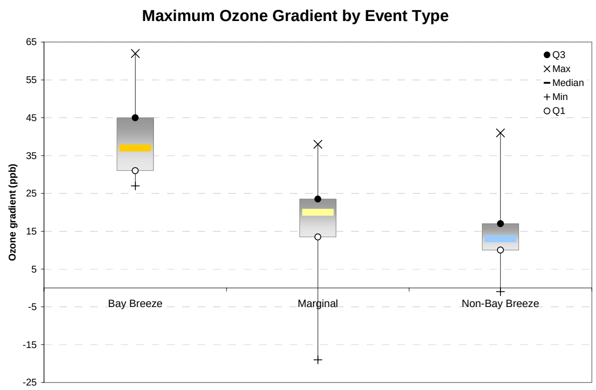

Figure 7. The box plot displays maximum ozone gradient trends found with each event type.

relationship of bay breeze events developing greater gradients than non-bay breeze events was correct based on each event type's mean as well as the range from each event's first to third quartile (Fig. 7).

When separated by the Edgewood-Aldino vs. Essex-Padonia pairings, bay breeze events' mean maximum ozone gradient became 41.6 ppb at Edgewood-Aldino and 37 ppb at Essex-Padonia. For marginal events, these gradients became 22.8 ppb and 11 ppb, respectively. In both instances, it is interesting to note how the maximum ozone gradient appeared to be more extreme at Edgewood-Aldino, though the difference was subtle for bay breeze events. Also, approximately half (52%) of the bay breeze maximum ozone gradients were found to occur at the Edgewood-Aldino rather than Essex-Padonia. Marginal events' gradients were seen more often at Essex-Padonia at about 60%. Finally, non-bay breeze events had similar results to bay breeze events in that 50% of maximum ozone gradients were experienced at Edgewood-Aldino.

To generate a large maximum ozone gradient for marginal events, it was found that these events rely greatly on the time of day the bay breeze was triggered. In Figure 7, marginal events had a minimum value of -19 ppb. This value represents an event with an hour of onset at 1400 UTC. Because marginal events were defined as bay breeze events that only last one to two hours, an hour of onset at 1400 UTC does not give ozone sufficient time to develop high concentrations as it is early in the morning and the photochemical process that produces ozone would have just begun.

The duration of the bay breeze boundary does not have a significant threshold by which to distinguish a large maximum ozone gradient from a small one (Fig. 8). One relationship that can be

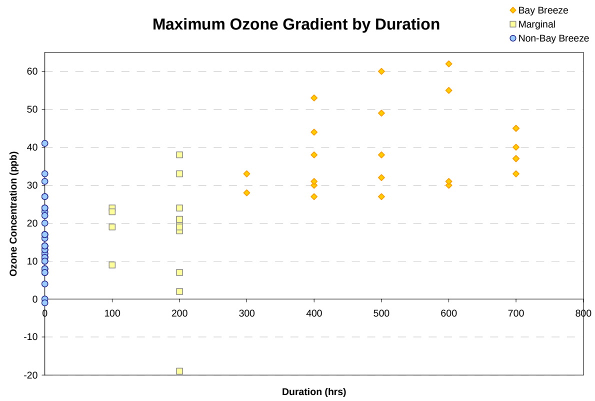

Figure 8. The scatter plot displays each event type distributed by duration.

found is that a bay breeze lasting four hours or more has a greater chance of developing a large ozone gradient. This seems to indicate that a bay breeze with a duration of only three hours does not have a great impact on air quality and could perhaps be included in the marginal bay breeze category.

Altering the criteria could have also yielded very different maximum ozone gradient results. As an example, the highest maximum ozone gradient throughout the dataset was found on July 12, 2005 of 62 ppb from Essex-Padonia. If the wind speed criterion were relaxed to include less than three knots for a longer period of time, a larger gradient of 76 ppb would have been found from Edgewood-Aldino (Fig. 9). On the other hand, a new problem would arise if this was implemented. The wind speed criterion acted to ensure accuracy of the wind data due to the limited resolution of the

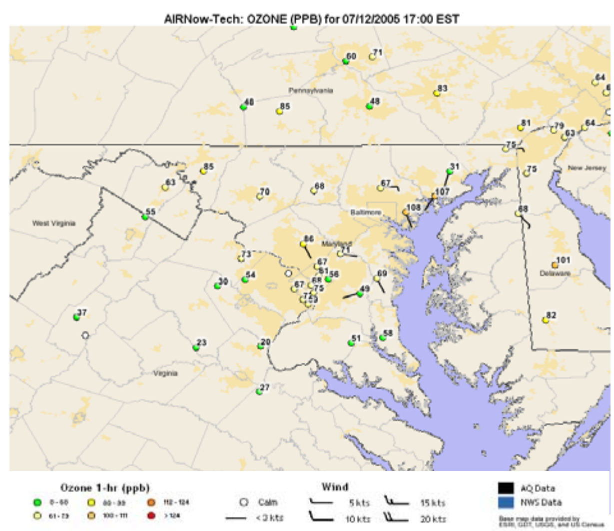

Figure 9. Map of air monitoring sites with hourly ozone concentrations color-coded to the AQI, and wind barbs on July 12, 2005 at 2200 UTC. (www.airnowtech.org)

