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Fog and Icing Occurrence, and Air Quality Factors

for the Rhode Island Ocean Special Area Management Plan 2010

by

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Executive Summary

An analysis of three focused environmental concerns for the Rhode Island Ocean SAMP area is presented here. The occurrence of fog and the potential for accumulation of ice on moving vessels, both potentially significant hazards to navigation and marine operations, are estimated based on meteorological and oceanographic data from nearby offshore towers. Also, the annual variation of surface ozone mixing ratios observed at Narragansett, RI, adjacent to the Ocean SAMP domain, is presented and analyzed. Rhode Island (and other New England states) does not meet current ambient air quality standards. Extensive marine operations in the offshore area would lead to additional emissions of pollutants, including ozone precursors. An analysis of the impact of extensive offshore marine operations is beyond the scope of this work.

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Abstract

An analysis of three focused environmental concerns for the Rhode Island Ocean SAMP area is presented here. The occurrence of fog and the potential for accumulation of ice on moving vessels, both potentially significant hazards to navigation and marine operations, are estimated based on meteorological and oceanographic data from nearby offshore towers. Also, the annual variation of surface ozone mixing ratios observed at Narragansett, RI, adjacent to the Ocean SAMP domain, is presented and analyzed. Rhode Island (and other New England states) does not meet current ambient air quality standards. Extensive marine operations in the offshore area would lead to additional emissions of pollutants, including ozone precursors. An analysis of the impact of extensive offshore marine operations is beyond the scope of this work.

1 Introduction

This report summarizes work and results on study of three focused environmental concerns for the Rhode Island Ocean SAMP area. These are the occurrence of fog, the occurrence of icing conditions, and the mixing ratio of ozone in the context of air quality standards. These topics would fall naturally into a comprehensive analysis of the meteorology of the area, but have been studied separately given the organizational approach selected for the overall study.

2 Background

The occurrence of fog, and of vessel icing, present distinct hazards to marine operations in many areas, and the Ocean SAMP domain is among them. While these hazards are well known to experienced mariners, particularly those who have worked in New England coastal waters, it is deemed important to describe and document the nature and extent of their occurrence. The ozone air quality information provided here is less directly tied to marine operations. Rather it relates to the interplay of ambient air quality regulations, impacts of local emissions and downstream effects.

Fog forms in various circumstances in different places, and these varying conditions lead to its characterizations as radiation fog, advection fog, arctic steam smoke, or inversion fog. These and other types are described with specific reference to the marine environment by Kotsch (1983). The most common type in coastal marine environments, and the type most often observed by far in the Ocean SAMP area, is advection fog. When warmer air blows over cold water, the air gives up heat, and if it cools to the dew point, condensation takes place and fog forms. Because of the relatively low drag in the marine environment (relative to wind flow over a land surface), little mixing occurs even when near-surface wind speed approaches 15 m s^{-1}, and fog persists. In contrast, when winds are stronger or the drag greater, mixing through a deep layer reduces the likelihood of fog formation in favor of a stratiform cloud deck.

A concise but informative discussion is in Hsu (1988), Section 7.3. This includes figures from Kotsch (1983) illustrating areas where fog formation is common in US coastal areas. The broad estimates of the frequency of fog formation in New England shown there provide a useful point of comparison for the frequencies calculated here, as discussed in Section 5, below.

Ice accretion is a significant safety hazard in cold waters, especially for small vessels with limited freeboard, and in circumstances where wave-generated spray is common. An extended discussion is in Kotsch (1983), Chapter 10. As detailed below, however, in the work presented here a more recent formulation is used. Overland *et al*. (1986) presented a method for estimating icing potential dependent upon ambient environmental variables. The method is based on numerous observations of icing events, but by design is not specific to a particular vessel type or a specific location. The target application was operational forecasting by the weather service, using data fields for sea surface temperature and forecast wind and air temperature fields. In Overland (1990) additional analysis led to a slightly revised formulation. The careful statistical analysis of Overland *et al*. (1986) and the discussion of operational forecasting and verification in Overland (1990) constitute a convincing case for the usefulness of this approach.

The analysis of air quality data presented here is limited to near-surface ozone mixing ratio data. Ozone is one of the 6 “criteria pollutants” regulated by the Environmental Protection Agency. Attainment of compliance with clean air requirements is based on the National Ambient Air Quality Standards (NAAQS). The focus on ozone here is based on its being the substance for which compliance is most often not attained in onshore areas adjacent to the Ocean SAMP domain, and on the availability of routine air quality monitoring data for ozone at a site in Narragansett. The NAAQS 8 hour standard for O_3 is met if the 3 year average of the fourth-highest daily maximum mixing ratio at each monitoring site does not exceed 0.075 ppm (parts per million) by volume. At each site the three highest 8-hour values are noted, but do not constitute a violation. It is worth noting that peak 1-hour values and longer-term averages are not regulated directly.

