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Surface level measurements of ozone and precursors at coastal and offshore locations in the Gulf of Maine

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Abstract. The northeastern United States has episodic high ozone several times each year at locations remote from urban and industrial centers. Extended measurements of ozone and the ozone precursors, volatile organic compounds (VOC) and nitrogen oxides, were made at Acadia National Park, Cape Elizabeth, and other coastal Maine locations during the North Atlantic Regional Experiment (NARE) intensive. In addition, ozone was measured from a commercial ferry, the *Scotia Prince*, in the Gulf of Maine where ozone concentrations up to 129 ppb were observed. Two high-ozone episodes were observed during late August 1993 when ozone was greater than 90 ppb along much of the Maine coast. NO_y concentrations at Acadia averaged 2.0 ppb (±1.97), maximum 12.0 ppb. During the high-ozone episodes, NO_y had linear relationships to ozone with slopes of 4–16. The timing of maximum values and extent of the high-ozone air mass suggests that urban plumes transported over the Gulf of Maine are brought inland by sea breezes to the coastal regions but not to the interior areas of Maine.

1. Introduction

Ozone concentrations in rural areas of the northeastern United States are significantly higher than background levels suggested by computer models [*Meagher*, 1987; *Logan et al.*, 1989; *Eder et al.*, 1993; *Kleinman*, 1994] and well above remote oceanic concentrations [*Oltmans and Komhyr*, 1986; *Ray et al.*, 1990a]. The coastal states along the Gulf of Maine (Maine, Massachusetts, New Hampshire) demonstrate a high background level of ozone and episodic high-ozone events that are dependent on meteorological conditions. Continental ozone and precursors are transported [*Dattore et al.*, 1991; *Cleveland et al.*, 1976; *Pinkerton and Lefohn*, 1987] from the central United States and from urban areas along the U.S. East Coast to the Maine coastal regions. The land-sea interface is the last location for routine observation of ozone concentrations before transport of air masses out over the northern Atlantic Ocean [*Fehsenfeld et al.*, this issue]. Since inputs of ozone precursors effectively cease after air masses leave the continent [*Helas and Warneck*, 1981; *Ray et al.*, 1990b], measurements along the coast can help define the initial conditions for air that will undergo photochemical processing over the Atlantic Ocean.

The northeastern United States has a band of ozone nonattainment areas that stretches from northern Virginia to Maine along the coastal portions of these states [*Environmental Protection Agency (EPA)*, 1992, 1994]. The nonattainment status was determined by measurement of multiple exceedances of the National Ambient Air Quality Standard (NAAQS) of 0.12 ppmv within those areas. The Maine state standard for ozone is more stringent, at 81 ppb; this standard is exceeded often along the Maine coast. The region from Virginia to Maine has high densities of anthropogenic NO_x (defined as $NO + NO_2$) and volatile organic compound (VOC) emissions. Many of the northern states in the region, like Maine, have significantly lower local anthropogenic emissions of NO_x and VOC. Maine can be described as NO_x limited; VOC from point, area, mobile, and biogenic sources total 3790 metric tons/summer weekday, and 3486 metric tons (92%) of that are derived from the biogenic sector. These same sources produce 303 tons/summer weekday of NO_x (State of Maine DEP 1990 Emissions Inventory). These emissions of NO_x and anthropogenic VOC are a small fraction of the total emissions from the urban corridor to the south. Thus transport is expected to play a significant role in the high ozone concentrations observed along the Maine coast.

The highest-ozone events recorded in Maine have been documented to coincide with transport episodes originating from the major metropolitan centers to the south and southwest (e.g., the summer of 1988, with 19 days of national ozone standard exceedances). Photochemical computer models [*McKeen et al.*, 1991; *Sillman et al.*, 1990] have been used to explore the interactions and to predict results from different control strategies. As a rule, modeling predicts that reductions in NO_x yield greater decreases in ambient ozone concentrations than that of equal reductions in VOC. *Samson and Shi* [1988] examined the wind flow for all days in 1983–1985 when ozone exceeded 80 ppb in 17 rural sites across the NE using trajectory calculations integrated backward to the source region. They found that days with concentrations above 120 ppb were generally associated with low wind speeds, with one exception: in Portland, Maine, high-ozone days were associated with moderate winds, presumably due to long-range transport of ozone from the south and west.

