DD16

Technical Support Document

The Long-Range Transport of Ozone in the Ozone Transport Region

January 1994

Ozone Transport Commission
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Washington, DC 20001

I. INTRODUCTION

A. PURPOSE OF REPORT

It is widely agreed that the severe ozone pollution problem experienced in the northeast and the mid-Atlantic states during the summer months cannot be solved without addressing the long-range transport of ozone and its precursors which is a dominant feature of the ozone problem in this area of the country.[1] (Long-range transport in this report refers to transport distances of up to hundreds of kilometers and over a period of two to seven days). Convinced of the necessity of regional ozone control strategies, Congress, under Section 184(b) of the 1990 Clean Air Act Amendments (1990 CAAA), required all states within the Ozone Transport Region (OTR) to implement a basic menu of region-wide controls. The purpose of imposing these minimum regional controls was to ensure that the OTR states made speedy progress in beginning to address the problem of long-range transport of ozone and its two precursors, volatile organic compounds (VOC) and oxides of nitrogen (NOx) as they affect the violation of National Ambient Air Quality Standard (NAAQS) for ozone at locations far downwind of the sources of pollution. However, Congress recognized that the regional controls prescribed under Section 184(b) were unlikely to be adequate to address the problem of ozone transport in the mid-Atlantic/northeast region. Hence, under Section 184(c), Congress empowered the Ozone Transport Commission (OTC) to develop recommendations for additional control measures to be applied within all or part of the OTR whenever a majority of OTC states determine that such measures are necessary to bring about attainment of the NAAQS for ozone anywhere within the OTR.

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[1] Sillman and Samson, "Nitrogen Oxides, Regional Transport, and Ozone Air Quality: Results of a Regional-Scale Model for the Midwestern United States." Water, Air & Soil Pollution: An Internation Journal of Environmental Pollution, 67, March, 1993, pp 117-132.

The purpose of this document is to outline the technical justification underlying the OTC's determination that additional regional ozone control strategies must be adopted under Section 184 in order for the entire OTR to reach attainment.

B. PROBLEM DESCRIPTION

Extent of Ozone Nonattainment

As Figure 1 shows, the states in the OTR experience various levels of ozone nonattainment. The problem of nonattainment is widespread, and presently all of the OTR states, with the exception of Vermont, are partially or entirely designated as exceeding the ozone NAAQS. As Table 1 shows, there are currently 28 ozone nonattainment areas in the OTR. According to the classification system prescribed in the 1990 CAAA, 12 are designated as marginal ozone nonattainment areas, seven as moderate, six as serious, and three as severe ozone nonattainment areas. Marginal nonattainment areas must demonstrate compliance with the NAAQS by 1993, moderate areas by 1996, serious areas by 1999, and severe areas by either 2005 or 2007. The Philadelphia consolidated metropolitan statistical area (CMSA), which includes a portion of New Jersey and Baltimore, has until 2005 to attain the standard. The New York City metropolitan area, which includes portions of Connecticut and New Jersey, must demonstrate attainment by 2007.

The frequency of ozone violations for two recent years, 1992 and 1993, is shown in Figure 2 in terms of the number of days of elevated ozone concentrations. For 1993, New Jersey had the highest number of ozone violations (18), followed by Maryland (16), Connecticut (15), and Virginia (10). All OTR states, with the exception of Vermont, had more violations in 1993 compared to 1992.

The maximum ozone concentrations measured in each state for 1993 are shown in Table 2. Over the 1993 ozone season, maximum ozone concentration of 0.20 ppm was measured at Babylon, New York; four other states reported ozone above 0.15 ppm; Vermont was the only state with no violations.