Surface ozone mixing ratios have been declining in recent years in the US in response to regulatory measures. Nevertheless, Rhode Island remains a moderate non-attainment area, and the standard is not met at any of the three monitoring sites in Rhode Island. The ozone mixing ratio varies in time in a way that differs among the monitoring sites. This variation is informative in the context of on-shore/off-shore variations. Also, the EPA has proposed strengthening the standard for ozone to make it consistent with the recommendations of its panel of advisors. This change will make meeting the standard more challenging.

3 Methods

Data acquired at two offshore towers have been analyzed for the occurrence of fog, and at one of them of icing conditions. Surface ozone data acquired for air quality monitoring have been used to prepare a composite view of the ozone distribution and variation. In this section the sources of the data and the methods used in the analysis are described.

The first set of offshore meteorological data are from sensors mounted on the Buzzard's Bay Tower, BUZM3, which is owned and maintained by the National Data Buoy Center. The observations are distributed and archived under WMO Station ID 44070. The tower is at 41.397˚N, 71.033˚W, in Buzzard's Bay, west of the Elizabeth Islands (and Martha's Vineyard), and SSW of New Bedford, MA. The relevant meteorological sensors are located between 24 and 25 meters above mean sea level. Sea surface temperature measurements, needed for the analysis of icing conditions, are from 1 m below the water surface.

The estimates presented here are based on data from BUZM3 for the period 1997-2009. Data are recorded continuously, but there are gaps in the availability of some data owing to equipment failures. In the case of the meteorological instruments at BUZM3 the outages typically extend over weeks or months, and short-lived outages are uncommon. This patterns has implications for dealing with the missing data, as discussed further below.

The second site with offshore meteorological data is the Martha's Vineyard Coastal Observatory, MVCO, which is owned and maintained by the Woods Hole Oceanographic Institution. The Air-Sea Interaction Tower at the MVCO is 3 km offshore of South Beach, Martha's Vineyard, MA, in 15 m deep water in the Atlantic Ocean at 41.325˚N, 70.567˚W. Air temperature and relative humidity data from the offshore tower are used here. Outages in the data from the ASIT instruments are infrequent and brief during the period analyzed here. The available data are for the years 2007-2009.

The ozone mixing ratio data used here are in an archive maintained for the US EPA. The data are acquired by the Rhode Island Department of Health using instrumentation at the Narragansett Laboratory of the EPA, at the northern edge of the Bay Campus of the University of Rhode Island. Hourly average ozone mixing ratio values are available; periodic calibration procedures lead to missing data points every other day or so.

3.1 Analysis of meteorological data for fog.

Air temperature and dew point values were used for fog occurrence estimation at the BUZM3 tower. Here an hourly observation period is considered foggy when the air and dew point temperatures are equal. It is important to note that fog can persist when the indicated relative humidity is less than 100%, and that non-foggy conditions can occur and prevail for some time at 100% relative humidity.

At the BUZM3 tower the aggregate data availability for the suite of sensors needed here for the period used is close to 60%, so that in most months there are the equivalent of approximately 8 years of data for the years 1997-2009. Fog occurrence frequency estimates have been averaged over the heterogeneous, temporally discontinuous periods of data availability. The assumption that the absence of data is uncorrelated with the presence or absence of fog is well justified.

3.2 Analysis of meteorological data for icing

The icing potential was evaluated using a formulation based on data analyzed by Overland *et al.*, 1986, as revised and discussed by Overland (1990). The underlying analysis is for a categorical prediction of potential icing rate: light, moderate or heavy. In Overland (1990) a fourth category, extreme, was added. Data (or forecast estimates) for the wind speed and the air and water temperature are used to calculate a predictor, and the potential icing rate categories correspond to specified ranges of the predictor value. The predictor value is proportional to $V_a(T_f - T_a)$, that is, to the product of the wind speed V_a and the difference between T_f, -1.8˚C, the freezing temperature of sea water, and the air temperature, T_a. The predictor value decreases with increasing values of $(T_w - T_f)$, the difference between the freezing temperature of seawater and the ambient sea surface temperature. Heavy and extreme ice accretion potentials are not expected in the Ocean SAMP area, as these are present only when the ambient water temperature is below 0˚C. Icing is generally not observed when the water temperature is greater than 6˚C, so in most months of the year, and on many days during the winter months there is no potential for ice accretion. In the analysis presented below we converted the ice accumulation predictor from a categorical variable to a continuous variable using a polynomial formulation from Overland (1990). In the results presented in the following we used directly observed values of these environmental parameters, not the forecast or analysis data type for which the underlying analysis was designed. This difference is not expected to weaken the analysis to any significant extent, as the categories cover a range of ice accumulation rates, and the accuracy of the observations is high. It is important to note that the analysis presented here relates to vessels underway in marine operations. It is not suited to vessels that are stationary, nor to stationary structures of any kind. The estimates presented and discussed below can, however, be considered as very conservative upper limits for icing potential for stationary vessels and structures. In these situations the reduced occurrence and intensity of wave breaking because the hull or structure is stationary lessens the volume of water raised above the sea surface, reducing the icing potential dramatically.