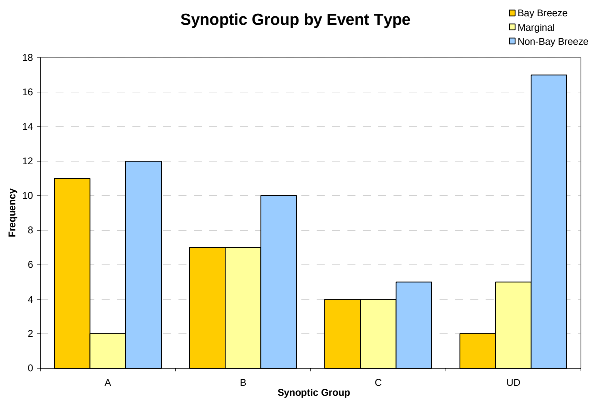

Figure 10. The bar chart displays each event type distributed by synoptic group.

meteorological sensors at low wind speeds. Most wind sensors have a threshold of three knots where a wind speed less than three knots introduces a higher chance of error than with greater wind speeds. The image further illustrated this issue because although the bay breeze still appeared to be in place between Edgewood-Aldino at 2200 UTC in relation to the large ozone gradient, Aldino did not indicate a contrasting wind direction to Edgewood. A northerly wind at Aldino, for example, would have been more consistent with the bay breeze boundary.

3.2 *Synoptic Scale Setup*

The research by Miller and Keim (2003) further classified the events into commonly observed wind flow regimes. These regimes were characterized into northwesterly flow, or westerly to northerly-varying flow, as group A. Group B included southwesterly flow, or southerly to westerly-varying flow, and group C included northeasterly flow, or northerly to easterly-varying flow. The groups were then divided into six variations of synoptic scale pressure system setups. Group A was divided into three setups or classes, group B into two, and group C as one. For those groups and/or classes that were not identified as the classics found by Miller and Keim (2003), they were labeled undefined, or UD.

About 46% of all bay breeze events seemed to occur more often as group A, or westerly to northerly wind flow (Fig. 10). Group B was second with approximately 29%, group C was third, and the undefined category was ranked last. Marginal events were somewhat evenly distributed through the groups. Nearly 40% of non-bay breeze events represented the undefined group. Groups A and B ranked second and third, respectively, while Group C fell in last place. Events were further categorized into synoptic classes. A high

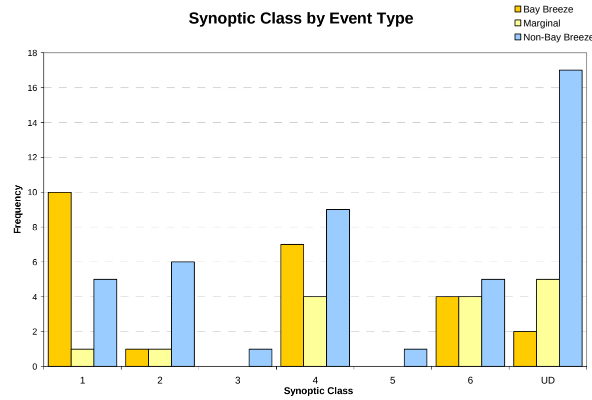

Figure 11. The bar chart displays each event type distributed by synoptic class.

frequency of class 1 bay breeze events was found with class 4 ranking second (Fig. 11). No bay breeze events were found to be class 3 or 5, which were postfrontal conditions. However, these two classes obtained one non-bay breeze event each. Second to the undefined group, class 4 observed the highest frequency of non-bay breeze events. Marginal events were generally classes 4, 6, and undefined, but like bay breeze events, they were never class 3 or 5.

Throughout the classification process, the predefined synoptic classes were difficult to identify for this study's cases. This led to a large number of cases labeled as undefined which included a total of 24 events of all types. It was found that among synoptic classes, this study would have benefited from the introduction of a new synoptic class which would resemble class 1 with all isobars rotated 90° counterclockwise. This would allow the dominant pressure system to be a broad scale high pressure system like class 1, but centered off the coast to induce southwesterly to westerly wind flow. The result would be fewer events placed in the undefined group.