Rosenbaum et al. [1994] have mapped areas in the United States where ozone levels exceed critical levels for impact on crops, forests, and natural vegetation. Much of the seaboard areas of the northeastern United States exceeded the critical levels, including the coastal areas of Maine. Since effects on

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Table 1. Summary of the Air Quality Instrumentation Available at the Two Coastal Maine Sites

Species or Parameter	Principal of Measurement	Detection Limit
	Acadia National Park, Mount Desert Island, Maine	
O_3	UV absorption	1 ppb
NO	O_3 chemiluminescence	<0.1 ppb
NO_y	measured as NO following reduction by externally mounted molybdenum catalyst	<0.1 ppb
Hydrocarbons	canister samples, GC-FID	0.01 ppbC
Wind speed	anemometer, photocoupled chopper	13 m/min
Wind direction	rotating vane/potentiometer	1.0°
Temperature	thermistor	0.1°C
Dew point	thermistor	0.5°C
	Two Lights State Park, Cape Elizabeth, Maine	
O_3	UV absorption	1 ppb
NO	O_3 chemiluminescence	0.1 ppb
NO_2	calculated as the difference NO_x − NO	0.1 ppb
NO_x	measured as NO following reduction by a molybdenum catalyst	0.1 ppb
Hydrocarbons	continuous GC-FID	0.01 ppbC
Wind speed	anemometer, photocoupled chopper	13 m/min
Wind direction	rotating vane/potentiometer	1.0°

vegetation by ozone are expected at levels below the NAAQS, even high-ozone events of 80 ppb or above can be significant. The number of ozone events within areas determined by principal component analysis of rural ozone data in the east was addressed by *Eder et al.* [1993]. A regional factor for the United States from Pennsylvania and northward was found to differ in the number and type of ozone events from other regions. The NE region has high-ozone episodes that are thought to be largely controlled by migratory anticyclones [*Korshover*, 1975] guided by the summer jet stream; these anticyclones sweep across the northern United States before passing through the NE region. A dynamic balance occurs along the coastal NE United States between two influences: that of the flow around the Bermuda high, which has a strong effect on the mid-Atlantic region, and that of the migratory anticyclone paths which sweep west to east across the northern parts of the United States.

This article examines the surface-based records for high-ozone events, compares measurements of ozone precursors and their relationship with ozone concentrations, and examines periods of high ozone during the North Atlantic Regional Experiment (NARE) intensive with emphasis on observations from sites at Acadia National Park and Cape Elizabeth, Maine. In addition, it presents historical records and other recent measurements for comparison.

2. Experiment

Air quality instruments were operated at two coastal Maine sites during August and September 1993 in cooperation with the NARE intensive. The Mount Desert Island site is located in a clearing within Acadia National Park (44.3736°N, 68.2608°W) on a ridge at 120 m elevation. The area is lightly populated and the major local industries are tourism and fishing. It is surrounded by ocean, with the mainland to the east 10 km and numerous other islands within sight.

Ozone and other pollutant measurements have been made at this site since 1983. However, for this experiment, measurements (Table 1) of ozone, NO, NO_y, VOC, and meteorology were made. A Thermo Environmental Instruments model 42s analyzer was modified so that the molybdenum converter could be mounted externally on a 5-m tower. The inlet to the converter was a 3-cm stainless steel tube with a Teflon tee where NO calibration gas could be delivered. During operation the analyzer switched sampling modes among NO, NO_y, and a prereactor zero.

The ozone and NO_y analyzers at Acadia National Park were operated continuously from August 10 to September 17. The ozone analyzer was compared to a transfer standard twice annually and a multiple-point calibration was performed monthly with an on-site transfer standard and ozone source. In addition, a zero and span check was activated automatically each night to monitor the instrument performance. Multiple-point calibrations and converter-efficiency checks for the NO_y analyzer were performed during installation and again before deactivation. Nightly zero/span checks for the NO_y analyzer were automatic and timed to be just after the ozone analyzer check. Calibration of the NO_y analyzer was also checked by comparison of a cylinder of standard NO with the NO_x analyzer run by the State of Maine at Two Lights State Park and with a standard cylinder of NO provided by the NOAA Aeronomy Lab.

The measurement site at Two Lights State Park is on an exposed point, Cape Elizabeth, just south of Portland, Maine (43.5608°N, 70.2078°W). Ocean and rocky cliffs surrounds the site on three sides. This state-operated station measured O_3, NO, NO_x, and VOC in addition to meteorological parameters (Table 1). Measurements of NO and NO_x at the site were made with a Thermo Environmental Instruments model 42s analyzer operated in the standard configuration, i.e., with the molybdenum converter internal to the analyzer. As such, the NO_x values represent more than NO + NO_2 but less than the NO_y measurements, which are defined as the sum of all oxidized nitrogen oxide species. Nightly zero/span checks and periodic multiple-point calibrations using a National Institute of Standards and Technology (NIST) traceable standard were made to the span port of the analyzer.