AREAS DESIGNATED AS NOT MEETING THE NATIONAL AMBIENT AIR QUALITY STANDARD (NAAQS) FOR OZONE

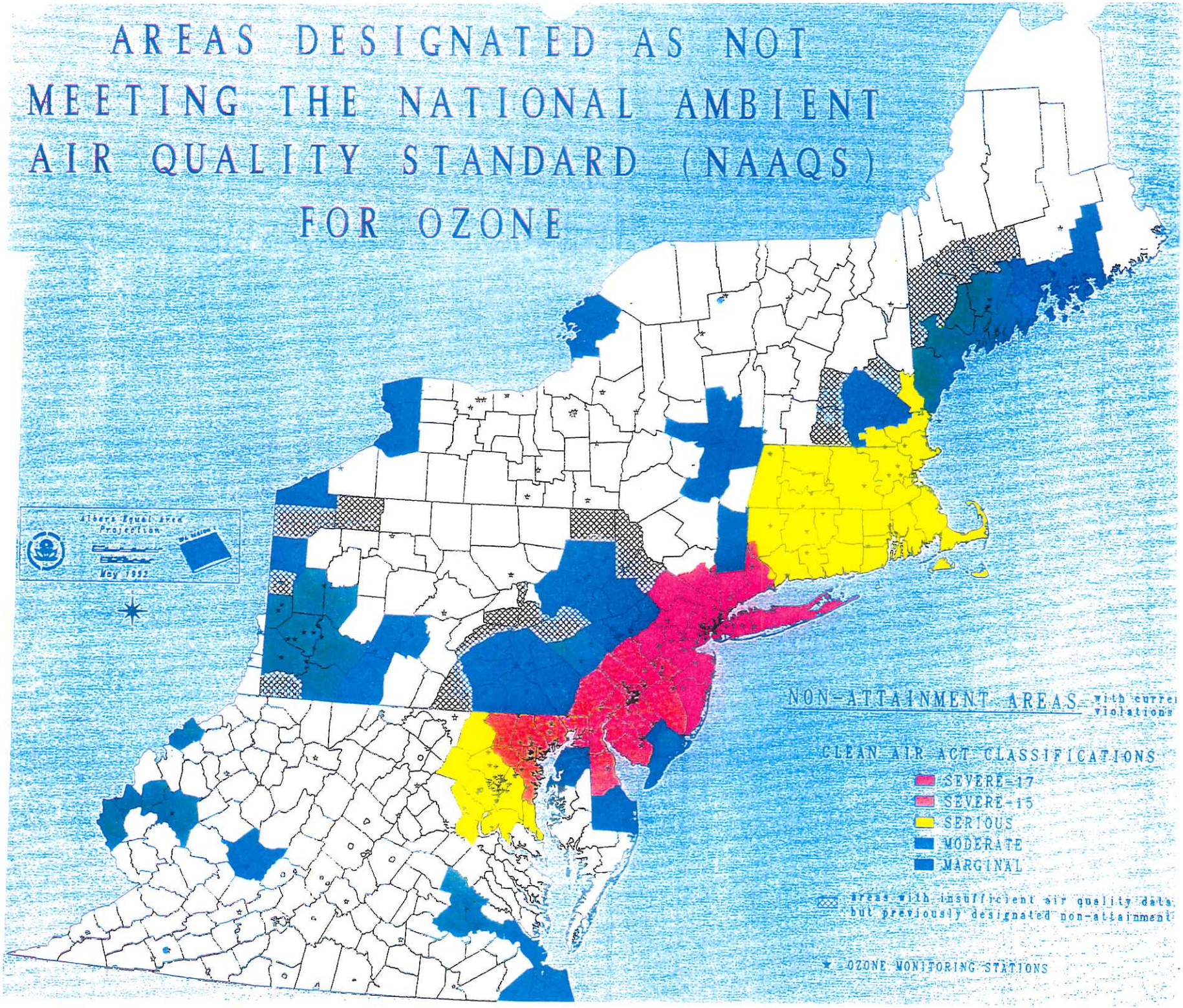


TABLE 1.
Ozone Nonattainment Areas in the Ozone Transport Region

CMSA/MSA	*Ozone Nonattainment Classification**
1. Albany, NY	Marginal
2. Allentown, PA-NJ	Marginal
3. Altoona, PA	Marginal
4. Atlantic City, NJ	Moderate
5. Baltimore, MD	Severe
6. Boston, MA-NH (Eastern MA)	Serious
7. Buffalo, NY	Marginal
8. Dutchess Co., NY	Marginal
9. Erie, PA	Marginal
10. Essex Co., NY	Marginal
11. Hancock & Wald Cos., ME	Marginal
12. Harrisburg-Lebanon-Carlisle, PA	Marginal
13. Hartford, CT	Serious
14. Jefferson Co., NY	Moderate
15. Johnstown, PA	Marginal
16. Knox & Lincoln Cos., ME	Moderate
17. Lewiston, ME	Moderate
18. Manchester, NH	Marginal
19. New York, NY-NJ-CT	Severe
20. Philadelphia, PA-NJ-DE-MD	Severe
21. Pittsburg-Beaver Valley, PA	Moderate
22. Portland, ME	Moderate
23. Portsmouth, NH-ME	Serious
24. Providence, RI	Serious
25. Putnam Co., NY	Marginal
26. Reading, PA	Moderate
27. Springfield-Worcester, MA	Serious
28. Washington, DC-MD-VA	Serious

* The classification is according to Sec. 181 of the Clean Air Act Amendments of 1990. Sec. 181 classifies areas according to the ozone design value, which is a measure of how the air quality in an area compares with the ozone standard.

The ozone standard is 0.12 ppm, 1-hour average with no more than one expected exceedance per year. Because the standard is usually examined over a 3-year period, the design value normally reflects the fourth highest hourly value in 3 years.

FIGURE 2.

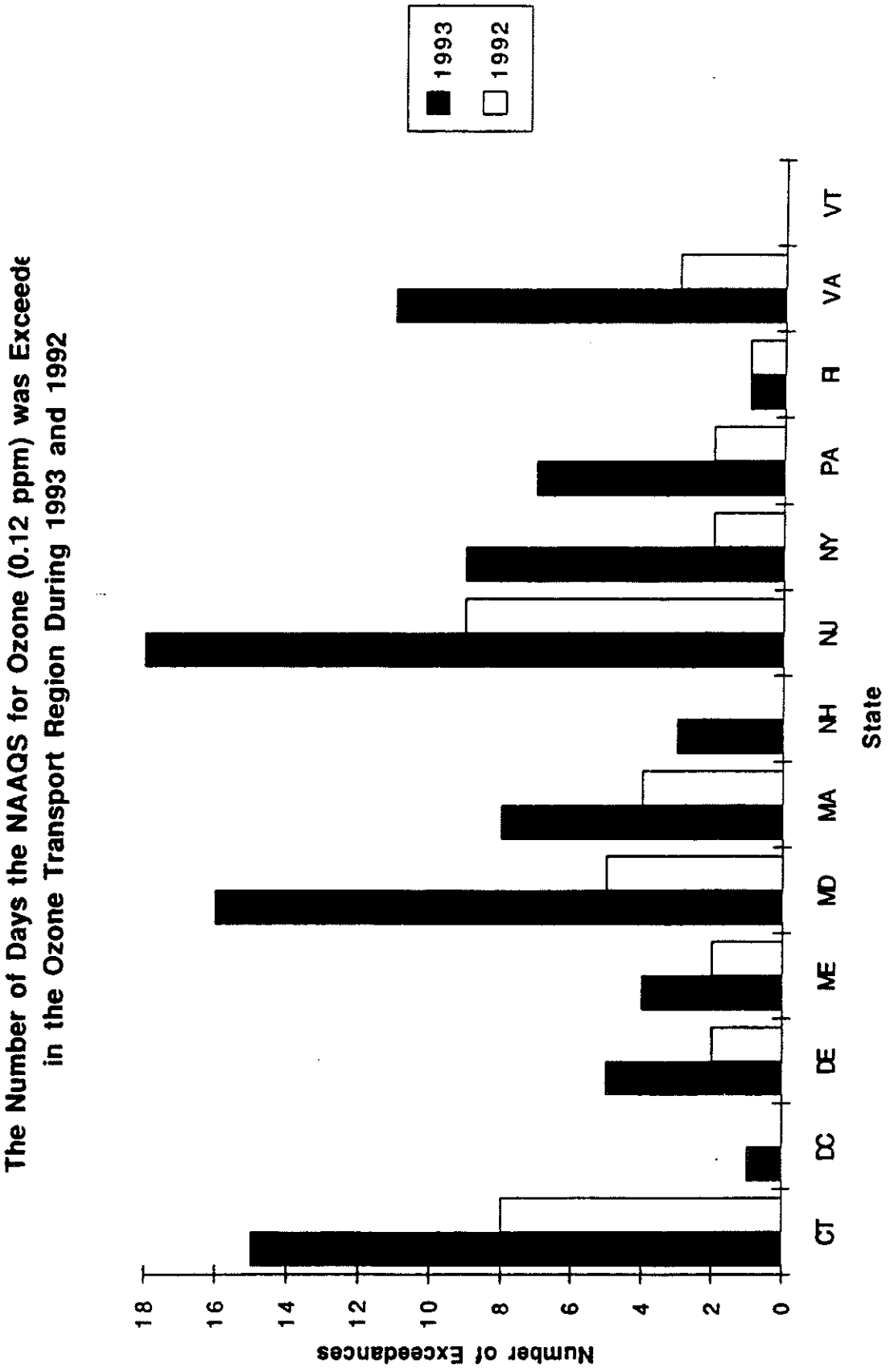

The Number of Days the NAAQS for Ozone (0.12 ppm) was Exceede
in the Ozone Transport Region During 1993 and 1992
1993
1992
Number of Exceedances
0
2
4
6
8
10
12
14
16
18
CT
DC
DE
ME
MD
MA
NH
NJ
NY
PA
RI
VA
VT
State

TABLE 2.

HIGHEST RECORDED CONCENTRATIONS OF OZONE (ppm) IN THE OZONE TRANSPORT REGION DURING 1993

State	Location	Ozone Concentration	Date
Connecticut	Stratford	0.170	7/7/93
Washington, DC	River Terrace	0.137	8/25/93
Deleware	Bellefonte	0.141	8/2/93
Maine	Kennebunkport	0.134	7/9/93
Maryland	Edgewood	0.160	6/18/93
Massachusetts	Agawam	0.163	7/29/93
New Hampshire	Nashua	0.127	6/25/93
New Jersey	Monmouth College	0.162	7/8/93
New York	Babylon	0.200	7/8/93
Pennsylvania	Bristol	0.137	7/25/93
Rhode Island	Alton Jones	0.135	8/27/93
Vermont	Bennington	0.112	7/6/93
Virginia	Mt. Vernon	0.154	8/25/93

Table 3 clearly illustrates the regional nature of ozone problem in the Northeast by providing additional data on both the spatial and temporal extent of ozone episodes. An ozone episode can be defined as a multi-day, multi-state event when ozone monitors in two or more states record ozone concentrations above 0.12 ppm over a period of two or more days. Over a period of seven years (1987-1993), about 30 regional ozone episodes have occurred in the Northeast and the number of "episode days" has typically ranged from 10 to 20 days per year, with a maximum of 39 days in 1988 and a minimum of two days in 1992. The data presented here corroborates the historical field surveys and data analyses (Chapter II), the detailed transport analyses of specific episodes in 1992 (Chapter III), and clearly demonstrates the regional nature of the problem with interstate transport of ozone and its precursors significantly contributing to ozone violations across the whole OTR. This data also indicates that urban sources of air pollution have a major impact on elevated ozone levels at locations hundreds of miles downwind of these urban sources.