3.3 Analysis of air quality data

The ozone data have simply been plotted in a way that makes clear the multiple forms of variation present in the data themselves. Hourly average data for each day are juxtaposed in a vertical column, with data for each day adjacent to that for the next. The result is a time of day vs. day of year display of the data, with color-fill values indicating the hourly-average ozone mixing ratio for each day and time.

4 Results

The annual distribution of the **occurrence of fog** estimated using thermodynamic data at the BUZM3 tower is shown in the upper panel of Fig. 1, while the lower panel shows the quantity of data available in each month. During the months of March-May and October-December there are typically between 3 and 4 foggy days per month at this site. As expected, there is a significantly higher occurrence of fog during the months of June, July and August. In these months the flow of warm, moist air over water that has not yet reached its maximum temperature is particularly favorable for the formation of fog. The occurrence of foggy days in these months is between 6 and 10 days per month, on average. Given the assumptions needed to complete this analysis and the variability in the formation and persistence of fog, a judicious interpretation of these results would be that during these three months the occurrence of fog is more likely than at other times, and that fog may be present on approximately 20-30% of the days. We also determined the average number of hours of saturation on days when saturation occurs at BUZM3. The number of hours varies through the year from approximately 4.5 to 7.5, and averages approximately 6. Inspection of the saturation time series shows that this is a slight underestimate, as occasionally periods of saturation begin close to the midnight hour and continue for 4-8 hours. There is no indication of a significant seasonal variation in this average.

As noted above, these are aggregate results for periods when data from both the air temperature and dew point instruments are available, for the period 1997-2009. As indicated in the bottom panel of Fig. 1, the joint availability of the two data types varies around 60%.

Related results for the occurrence of fog using thermodynamic data from the offshore Air-Sea Interaction Tower near the Martha's Vineyard Coastal Observatory are shown in Fig. 2. Both the overall frequency of occurrence and the variation through the year differ from the BUZM3 site data shown in Fig. 1. The highest rate of occurrence at the MVCO site is somewhat lower than at the BUZM3 location, and elevated frequencies extend into September and October at MVCO, later in the year than at BUZM3. However, the differences may have limited significance. The peak frequencies are in the same range, and the occurrence of persistent, widespread fog may not differ significantly between these sites.

The annual variation of the **occurrence of icing days** at the BUZM3 site and the corresponding days of data availability are shown in the upper and lower panels, respectively, of Fig. 3. The count of days when light and moderate accumulation of ice could be expected on vessels underway is shown by the light and dark bars in the upper panel of Fig. 3, respectively. As expected, the threat of icing conditions is greatest during the winter months, when air temperatures are low and wind speeds are relatively high. The number of days when the icing potential could be expected to fall in the moderate category is less than 1 per month at all times, and approaches this value only in January. The corresponding estimate for the light accumulation category is higher than 5 days per month in December, January and February.

The uncertainty in the peak values as estimated here may be significant because of the limitation in the availability of data. Because icing is not especially common in this area, missing data periods may happen to include the very conditions we seek to document. In this context it is worth noting that some of the months with the least days of data availability fall in the winter, when icing conditions are most common. Thus the values shown in Fig. 3 should be taken as a lower limit. However, as discussed in the following paragraph, the majority of the icing predictor estimates suggest only very light accumulation rates.

As noted in Section 3, above, the icing rate estimation algorithm yields values in three or four categories. The distribution of the occurrence of (days of) icing *vs*. expected rate of icing is shown in Fig. 4, using the parameterized characterization for the icing potential as a continuous variable discussed by Overland (1990). The upper limit of the low and moderate categories are indicated by the red, vertical lines. Note that the vast majority of cases in the low category fall are at the low end of the accumulation rate scale. The relatively few cases in the moderate category, similarly, fall at the low rate side of the category domain. There are no cases that fall in the high accumulation potential category.