Other monitoring station data were obtained for the intensive period, including ozone measurements from the Scotia Prince, a 144-m international ferry that makes a daily round trip from Portland, Maine, to Yarmouth, Nova Scotia. The

Table 2. Summary of High-Ozone Events in the Northeast United States

Year	Number of Days >80 ppb			Maximum O_3 During Year		
	Acadia National Park	Cape Elizabeth, Maine	Cape Cod National Seashore	Acadia National Park	Cape Elizabeth, Maine	Cape Cod National Seashore
1983	25	...	...	138	...	...
1984	26	...	...	140	...	...
1985	20	28	...	120	167	...
1986	8	15	...	109	131	...
1987	11	19	...	130	156	...
1988	34	39	...	179	178	...
1989	5	17	...	130	146	...
1990	10	18	...	123	148	...
1991	18	30	...	128	145	...
1992	9	20	20	108	128	122
1993	12	17	18	112	122	124
Average	15.5	22.6	19.0	126.6	146.8	123.0
Standard deviation	8.6	7.6	1.0	19.6	17.3	1.0

ship remains in each port for exactly 1 hour before traveling the distance between ports (327 km) in 11 hours. Dead-reckoning positions (i.e., position determined by speed and time along a heading) correspond to hourly averaged measurements by the ozone monitor. The monitor placement near the bridge, on the bow side, was away from any emission sources on the ferry; thus contamination of the inlet air by onboard sources was unlikely when the ferry was under way at its normal speed of 32 km per hour. Quality assurance of this data set followed EPA-recommended methods. Data from other monitoring sites along the east coast were obtained either from the State of Maine or from the U.S. Environmental Protection Agency AIRS database.

3. Results and Discussion

The synoptic meteorology for the entire month of August 1993 has been described by *Angevine et al.* [this issue] and *Merrill and Moody* [this issue]. It is also important, however, to describe some local climatology. Widespread exceedances of the federal ozone standard in the northeast have been associated with large, stagnant air masses characterized as summer days with high solar radiation and warm temperatures. During the summer of 1993, the National Weather Service office in Portland, Maine, recorded one of the warmest, driest, sunniest summers in 53 years of data collection. August 1993 daily average temperature varied from the norm by +1.19°C and by +1.17°C for maximum average temperature. A deficit of 4.22 cm of measurable precipitation for the month and an additional 13 hours of sunlight above the normal were recorded. Yet, only the years of 1986 and 1981 have produced fewer exceedances of the national ozone standard than did 1993.

A series of coastal sites from Cape Cod to northern Maine were examined to determine how often high-ozone events occurred. Table 2 summarizes for three sites the number of days when the ozone was above 80 ppb as well as maximum ozone concentrations observed each year. The high-ozone days occur almost exclusively from May to September. Acadia averages 15.5 days per year when ozone is above 80 ppb, whereas Cape Elizabeth averages 22.6. During 1993 the number of greater than 80 ppb days was below average at Acadia (12) and Cape Elizabeth (17). Another coastal site farther south, Cape Cod National Seashore, had 18 greater than 80 ppb days. Each of these events represents days when high ozone concentrations were likely to be transported eastward and north into the Gulf of Maine and subsequently over the Atlantic Ocean.

Although maximum ozone concentrations have declined in the years since 1988, no regular and consistent trend based on hours of ozone greater than 80 ppb emerges. An analysis by *Zurbenko et al.* [1995] showed no significant trend in O_3 maxima in the NE United States after accounting for the effects of meteorology (temperature) during the period 1980–1992. However, for just the period after 1988, most of the NE United States and the Maine coastal area have decreased slightly in temperature-independent ozone concentrations.