Emission Inventory

In seeking to design effective and cost-efficient ozone control strategies, the first step is to identify the major sources of VOC and NOx emissions in the OTR. The OTR states are presently in the process of completing state-specific inventories to be used in the November 1994 SIP attainment demonstrations. Figures 3 and 4 depict an estimate of the VOC and NOx inventories in the OTR developed by the US EPA using a top-down, national approach. This is referred to as the "interim inventory." While the final state-specific and region-wide figures are expected to vary somewhat from the EPA's interim inventory, the fundamental conclusion of inventory analyses conducted over the last several years is that light-duty motor vehicles remain the largest single category of VOC and NOx emissions within the states comprising the OTR. In the case of NOx, emissions from electric utilities rank a close second.

While substantial strides have been made to reduce vehicular emissions over the past two decades, increases in vehicle use and the failure of vehicles to maintain low

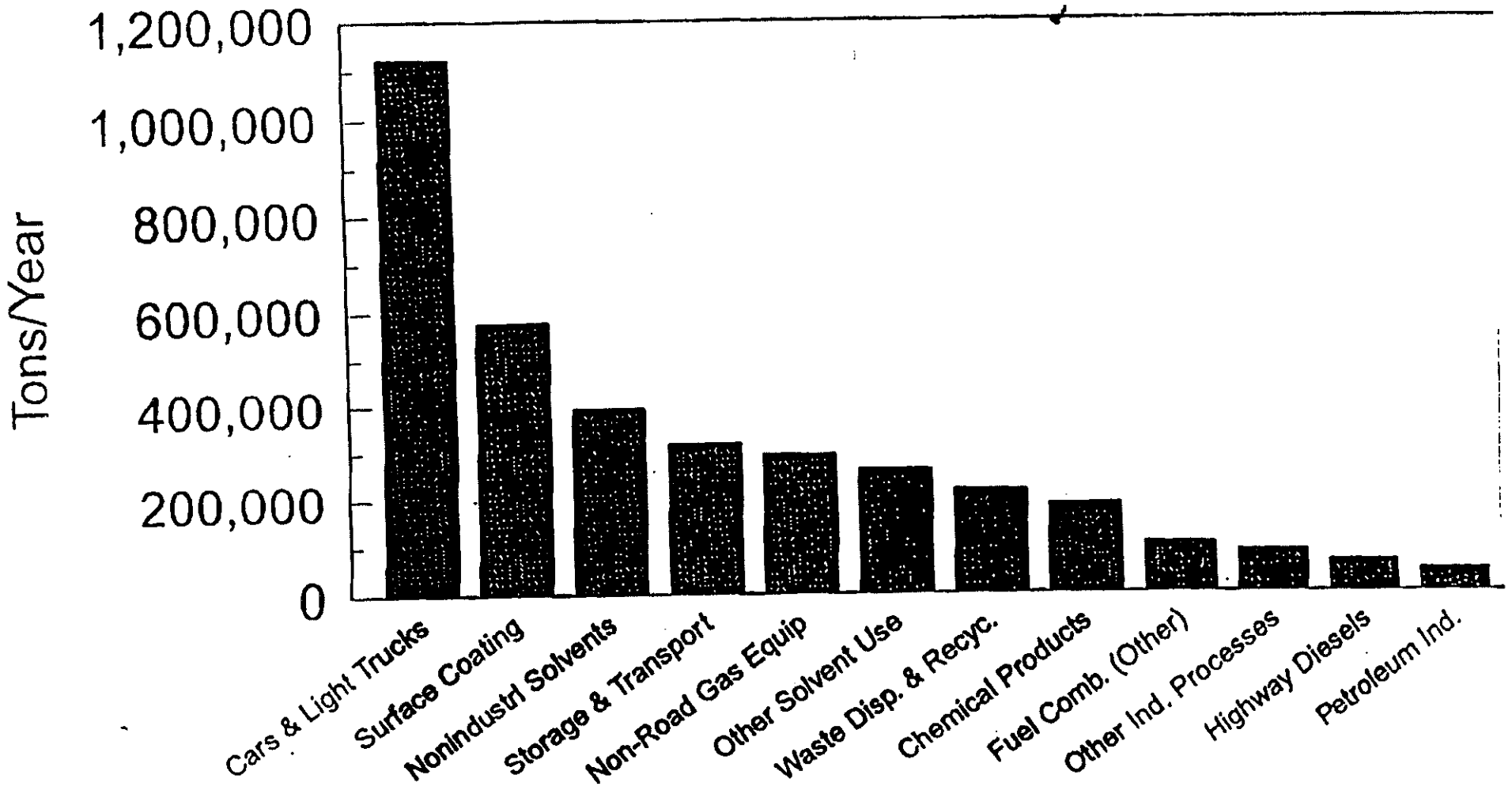
TABLE 3.

Multi-day/Multi-state Ozone Episodes* in the Northern Region of the Ozone Transport Region (1987-1993)

EPISODES	STATES	HIGHEST RECORDED CONCENTRATIONS
1987		
May 29-June 1	NJ, CT, RI, MA	CT-0.173 PPM
June 13-15	CT, RI	CT-0.196 PPM
June 18-20	NJ, NY, CT, RI, ME	NY-0.294 PPM
July 9-13	NJ, NY, CT, MA	NJ-0.249 PPM
July 22-25	CT, RI, MA, NH, ME	CT-0.201 PPM
August 15-18	MA, NH, ME	NH-0.180 PPM
1988		
June 13-18	NJ, NY, CT, MA, NH, ME, VT	CT-0.187 PPM
June 20-22	NJ, NY, CT, MA, NH, ME	CT-0.239 PPM
July 10-18	NJ, NY, CT, RI, MA, NH, ME	NJ-0.216 PPM
uly 29-August 8	NJ, NY, CT, MA, NH, ME	CT-0.200 PPM
August 9-15	NJ, CT, RI, MA, ME	MA-0.170 PPM
1989		
June 25-27	NJ, NY, CT	CT-0.187 PPM
July 1-4	NJ, NY, CT, MA	CT-0.165 PPM
July 25-27	NJ, NY, CT, NH, ME	CT-0.202 PPM
September 9-11	NJ, CT	CT-0.162 PPM
1990		
July 4-5		
July 17-20		
August 12-13		
August 16-19		
1991		
June 15-17	NJ, CT, RI, MA	MA and NJ-0.161 PPM
June 25-28	NY, CT, MA, ME	CT-0.193 PPM
July 18-23	NJ, NY, CT, MA, NH, ME	NY-0.175 PPM
August 1-2	NJ, CT, MA, NH	CT-0.175 PPM
August 29-30	NJ, NY, CT	NY-0.217 PPM
1992		
June 13-14	CT, RI, MA	MA-0.137 PPM
1993		
June 18-19	NJ, CT, MA, NH	CT-0.156 PPM
July 6-10	NJ, NY, CT, MA, NH, ME	NY-0.200 PPM
August 3-4	NJ, CT, MA	CT-0.138 PPM
August 25-29	NJ, NY, CT, RI, ME	NJ-0.158 PPM

* A multi-day/multi-state episode = two or more days when at least one monitor in two or more states record ozone concentrations above the NAAQS of 0.12 ppm.