Time of day vs. day of year displays of the surface ozone mixing ratio measured onshore at Narragansett, RI, are shown in Fig. 5; panels a) through g) show data for 2003 through 2009. The filled colors indicated mixing ratio values in 5 ppbv (parts per billion by volume) increments, as indicated by the color bar at the right, and the intervals in black include values exceeding 125 ppbv. The green/yellow transition is at 75 ppbv, a limit in current regulations; periods of 8 hours at or above this mixing ratio are counted toward non-compliance with EPA ambient air quality standards. Periods exceeding this value occur irregularly each year. Ozone decreases at night, in the absence of light to drive photochemical production, and low values are observed to extend well after sunrise on many days at this site.

In 2004 there were unusually few occurrences of high ozone at Narragansett. In 2006 there was a highly polluted period in July. In 2007 there were frequent pollution outbreaks in June, July and August, and an event extending over several days occurred in July, 2008. The structure and variability of the ambient ozone concentration as observed adjacent to the Ocean SAMP area is a reminder of the role of anthropogenic emissions of precursors, leading to significant pollution events.

5 Discussion

The conditions conducive to the formation of fog indicated at the two offshore tower sites are believed to be representative of the Rhode Island Ocean SAMP area, given their similar environments and relative proximity. Additional analysis of the distribution of the depression of the dew point temperature below the ambient air temperature at BUZM3 (not shown) indicates that the lower quartile of the distribution of this difference exhibits especially low values indicating saturation and the potential for fog formation or persistence, during the summer months. In particular, the difference falls at 0˚C during June, July and August, consistent with the counts of days when fog is expected, as shown in Fig. 1. Similarly, analysis of the air/water temperature difference (not shown) indicates warm air flowing over cooler water in the months March-September, and most commonly in June, July and August, again consistent with the analysis shown in Fig. 1. Kotsch (1983) presents a figure (also shown in Hsu, 1988) mapping areas of common occurrence of fog during the summer months along the northeast coast of the

US and Canada. The broad characterization of "20 to 30 days" of foggy conditions during June-August shown there is consistent with the results presented here.

Observations of fog at onshore and island sites also corroborate the analysis presented here. Estimates of the frequency of occurrence of fog at the airport at Block Island were tabulated in the Annual Summary of Local Climatological Data. For example, in 1982 a summary for a 14-year period ending in 1982 indicated that heavy fog, with visibility restricted to 0.25 miles or less, occurred most commonly in May – August. The average number of days with heavy fog during these months was reported as 11, 11, 12 and 11 over this period. In contrast, fewer than 5 days per month with fog were reported for the months October – February. Conditions favorable for fog formation differ between the airport location and the open waters of the Ocean SAMP domain, but the widespread distribution of fog observed in these coastal environments is evident in the correspondence between these fog frequency estimates.

As noted above, air saturation can occur in the absences of fog, for example during precipitation, when evaporation leads to moistening of the air. Consequently, counting air saturation as an indicator of fog overestimates fog occurrence. However, intense rainfall can reduce visibility, so that the overestimation of the frequency of fog events may improve the utility of this estimate as an indicator of the frequency and duration of impaired visibility.

The estimates of the occurrence of conditions favorable to the accumulation of ice on vessels underway discussed above are based on data from the BUZM3 site, but these, too, are believed to be representative of conditions likely to be encountered in the Ocean SAMP area. The infrequent occurrence of water temperatures lower than 6˚C is a primary determinant of icing potential, and the Ocean SAMP area has similar characteristics to Buzzards Bay in this regard.

6 Conclusions

The analysis of the occurrence of foggy conditions presented here is based on meteorological data from two instrumented towers. The towers are the BUZM3 facility in Buzzards Bay, MA and the Coastal Observatory, offshore of Martha's Vineyard, MA. The data records are relatively short by the standards of climatological analysis, but the consistency with generally accepted knowledge supports a sanguine view of this limitation. Based on a data record corresponding to about 8 years of observations at BUZM3 and 3 years of data at MVCO, the annual variation of foggy periods has its peak values during the months of June, July and August, with peak frequencies in the range of 6-11 days per month with one or more hours of fog. In the winter months fog is much less common in this area, with occurrence on fewer than 3 days expected in each of these months. Hours of air saturation conditions on days when saturation occurs vary from 4.5 to 7.5 hours, with an average value of approximately 6 hours. There is no apparent seasonal variation in this figure.