The rural nature and absence of major combustion sources for the Acadia observation site is indicated by several different factors. The average diurnal ozone cycle for Acadia in the last week of August had a day-night difference of about 15 ppb and an overnight low of about 38 ppb. By comparison, the diurnal cycle at Cape Elizabeth near Portland, Maine had a day-night difference of 23 ppb and an overnight low of 24 ppb. The Chelsea, Massachusetts, site outside Boston had a day-night difference of greater than 80 ppb and an overnight low of 0 ppb. Low overnight concentrations are typically due to titration by NO in fresh NO_x emissions and by deposition. At the state operated Chelsea site, observed ozone and NO_2 peaks lag each other and are anticorrelated. Cape Elizabeth has a similar offset and anticorrelation but less pronounced. At Acadia, ozone and the total NO_y were correlated only during periods of high ozone (Figure 1); This is an indication of aged pollutants and that titration of ozone from fresh NO_x emissions at night is minor.

During the NARE intensive, two high-ozone episodes were observed in late August at the ground stations in Maine. Figure 1 shows the hourly averaged ozone and NO_y concentrations observed at Acadia National Park for the selected period. The first episode occurred August 24 when a 1-hour high of 90 ppb ozone was observed at about 1400 LT; NO_y concentration also peaked at this time and NO concentrations were <0.1 ppb. The second episode occurred August 27–28; a 1-hour high of 112 ppb was observed at 1800 on August 27 and a high of 87 ppb was observed on the next day. The ozone peaks on August 27 and 28 also had high NO_y concentrations associated with them.

Surface winds during the high-ozone days were generally

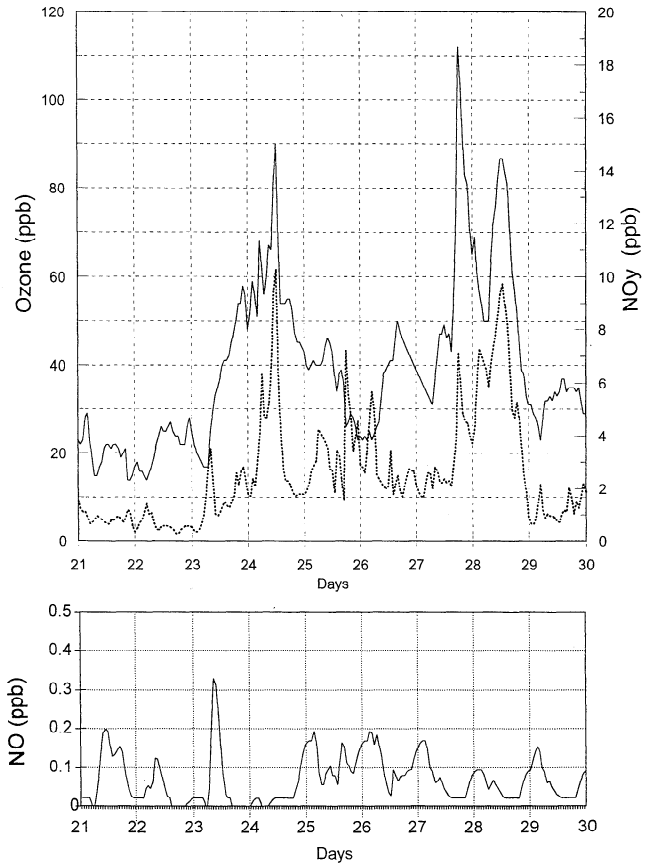

Figure 1. Observed mixing ratios for ozone (solid line) and NO_y (dashed line) at the Acadia National Park site during August 1993. The NO concentration during the same time period is shown in the bottom plot.

from the southwest or south. The dominant wind direction blows onshore during the day as a sea breeze for both the Cape Elizabeth and Acadia sites during August. Wind speed follows a diurnal cycle: winds are low at night (3–8 m/s) and higher in the afternoon (9–14 m/s), a pattern also typical of land-sea breezes. The land-sea breeze pattern was especially evident at Cape Elizabeth during the period between August 24 and 28 when the winds were from the south during the day and the northwest at night. At that time, the NE United States was dominated by a high-pressure area over the eastern United States [*Merrill and Moody*, this issue]. Maximum daily temperatures for much of the East were in the low 30°C range for August 27 and 28. The end of the ozone episode on August 28 was marked by a rapid shift in winds to northwesterly and a drop in temperature. The passage of a front from west to east was characterized by scattered showers, mostly along the coastal areas.

These two high-ozone episodes had different characteristics. On August 24 at Acadia the winds were from the south and NO_y was high (10 ppb) and strongly correlated to the peak ozone. In contrast, on August 27 and 28 winds were from the southwest and NO_y was lower. On August 26, ozone exceeded the State of Maine standard (81 ppb) at Isle Au Haut at 2200 and 2300. On August 27, five of the seven coastal air quality monitoring stations reporting to the EPA AIRS database exceeded the state standard at 1800, and the other two monitoring stations exceeded the standard at 1700 and 2100. Ozone readings at this time at inland sites (Figure 2) were in the 30 to 60 ppb range.