1990 Ozone ansport Region
VOC Emission Inventory
Major Categories



Remaining Individual Categories < 1.0% of total

Excludes Virginia nonattainment counties

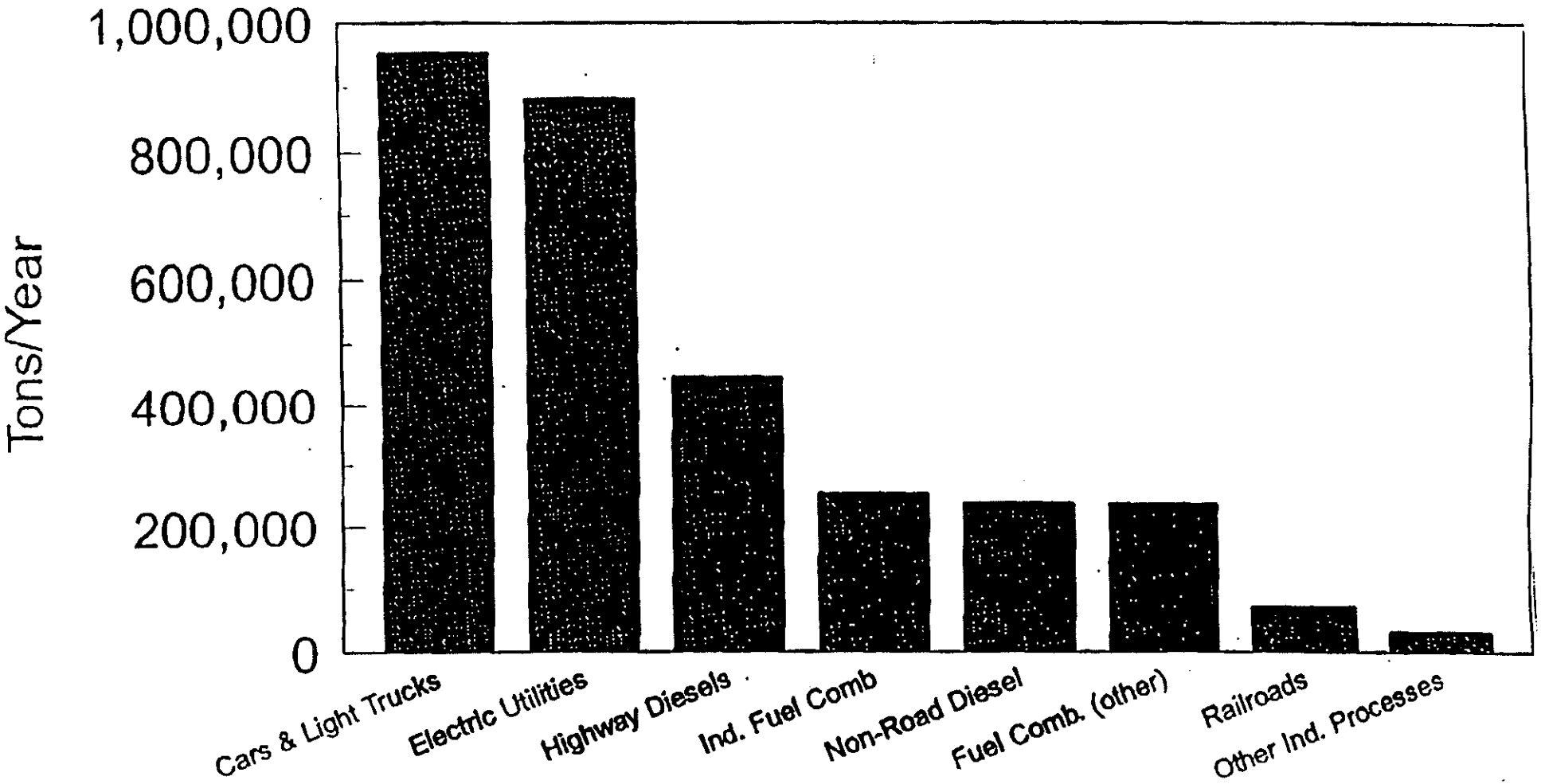
Based on USEPA Interim Inventory (Nov. 1993)

FIGURE 3.

1990 Ozone 'ansport Region

NOx Emission Inventory

Major Categories



Remaining Individual Categories < 1.0% of total

Excludes Virginia nonattainment counties

Based on USEPA Interim Inventory (Nov. 1993)

FIGURE 4.

emissions over time has significantly offset the benefits of stricter standards. The continued dominance of motor vehicle emissions is particularly notable in light of the fact that the motor vehicle component of the inventory was substantially reduced in the late 1980s through adoption of emission limits for Reid Vapor Pressure (RVP), thus limiting the volatility of gasoline sold during the summer ozone season. Recognizing the dominance of vehicular emissions, the OTC has committed to pursue a comprehensive strategy to reduce mobile source emissions, including the region-wide use of federal reformulated gasoline, adoption of enhanced vehicle inspections and maintenance programs and adoption of strict tailpipe standards for new vehicles (see Attachment A: March 10, 1992 Memorandum of Understanding).

Also noteworthy when examining the regional inventory are the substantial differences in the amount of VOC and NOx emitted in various OTR states. As depicted in Figures 5 and 6, New Jersey, New York and Pennsylvania are responsible for roughly two-thirds of the VOCs and NOx emitted in the entire OTR. Figure 7 shows the same information on a map of the region. Based on atmospheric chemistry and transport considerations in ozone formation and transport, it is expected that a given regional control strategy will have a larger regional benefit in the OTR when applied to upwind areas.

C. METHODOLOGY

Section 184(d) of the 1990 CAAA requires the EPA to prepare a document that describes criteria for assessing the effect of transported ozoneand its precursors on ozone concentrations observed in locations not attaining the NAAQS for ozone. EPA's May 1991 report, "Criteria for Assessing the Role of Transported Ozone/Precursors in Ozone Nonattainment Areas" addresses the role of transport and notes that such an assessment is necessary to help design control strategies which are most responsive to environmental conditions prevailing in a nonattainment area. The report recommends use of trajectory models to establish whether an exceedance is primarily due to local emissions or

FIGURE 5.