The analysis of conditions favorable for the accretion of ice on moving vessels requires joint availability of wind, air temperature and water temperature observations. The ice accumulation analysis was limited to the BUZM3 site here. The results indicate that light accumulation conditions can be expected to occur on 5 or more days per month in the offshore area during the months of December, January and February. The frequency of moderate ice accumulation conditions is much lower, with less than one day per month of such conditions expected during the coldest weeks of winter. It is important to note that the majority of cases of icing conditions correspond to very low rates of accumulation predicted.

The analysis of ambient ozone mixing ratios presented here is based on surface observations made for air quality monitoring in the regulatory context at Narragansett, Rhode Island, onshore and adjacent to the Ocean SAMP area. Frequent occurrences of ozone exceeding the current regulatory value of 75 ppbv (parts per billion by volume) are evident in the data. Pollution outbreaks tend to occur in the sunny, warm summer months, and can extend over periods of hours to days. Outbreak events are regional in character, with ozone and ozone precursors transported from distant sources playing a significant role. Nevertheless, these occurrences could be extended by emissions of ozone precursors from offshore marine operations, although the impact on surface ozone may be greater in the downwind area than locally. In any event, the EPA has regulatory authority in the study area, and an emissions permit will be required for any planned construction or maintenance activities.

7 Acknowledgments

The Rhode Island Ocean SAMP program provided support for part of the work presented here. Alexander Lataille carried out some of the data acquisition and analysis while working here as a summer intern, and GSO graduate student Michael St. Laurent helped put some of the results in graphical form. Ruth Platner assisted and enabled this work with advanced computer programming skills. The ozone profile data were acquired with support from the NOAA

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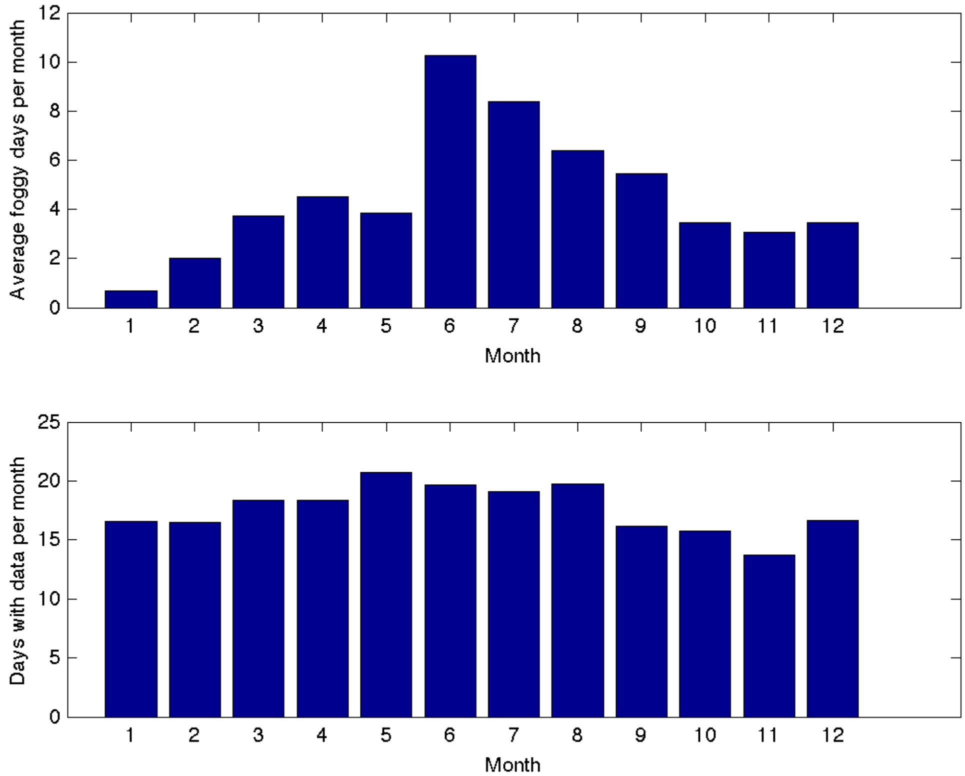

Figure 1. Annual distribution of days with one or more hours of fog at BUZM3 (upper panel) and days of available data (lower panel).