Although the map in Figure 2 would seem to suggest that the Boston urban area had lower ozone, the maximum ozone for the Boston area had already occurred early in the afternoon. The timing of the peak ozone periods at the different coastal sites (Figure 3) for the month of August tells much about the issue of transport. Ozone values peaked at slightly later times and the peaks increased for the progressively more northern sites on August 24, 27, and 28. Wind speeds were too low for transport of ozone on the same day from the Boston area to account for the observations. Minimum ozone values for each of the three observation sites decreased for the progressively more southern sites.

Ozone peaks differed in shape as well as time for the maximum concentrations on each of the high-ozone days (Figure 3). On August 28 the double peak observed at Portsmouth becomes progressively less distinguishable at higher latitude. August 23 and 26 show similar behavior; peaks distinguishable at Portsmouth are just barely distinguishable at Acadia. In some cases, ozone spikes in the urban areas are not distinguishable at Acadia at all. There are several possible reasons for this, one explanation might be that plumes coming off the urbanized eastern coast either are going away from the northern Maine sites or that they have not traveled that far as yet. Another possible explanation is that on some days the Acadia site at 120 m is above the boundary layer height that occurs over the water, whereas the Cape Elizabeth and Portsmouth sites are closer to sea level.

Ozone precursors that help to characterize the sites have been measured at Acadia and other coastal locations. VOC sampling was done manually only on selected days during the NARE intensive, based on forecasts of high ozone levels. Un-

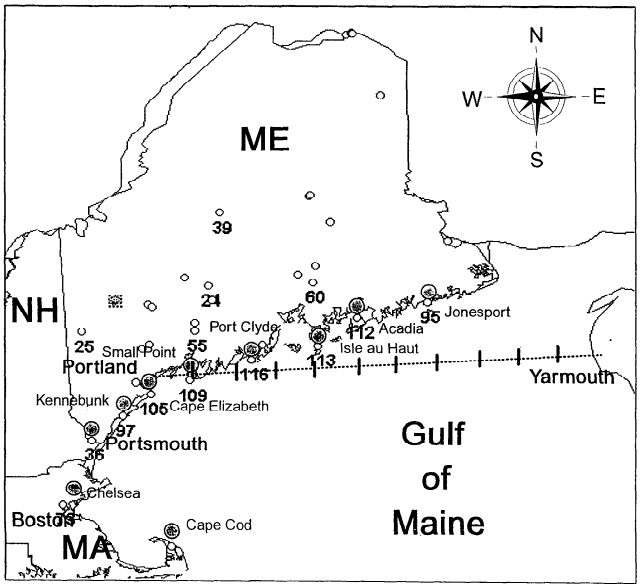

Figure 2. Map of the Gulf of Maine area showing ozone concentrations at selected coastal monitoring sites in the Northeast United States for August 27 at 1800 LT. The dotted line is the approximate path of the *Scotia Prince* on its trips between Portland, Maine, and Yarmouth, Nova Scotia. At the time of this map, the *Scotia Prince* was just off Small Point and the observed ozone concentration was 120 ppb. Hourly ozone concentrations are given for reporting coastal monitoring stations.