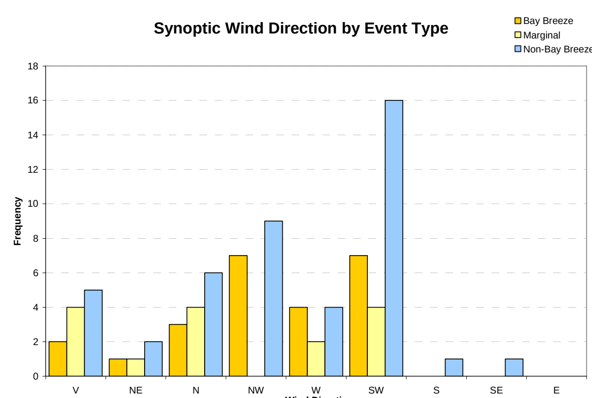

Figure 12. The bar chart displays each event type distributed by synoptic wind direction.

A second look at classifying synoptic setup by wind regime distributed events into the eight different wind directions with an additional category for varying winds. Surprisingly, northwesterly flow and southwesterly flow were split evenly among bay breeze events as the most frequently observed (Fig. 12). Westerly wind flow ranked third. For marginal events, there was a relatively even spread between varying, northeasterly, northerly, westerly, and southwesterly flows. Non-bay breeze events followed classic high ozone episode setup with southwesterly flow observed most often. Also following the classic episode example, exceedance days in the BNAA never occurred during easterly synoptic flow conditions. Furthermore, it is interesting to note the low number of westerly flow cases across all event types. This may be due to the time the wind flow was observed for each case. Wind flow was observed at 1200 UTC simultaneously with synoptic group and class identification. As a result, some cases with varying wind direction may, in fact, have developed a more predominant synoptic wind flow such as westerly later in the day.

4. SUMMARY

In an effort to investigate the Chesapeake Bay breeze in relation to air quality within the BNAA, BNAA exceedance days of the 75 ppb NAAQS were examined to identify bay breeze, marginal, and non-bay breeze events. The identification process followed methodology similar to Miller and Keim (2003). Bay breeze events were found to occur in about a third of all cases whereas non-bay breeze events represent just over half of the cases. Marginal events were shown to exist less than 20% of the time. Some marginal events looked to move inland beyond Aldino and Padonia, the air monitoring sites labeled as inland in this study. This theory could not be tested further as there are no air monitoring sites or NWS meteorological sites immediately north of Aldino and Padonia to observe a contrasting wind direction. Sea and bay breezes have been known to appear on radar imagery, however, inspecting radar images for these boundaries would not be a fool proof method. It would also be a time consuming process when applied to a large dataset.

As hypothesized, bay breezes did prove to negatively affect air quality. When the boundary formed, ozone concentrations on the coastal side would generally be higher than ozone concentrations on the inland side. To quantify this difference across the boundary (or lack of boundary in non-bay breeze cases), the maximum ozone gradient was calculated, where a positive gradient accounts for these higher coastal concentrations. Negative gradients would represent the reverse effect. The mean maximum ozone gradient was approximately 39 ppb for bay breeze events. This was the highest mean gradient of the three types of events. Marginal events were ranked next at about 17 ppb while Non-bay breeze events were last at about 14 ppb.

During bay breeze events, the location of the maximum ozone gradient was considered. The Edgewood-Aldino pairing produced a slightly higher mean maximum ozone gradient than the mean maximum ozone gradient measured at Essex-Padonia. However, the Essex-Padonia pairing indicated bay breezes formed more often which would perhaps moderate the mean maximum ozone gradient results overall. Altering the criteria could have also yielded very different results. By lowering the wind speed threshold within the criteria, a much higher maximum ozone gradient may have been found though this would also reduce the reliability of the wind speed and direction data.

Classifying each event into synoptic setup through the use of synoptic groups and classes showed that the undefined group was most common among non-bay breeze events. Group A occurred most frequently in bay breeze events while marginal events were split within all synoptic groups including the undefined group. The creation of a new synoptic class could have reduced the number of events in the undefined group. This new class would describe a widespread high pressure system, representing the Bermuda high, centered off the East Coast inducing southwesterly to westerly wind flow.

Expanding upon this study through the addition of new ozone seasons' data could significantly increase the statistical significance of the findings. Any future work should include this as well as potentially examining non-exceedance days to determine how often bay breezes occur but do not result in poor air quality within the BNAA.

5. REFERENCES

AIRNow, cited 2009: AIRNow-Tech. [www.airnowtech.org]

Miller, S. T. and B. T. Keim, 2003: Synoptically-driven controls on the sea breeze of the central New England coast. *Wea. Forecasting*, 18, 236-248.