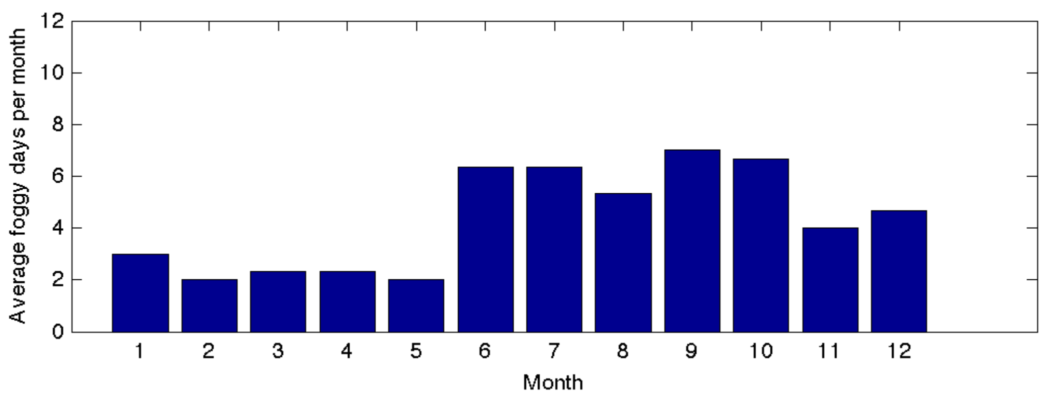

Figure 2. Annual distribution of days with one or more hours of fog at MVCO.

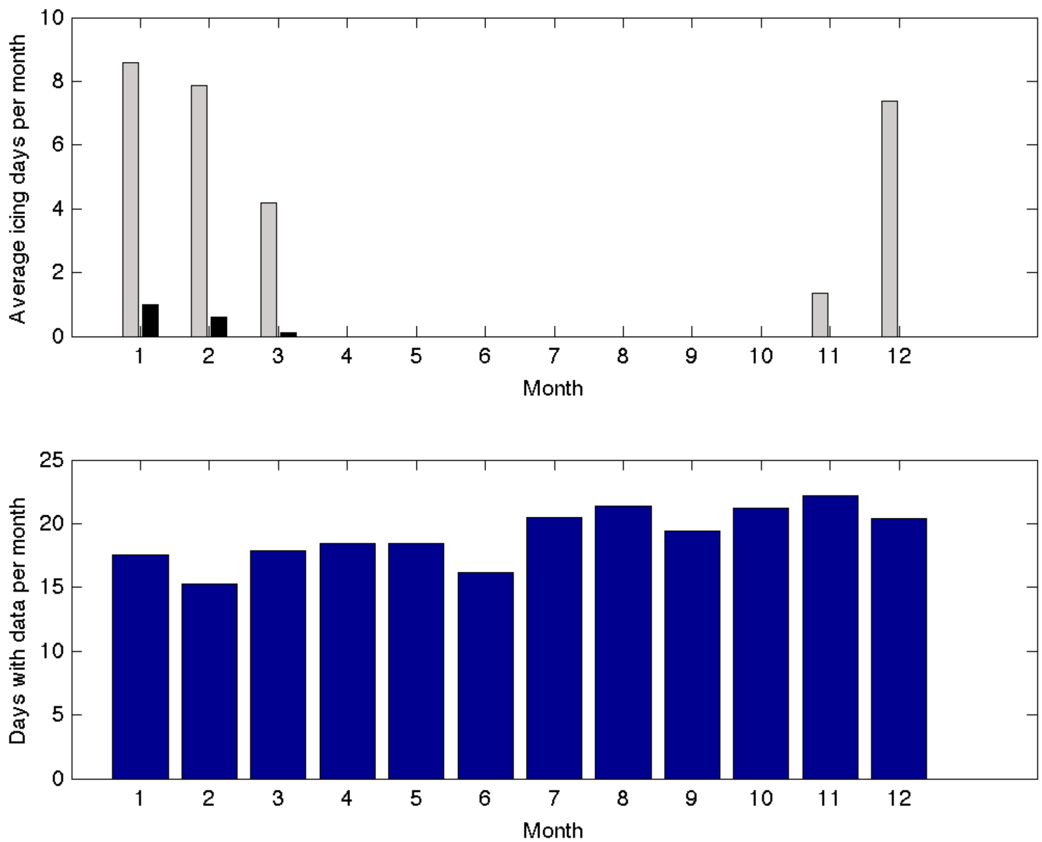

Figure 3. Annual distribution of icing days at BUZM3, in the light and moderate categories, in light and dark bars, respectively, (upper panel) and days of available data (lower panel).