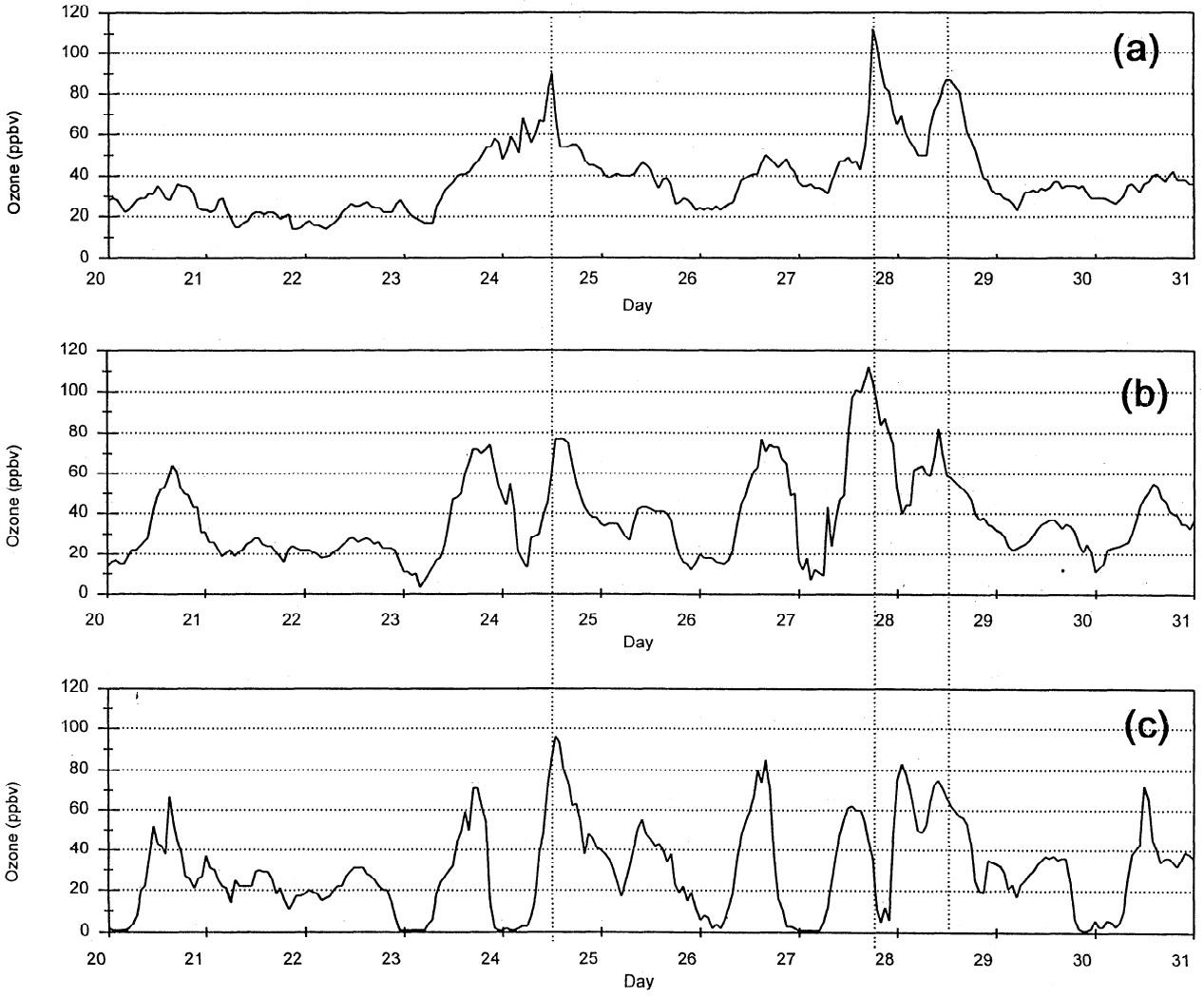

Figure 3. Ozone concentrations at three coastal northeast sites are compared during August 1993 for the timing of the ozone peaks: (a) Acadia National Park, Bar Harbor, Maine; (b) Cape Elizabeth, Portland, Maine; (c) Portsmouth, New Hampshire.

fortunately, the forecasts were unreliable and no samples were taken at either the Acadia or the Cape Elizabeth sites during the August 27 and 28 episode. Ozone forecasts relied heavily on forward trajectory analysis supplied by Atmospheric Environment Service of Canada, as well as NGM model prognostications. During the August 27 and 28 episodes, there appears to have been a "westerly bias" in the trajectories that probably did not account for boundary layer over the Gulf or local sea breeze effects. *Angevine et al.* [this issue] describes the boundary layer (BL) that develops over the Gulf and presents vertical profiles of potential temperature suggesting BL depths of approximately 100 m. The lack of routine, direct low-altitude weather measurements over the Gulf may contribute to the bias by the model.

Milford et al. [1994] suggested that NO_y concentrations can be used as indicators of the photochemical sensitivity of an air parcel. Simulations show that the ratio of reactive organic gases (ROG) to NO_x increase as the air parcels age, with more rapid increases for low initial concentrations. Peak O_3 is sensitive to NO_x in air parcels with low final NO_y concentrations below the 10–25 ppb range. Surface measurements at Acadia National Park during high-ozone days showed a positive correlation to NO_y concentration only when NO_y was in the 6–10 ppb range during the high-ozone days. On other days, ozone and NO_y were anticorrelated or uncorrelated. Since no separate nitric acid measurement was made, the amount of aged nitrogen oxides is unknown, but at an isolated rural location, NO_x concentration would be expected to be low. NO concentrations (Figure 1) were generally below 0.2 ppb; NO concentrations of 0.1 ppb or less were observed on the high-ozone days.