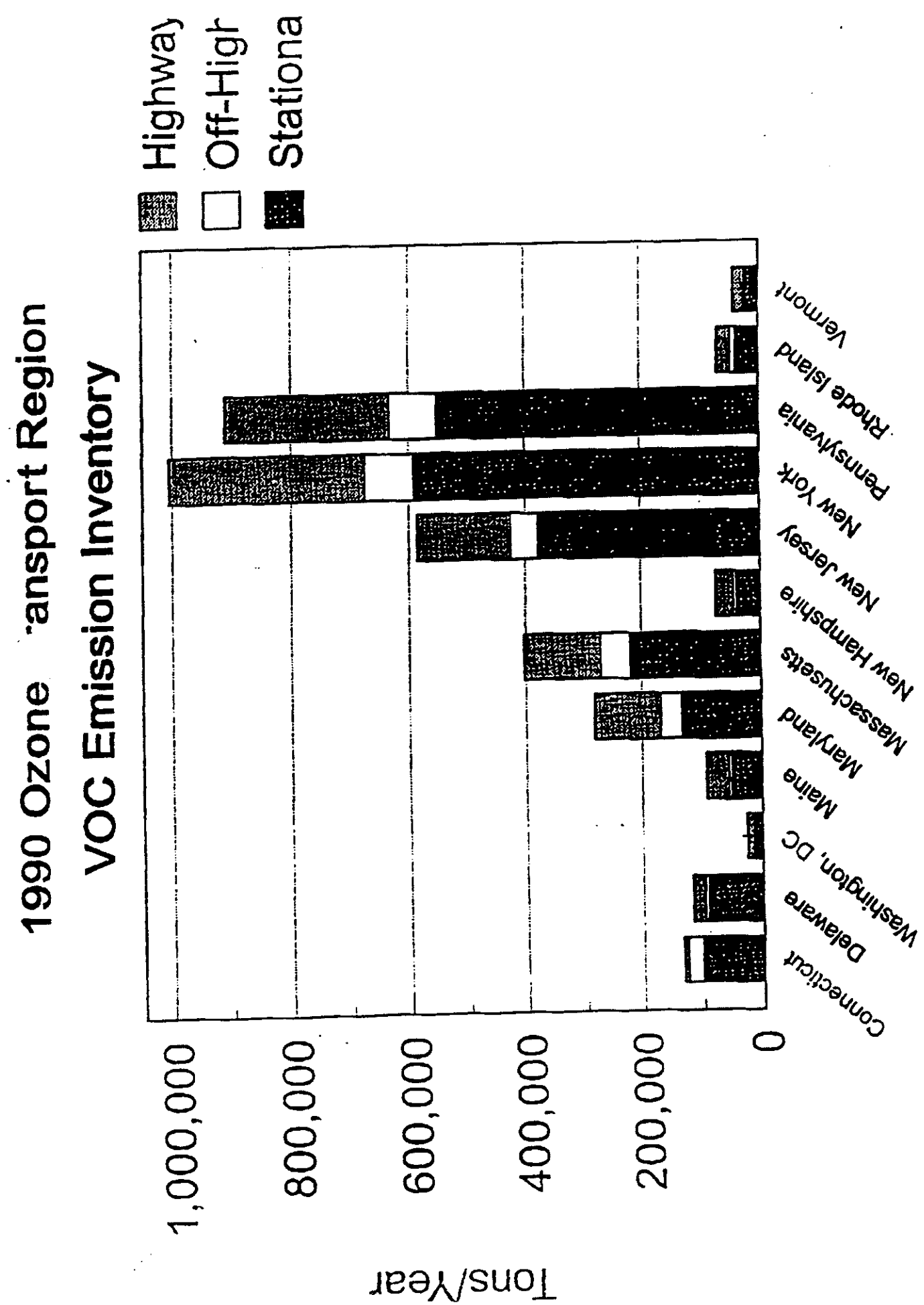

1990 Ozone ransport Region
VOC Emission Inventory
Highway
Off-High
Stationa
1,000,000
800,000
600,000
400,000
200,000
0
Tons/Year
Connecticut
Delaware
Washington, DC
Maine
Maryland
Massachusetts
New Hampshire
New Jersey
New York
Pennsylvania
Rhode Island
Vermont
Excludes Virginia nonattainment counties
Based on USEPA Interim Inventory

FIGURE 6.

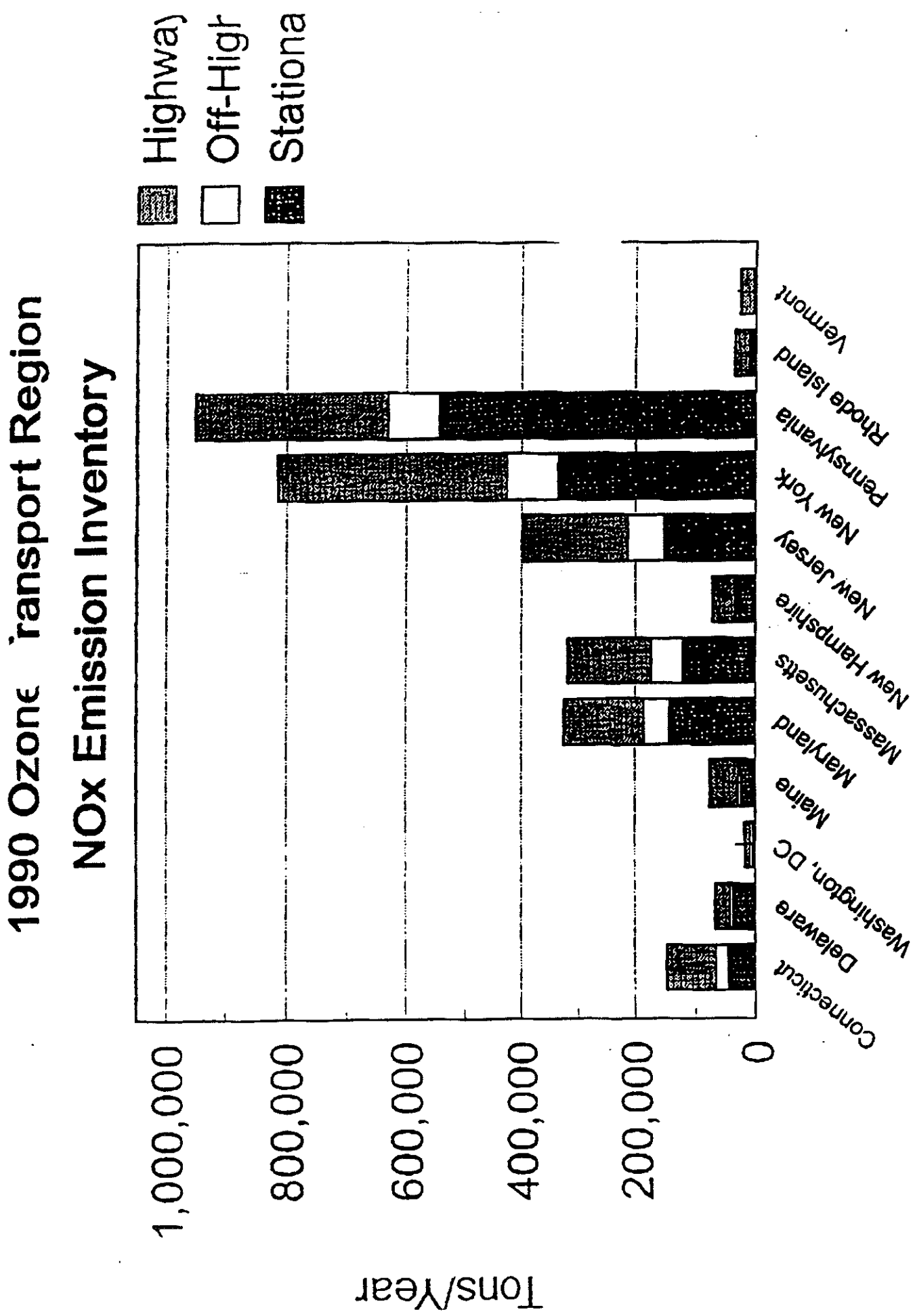
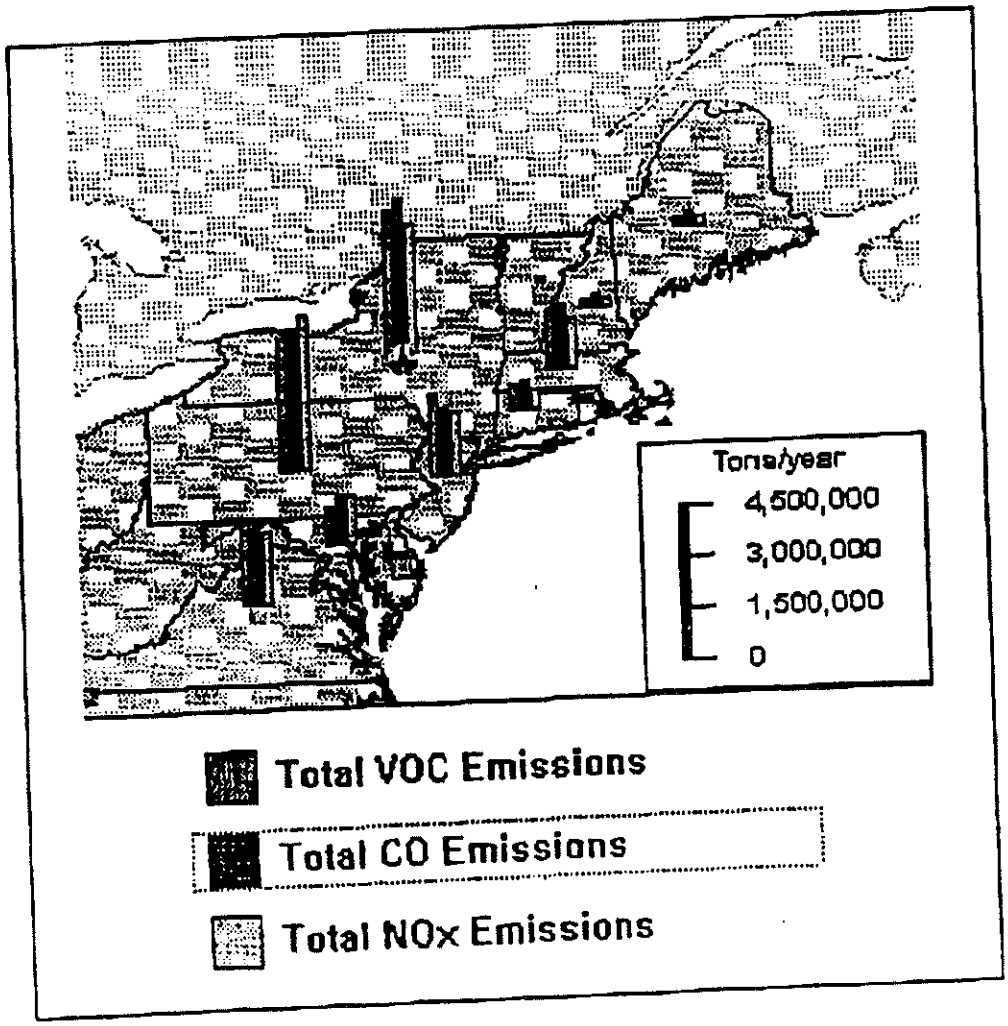