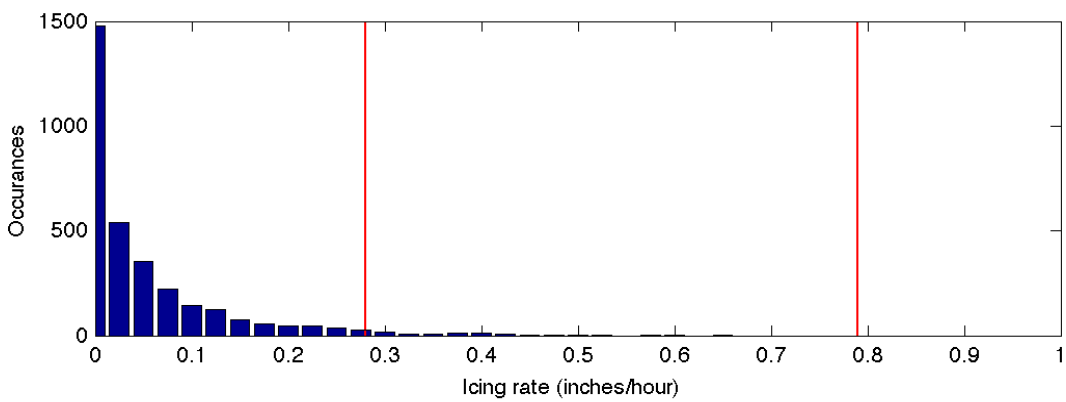

Figure 4. Occurrences vs. rate of icing, summed over available data periods at station BUZM3. The limits of the light and moderate accumulation categories are shown by the vertical bars.

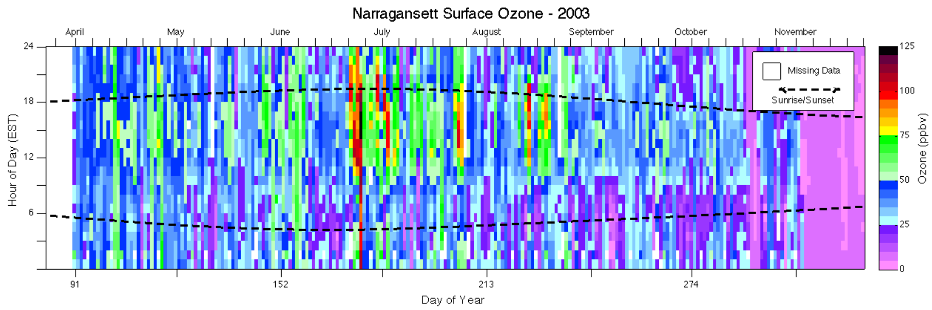

Figure 5a. Surface ozone mixing ratio, parts per billion by volume, displayed in hour of the day vs. day of the year form. Data for the Narragansett EPA laboratory site for the ozone season of 2003. Sunrise and sunset times are indicated, and blank areas represent missing data periods.

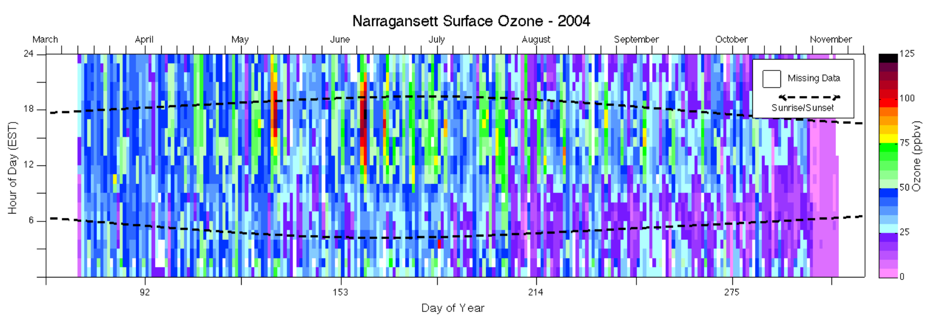

Figure 5b. Surface ozone mixing ratio data for Narragansett, 2004.

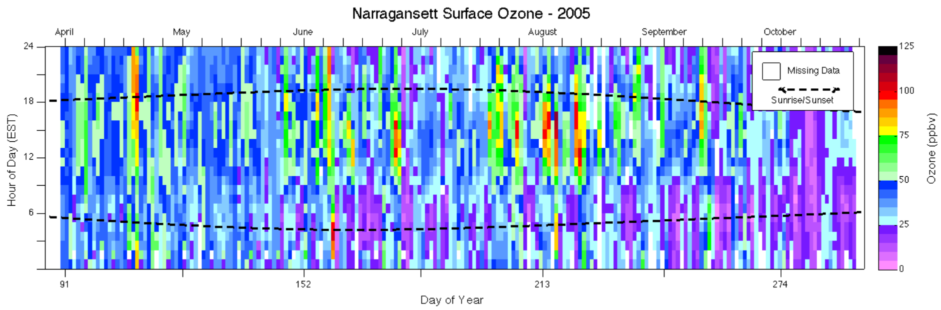

Figure 5c. Surface ozone mixing ratio data for Narragansett, 2005.