The plot of ozone versus NO_y for August data has a broad envelope of all the measurements with poor correlation (R^2 = 0.3). Specific high-ozone periods, however, had linear relationships during the daytime hours of 0900 to 2000 nighttime (Figure 4) when the NO_y was greater than 2.5 ppb. For example, the August 27 data had a slope of approximately 15 (R^2 = 0.97); for August 24 and 28 the slope was 4.5 (R^2 = 0.95). The slope implies the amount of ozone production per nitrogen oxide species emitted into that air parcel. A high correlation is expected only for those air masses in which ozone production has occurred in the relatively recent past [*Kleinman et al.*, 1994]. The slope is dependent on the specific NO_x concentrations and hydrocarbon precursors involved in the photochemical ozone production, which suggests that slightly dif-

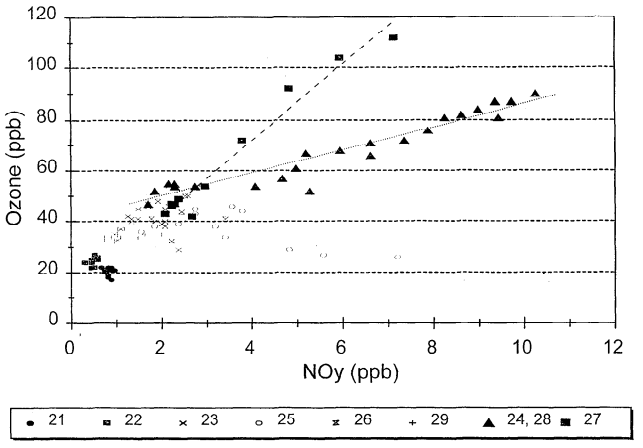

Figure 4. Hourly averaged ozone and NO_y for August 21–29. The long-dashed line is the approximate linear relationship for daytime hours of August 27; the dotted line is the approximate linear relationship for daytime hours August 24 and 28.

ferent source areas may be represented by the different slopes [*Liu et al.*, 1987; *Trainer et al.*, 1993]. Large slopes, such as on August 27, indicate higher production of O_3 and more highly photooxidized NO_x products. When O_3 correlates with NO_y and concentrations are less than 10 ppb, then simulations [*Milford et al.*, 1994; *McKeen et al.*, 1991] indicate that the regime is NO_x limited.

An explanation for the observed high-ozone concentration episodes along the Maine coast is that ozone precursors are transported to the area and photochemical production leads to peak ozone at about the same time for the different coastal sites. The isentropic flow probability fields for forward trajectories from Boston [*Merrill and Moody*, this issue] and the observations from the Scotia Prince suggest that the dominate flow is to the NE over the Gulf of Maine and that the Maine coast is at the edge of the flow. The fact that inland monitoring sites have lower maximum ozone concentrations during the high-ozone events along the coast is explained by transport SW to NE along the coast rather than being transported from the west. Transport of the ozone and precursors out over the Gulf of Maine followed by photochemical production adds to the pool of ozone during each day of transport and daily sea breezes bring the ozone to the coastal regions. A strong land-sea interface and the direction of airflow limits how far marine air can penetrate inland.

During the last three years of ozone measurements from the *Scotia Prince* ferry, numerous plumes have been observed in the Gulf of Maine, including observations of multiple plumes during a single passage between Portland and Yarmouth. The majority of plumes achieve their peak concentrations between 1 and 3 hours offshore (32–96 km). Ozone concentrations measured on the *Scotia Prince* generally decreased from the Maine coast to the Yarmouth side of the gulf as illustrated by data collected between August 26 and 28 (Figure 5). The maximum ozone concentration of 129 ppb observed on the *Scotia Prince* during the NARE intensive (Figure 5) occurred at 1700, August 27. At that time, the highest coastal ozone (122 ppb) was at Small Point. One hour later the ferry was closer to Small Point and the ozone concentration observed was 120 ppb compared to the coastal concentration of 109 ppb (Figure 2). Since the winds were blowing toward the coast, the high-ozone plume over the gulf provided a reservoir of ozone.

An examination of the ozone plots of the *Scotia Prince* (Figure 5) on August 26 shows ozone in the 50–60 ppb range within the gulf. By August 27 a significant plume with high ozone was observed off the coast of Maine but with ozone concentrations that decreased rapidly toward the eastern side of the gulf. On the return trip, the high ozone concentrations were found over a broader part of the Gulf and the peak ozone location had shifted to the east. This pattern was repeated on August 28 until a cold front pushed the plume out of the Gulf of Maine.