1990 Ozone Transport Region
NOx Emission Inventory
Highway
Off-High
Stationa
1,000,000
800,000
600,000
400,000
200,000
0
Tons/Year
Connecticut
Delaware
Washington, DC
Maine
Maryland
Massachusetts
New Hampshire
New Jersey
New York
Pennsylvania
Rhode Island
Vermont
Excludes Virginia nonattainment counties
Based on USEPA Interim Inventory

FIGURE 7.

1990 Emission Inventory for States in the Ozone Transport Region



"overwhelming" transport. The trajectory models can also be used to identify areas that substantially contribute to exceedances once it is recognized that transport over long distances plays an important part. The approach used in this document involves the generation of backward trajectories over long distances (hundreds of miles) and over long periods of times (three to five days). This is achieved through the use of a "nested grid model" (developed by the US National Oceanic and Atmospheric Administration), which is combined and corroborated with the temporal pattern of regional ozone concentrations to produce a more rigorous approach than that recommended by EPA. The episodes included in Chapter III include recently analyzed ozone episodes for June 17-18, 1993, and May 22-24, 1992, as well as the episode analyzed in ROMNET (July 4-16, 1988). These recent multi-day, multi-state episodes are typical of situations that result in regional high ozone levels in the Northeast. Chapter III also includes an innovative approach of "residence time analysis" applied to three locations in the Northeast, where backward trajectories, averaged over three summers (1989-1991), show the impact of source regions on locations hundreds of miles downwind in a statistically robust manner. This report also gives a summary of numerous transport studies performed in the last 20 years in the Northeast that confirm the important role that long-range transport plays in ozone exceedances in the Northeast. (Individual references are too numerous to be listed here. They are, however, included in the 1991 National Academy of Sciences' report, "Rethinking the Ozone Problem in Urban and regional Air Pollution.").

II. SUMMARY OF SCIENTIFIC AND REGULATORY EFFORTS TO ADDRESS LONG-RANGE TRANSPORT IN THE NORTHEAST

A. SURVEY OF ATMOSPHERIC TRANSPORT STUDIES IN THE NORTHEAST

As mentioned in the above section, a number of field studies and statistical analyses of ambient ozone data have been performed in the Northeast over the last 20 years. In the eastern US, the worst ozone pollution episodes occur when a slow-moving, high-pressure system develops in the summer, particularly around the summer solstice. This is the time of the year with the greatest amount of daylight, when solar radiation is most direct and daily temperatures become quite high (greater than about 80 degrees, F). As the slow-moving air in the shallow boundary layer passes over the major urban areas, pollutant concentrations rise, and as the air slowly flows around the high-pressure system, photochemical production of ozone occurs at peak rates. High ozone episodes are often terminated by the passage of a new front that brings cooler, cleaner air to the region.

In the Northeast, high concentrations of ozone in urban, suburban, and rural areas tend to occur concurrently on scales of over 1,000 km (with an aerial extent exceeding 600,000 square km). This cloud of ozone/ozone precursors sometimes persists for a number of days (three to seven days). Such episodes occur as many as seven to 10 times a year, and the ozone concentrations remain high (> 80 ppb) for several hours each day. A number of field studies sponsored by the EPA in the early- and mid-seventies found ozone concentrations above 80 ppb for several consecutive days over areas larger than 100,000 square kilometers. (The results of these studies are confirmed by the trajectory analyses shown in Chapter III for 1992, 1993, and 1989-1991, as well as for 1988 trajectory analyses performed for ROMNET). As expected, these episodes were associated with slow-moving, high-pressure systems with high temperatures, light winds, and clear skies. These early studies also showed a gradient in rural ozone values from west to east, with higher values in the eastern US. Later case studies completed in the late-seventies and eighties documented the occurrence of high concentrations of ozone in the Midwest,

Northeast, South, and on the Gulf Coast. In one of the more dramatic cases, very high ozone values (> 100 ppb) were found to extend from the Gulf Coast, throughout the Midwest, and up into New England. It appears certain that the presence of slow-moving, high-pressure systems is associated with high concentrations of ozone throughout the atmospheric boundary layer during the summer season.

Some of the highest concentrations of ozone are found in plumes of pollutants downwind of urban and industrial areas. Studies that rely on surface and aircraft data have shown that these high concentrations are superimposed on elevated background concentrations during high-ozone episodes. The plumes may maintain their integrity for 12 hours, and they can cover an area as large as 8,000 square kilometers. The length of the plume is typically three times its width. Small cities (populations of approximately 100,000) can generate 10-30 ppb ozone over background concentrations. Concentrations found in plumes downwind of larger cities (for example, Boston or Baltimore) are more typically elevated by 30-70 ppb over background levels. The most extreme cases, where concentrations are 60-150 ppb higher than background, are found over Connecticut, downwind of the New York-New Jersey-Pennsylvania industrial and metropolitan area.