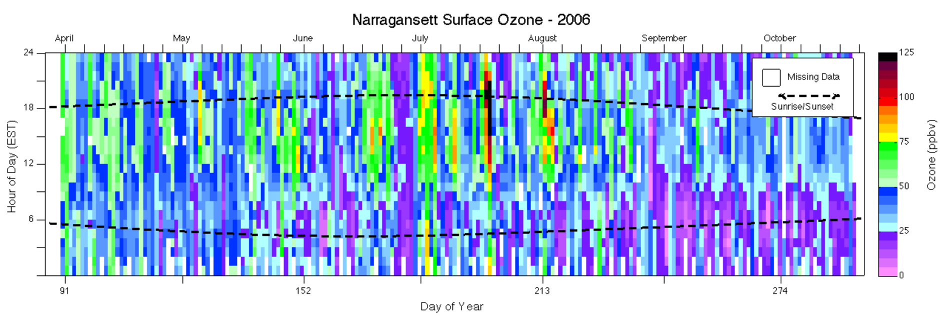

Figure 5d. Surface ozone mixing ratio data for Narragansett, 2006.

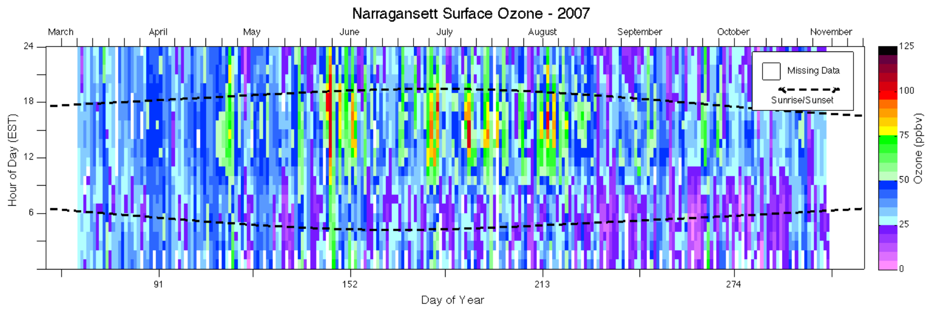

Figure 5e. Surface ozone mixing ratio data for Narragansett, 2007.

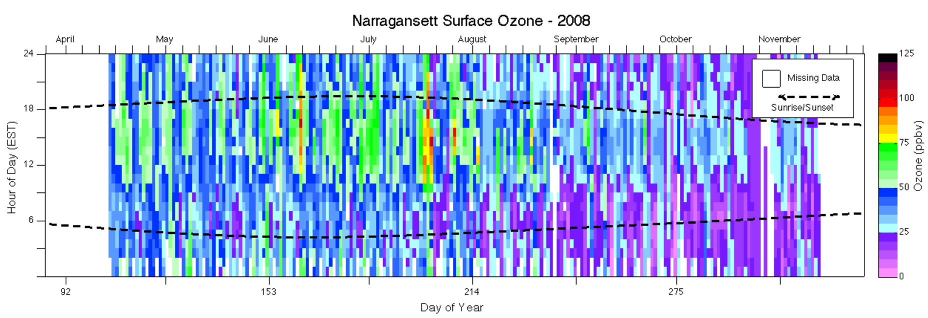

Figure 5f. Surface ozone mixing ratio data for Narragansett, 2008.

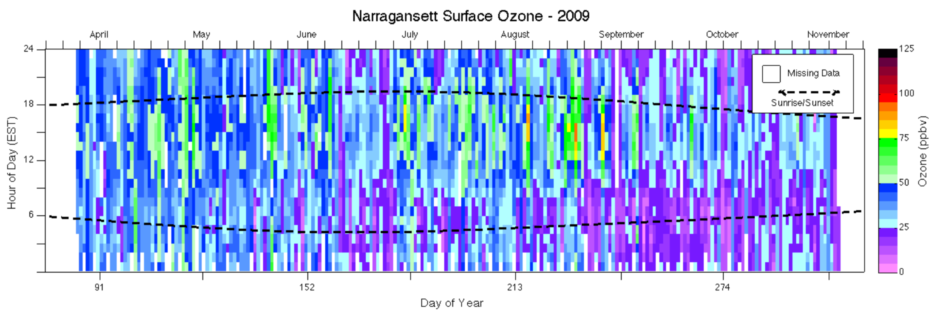

Figure 5g. Surface ozone mixing ratio data for Narragansett, 2009.