4. Conclusion

Coastal measurements of high ozone concentrations have been observed for several years. Although the number of high-ozone events and their magnitude vary from year to year depending on the meteorology, the number of events observed during the NARE intensive followed much the same pattern as in years past. There is a slight downward trend in ozone exceedances of the 1-hour national ozone standard in Maine and the Northeast; however, the number of days with ozone above 80 ppb do not show a significant trend. In general, 16–22 event days of ozone greater than 80 ppb are expected in a typical year.

The timing of the observed peak ozone concentrations along the coast of Maine and the pattern of only coastal high ozone concentrations certainly points to transport rather than ozone production from local emissions. The low NO_y concentrations and their correlation to ozone during high-ozone events supports a conclusion that the area is within a NO_x-limited regime. Further measurements and computer simulations will be needed to verify this and suggest control strategies for ozone. Because of the minimal influence of local sources in the development of a high-ozone event at Acadia National Park, it appears that regional strategies will be needed to reduce the ozone precursors that lead to these high-ozone levels.

The transport picture that emerges for the late August episodes is that a high-pressure zone located over the eastern United States generated airflow off the continental United States and to the NW across the Gulf of Maine. This air mass

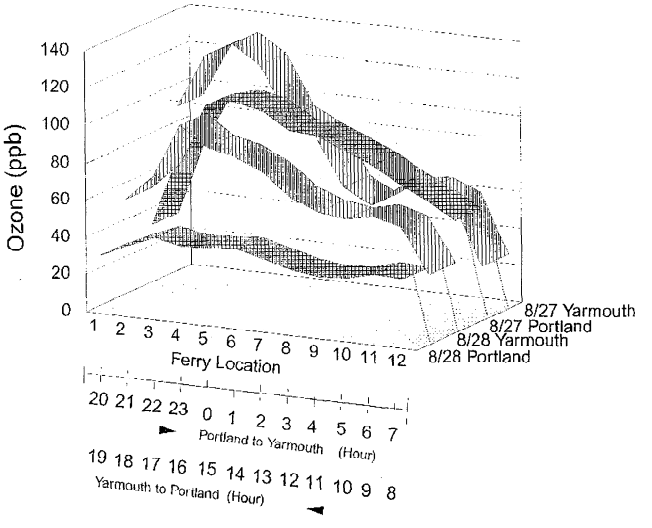

Figure 5. Ozone measurements from the ferry, *Scotia Prince*, showing a plume over the Gulf of Maine. On August 28 a cold front moved through the region and carried the plume to the east. The ferry location scale refers to equally spaced locations along the ferry path from Portland to Yarmouth (see Figure 2). The date and starting point are given for each ferry traverse.

contained background ozone and ozone precursors from the midwest and fresher ozone precursors from eastern seaboard urban areas [*Merrill and Moody*, this issue]. A lower-surface boundary layer formed and stratification occurred as warmer air overrode cooler air above the water [*Angevine et al.*, this issue]. During transport of the polluted air mass over the gulf, additional ozone was produced photochemically with little added input of precursors or deposition losses. The broad, downwind plume from the urbanized eastern coast showed its maximum ozone concentrations offshore in the gulf; however, during the day a land-sea breeze carried the ozone to the coast. Since the sea breeze was relatively shallow, only the coastal areas show high ozone concentrations; inland locations showed much lower concentrations. The air coming off the gulf may gain fresh NO_x and VOC precursors, especially biogenic organics, along the coast that may contribute to further ozone production. The timing of the peaks at measurement sites along the coast was determined then by factors, such as temperature (that determined the strength of the sea breeze), the location offshore of the plume, and the amount of photochemical ozone produced during the day.

Transport of air masses from the major urban areas south of Maine and from along the east coast was suggested from surface-wind observations, back trajectory analysis, and chemical indicators. The NO_y was indicative of aged air with ozone and precursors transported from more urban areas. Ozone plumes along and within the Gulf of Maine migrate not only eastward but westward as well. Observed plumes in the Gulf generally ranged in width from 55 to 93 km and could effectively stretch along the entire Maine coast at one time. Transport of these plumes from upwind locations plays a significant role in the air quality in Maine but may represent only the edge of the plumes that move northeast and out to the North Atlantic.

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