Many studies have been performed by Dr. Jennifer Logan of Harvard University on the regional effects of ozone pollution over the course of the last two decades. Several of these studies are relied upon in the National Academy's 1991 report. Analyses of the data from rural sites in the eastern US performed by Logan (1988, 1989) clearly show the substantial role of transport in the elevated ozone concentrations found at remote eastern rural sites. For example, monthly maximum concentrations (the average of the daily maxima) are quite high at these rural sites (60-85 ppb), indicating a substantial contribution via transport from upwind locations. Values within a few ppb of the daily maximum persist for 7-10 hours, from late morning until well into the evening at some sites. The cumulative probability distributions show that ozone exceeds 80 ppb at some of the remote rural sites quite frequently. For example, ozone concentrations exceeded 80 ppb on 39%

of days between May and August at 10 eastern sites in 1978, and on 26% of the days in 1979. The highest concentrations were observed at the central and eastern rural sites influenced by major urban and industrial sources of pollution (those in northern Indiana, Pennsylvania, Delaware, and Massachusetts in this case); high concentrations were less common at the more remote central and eastern sites (in Wisconsin, Louisiana, and Vermont).

Logan (1989) also analyzed the episodes of high concentrations for a region extending from Indiana east to Massachusetts, and south to Tennessee and North Carolina. Variations of ozone concentrations were highly correlated over distances of several hundred kilometers. The highest concentrations tended to occur concurrently, or within one to two days of one another, at widely separated stations. These episodes persisted for three to four days on average, with a range of two to eight days, and were most common in June. Daily maximum ozone concentrations exceeded 90 ppb at more than half of the rural sites during these episodes and often were greater than 120 ppb at some sites. An analysis of the weather for each episode showed that high-ozone episodes were most likely in the presence of weak, slow-moving, persistent high-pressure systems as they migrated from West to East, or from Northwest to Southeast, across the eastern US. Logan's current work continues to confirm and strengthen the conclusions of field studies undertaken for the past 15 years.

In another recent study of meteorological conditions associated with high-ozone days (above 80 ppb) in 17 cities, Samson and Shi (1988) examined the wind flow for all days in 1983-1985 when ozone exceeded 80 ppb in these cities, using trajectory calculations integrated backwards to the source region. They found that days with concentrations above 120 ppb were generally associated with low wind speeds, with the exception of Portland, Maine, where high-ozone days were moderately windy, implying long-range transport of ozone from south and west. One of the important finding of the study was that the median distance the air had traveled in the previous 24 hours was about 500 kilometers for the cities in the Northeast (Boston and New York city were included in

the study), suggesting long-range transport. This distance was twice as much when compared to the southern cities included in the study (for example, Dallas and Houston).

The historical data and recent analyses clearly demonstrate that ozone and its precursors are transported throughout the OTR at elevated concentrations. The regional transport mechanism delivers elevated ozone and ozone precursor concentrations to both rural and urban areas of the Northeast on a regular basis during summer months, making it extremely difficult for both urban and some rural areas to develop effective ozone attainment plans. The common sense conclusion to be drawn from this overwhelming historic evidence on the significant role of atmospheric transport of ozone and its precursors on downwind elevated concentrations of ozone is that major air pollution control strategies have to be designed for regional implementation in the OTR in order to attain, and maintain, ozone standards across the region.

B. PREVIOUS EFFORTS TO ADDRESS TRANSPORT IN THE REGULATORY PROCESS

The phenomenon of ozone transport in the Northeast has been identified for over 20 years. In 1973, a study of several urban areas in New York State concluded:

> "Local urban photochemical generation of ozone is not the dominant mechanism for ozone production...the high urban concentrations of ozone are principally the result of transport and mixing of ozone rich air into the city from the surrounding air mass."[2]

Relying on early Regional Oxidant Modeling (ROM) conducted in the mid-1980s, EPA concluded that long-range transport was occurring throughout, "a vast area roughly parallel to the East Coast, extending from Virginia into Southern Maine and extending inland from the coastline some 200 kilometers."[3] While recognizing that long-range transport was frustrating many states'

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[2] Coffey & Stasiuk, "Evidence of Atmospheric Transport of Ozone into Urban Areas," Environmental Science & Technology, v.9, 1975.

[3] EPA/600/3-86/038, "Numerical Simultions of Photochemical Air Pollution in the Northeastern United States: ROM 1 Application," July 1986.

attainment efforts, prior to the 1990 Amendments to the Clean Air Act (1990 Amendments), neither EPA or the states possessed an appropriate regulatory or legal mechanism to address the long-range transport of ozone and ozone precursors.

In 1977, Congress attempted to address transported pollution through the creation of the Clean Air Act Section 126 petition process which enabled downwind states to petition EPA to impose controls on upwind sources of pollution. However, downwind states' attempts to seek relief under Section 126(b) were frustrated by a standard of review that essentially required petitioning states to demonstrate that discrete upwind stationary sources were responsible for "preventing" their attainment of the NAAQS. In 1987, after completing a study indicating that the New York City Metropolitan Area (NYCMSA) would continue to violate the ozone NAAQS even if all ozone precursor emissions in the NYCMSA were abated,[4] New York State petitioned EPA for relief under Section 126. Although EPA never formally ruled on New York's Section 126 petition, it seems clear that had EPA been forced to render a decision, the Agency would have rejected the New York petition based on the unrealistic requirement that petitioning states attribute transported emissions to individual upwind sources and demonstrate that, but for these transported emissions, attainment would occur. Moreover, Section 126 was designed only to address transported emissions from "major" stationary sources and offered no potential for relief from transported pollution generated by mobile and area sources which dominate the emissions inventory. As a result, Section 126 was never successfully employed.

Nevertheless the illogic of requiring downwind areas to abate pollution they did not produce led EPA and the states to exclude transport-related violations from the calculation of design values[5] and, in the extreme case, led Rhode Island to request and receive in 1983 a designation of "Attainment but for Transport" even though the air quality in Rhode Island continued to exceed the ozone NAAQS.[6] The combined effect of these policies has been

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[4] OMNYMAP Study.

[5] EPA Publication. Guideline for use of City-Specific EKMA in Preparing Post-87 Ozone SIPs. 11/87.

[6] 48 Federal Register 31026, July 6, 1983.

essentially to absolve both upwind and downwind states from the responsibility of abating ozone transport. By joining the northeast states in a proactive compact, empowering the OTC to address all pollution sources located throughout the region, and creating a standard for EPA review that is scientifically achievable, Congress provided the states and EPA with a mechanism (e.g. 1990 CAAA Section 184(c)) to address the realities of regional ozone nonattainment.

III. TECHNICAL ANALYSIS

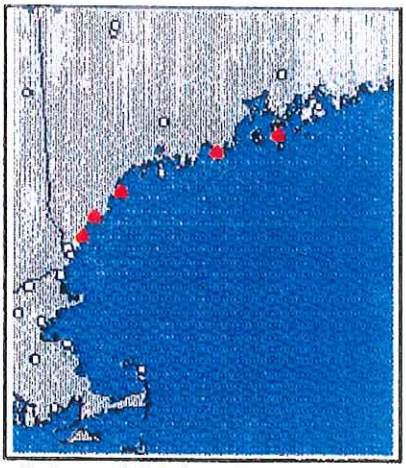
A. INTRODUCTION

An assessment of the contributions of synoptic scale transport to ozone exceedances in the OTC region requires a number of analytical tools. For example, multi-day runs of the ROM model (such as for the July 1988 episode period examined in the EPA "ROM 2.0" video) provide a clear illustration of the transport phenomena over scales in excess of several hundreds of kilometers or more (for example, from western PA to the East Coast Urban Corridor).

This discussion will employ several meteorological and empirical techniques to examine the transport phenomena. These techniques include an examination of selected hourly ozone data from sites in the OTC region during the years 1987 through 1993. In many cases, the raw data itself provides obvious evidence of the effects of transport on ozone concentrations. Where available, the raw ozone data will be viewed in concert with meteorological data for selected episodes, including the output from several airmass trajectory models (Jeffter, HY-SPLIT, CAPITA). Finally, we will employ an ensemble trajectory technique known as residence time analysis to examine predominant ozone transport pathways over long (3 year) averaging times.

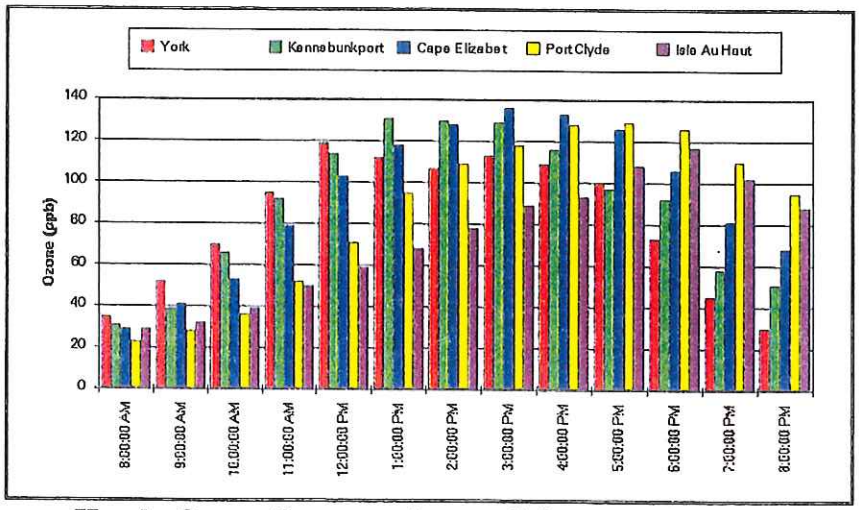
B. TEMPORAL AND SPATIAL PATTERNS: JULY 1987

The figure below displays hourly ozone levels on July 24, 1987 for 5 sites, running from Southwest to Northwest, along the coast of Maine - in the Northeastern corner of the OTC region. Given the northern latitude, low local emissions densities and the isolated nature of these coastal sites, there is no way to account for these high concentrations from local emissions alone.



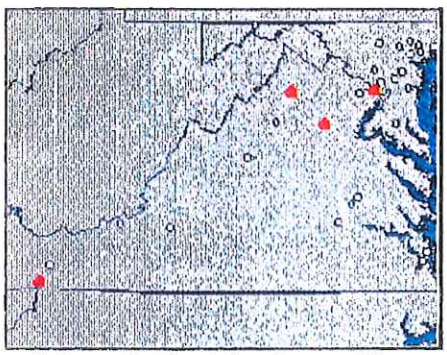
Selected Maine Ozone Sites

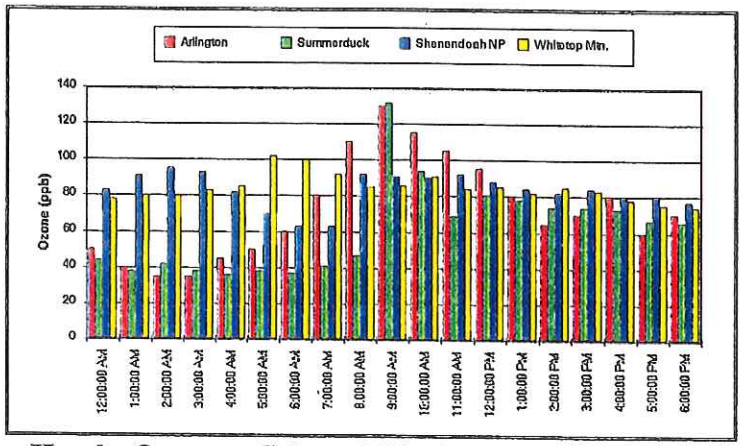
Note also the progression in the timing of maximum concentrations - beginning with a 12 Noon peak (just below Federal standards, but well above the 80 ppb State standard in ME) at the most southerly York site. Further North, Kennebunkport peaks (and exceeds Federal standards) an hour later at 1 PM, while Cape Elizabeth and Port Clyde peak (and exceed Federal standards) at 3 PM and 5 PM respectively. The most northerly Isle Au Haut site, in Acadia National Park, peaks just below standards at 6 PM - a time when the sunlight-driven production of ozone has been declining for several hours.



Hourly Ozone Concentrations at Selected Maine Sites

Earlier on the same morning of July 24, 1987, ozone levels at several Virginia sites also provides a clear illustration of transport effects on ozone exceedances at the southern extreme of the OTC region. An urban site in Alexandria, VA (in the OTC region) and a nearby rural site in Summerduck both exceed standards at the unlikely hour of 9 AM. Regardless of local emission densities, an ozone exceedance this early in the morning can only be explained by over-night transport of the previous day's (or earlier) ozone production from relatively distant sources.


Selected Virginia Ozone Sites

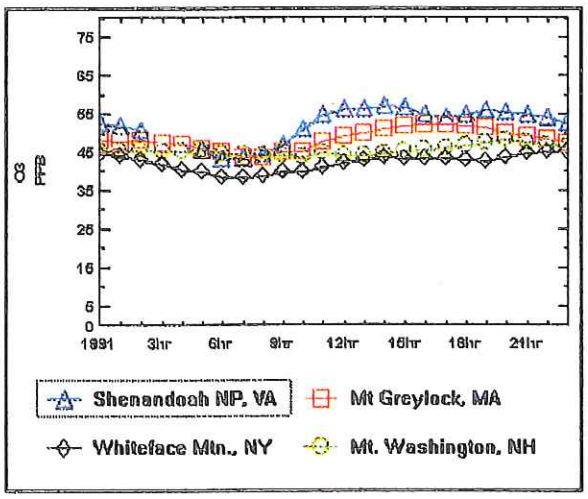


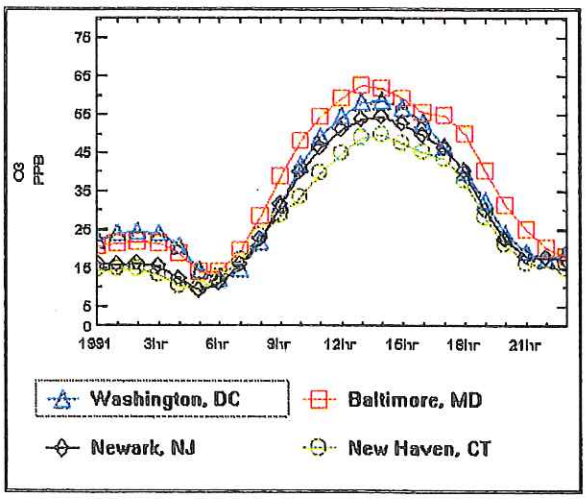
Hourly Ozone at Selected Virginia Sites on 7/24/87

This over-night transport contribution is illustrated by measurements from two relatively nearby high elevation sites - Shenandoah National Park (Northeastern VA), and Roundtop Mtn. (Southwestern VA). These sites are at sufficient elevation to provide a means for sampling a layer of the atmosphere which, at night, can become decoupled from the surface layer and therefor "protected" from the physical and chemical processes which destroy ozone at the earth's surface. These elevated layers of ozone - in this case in the range of 80 to 100 ppb at the Shenandoah and Roundtop sites - can and do mix down to the surface after sunrise the next day. The early morning exceedances at Alexandria and Summerduck represent a relatively small (30 to 40 ppb) increase over the transported nighttime background levels.

C. DIURNAL PATTERNS: SUMMER, 1991

High elevation sites like Shenandoah and Roundtop Mtn. provide an excellent viewpoint for observing the effects of nighttime transport. The figures below show the diurnal patterns for selected mountain and urban sites averaged over the months of June through August, 1991.



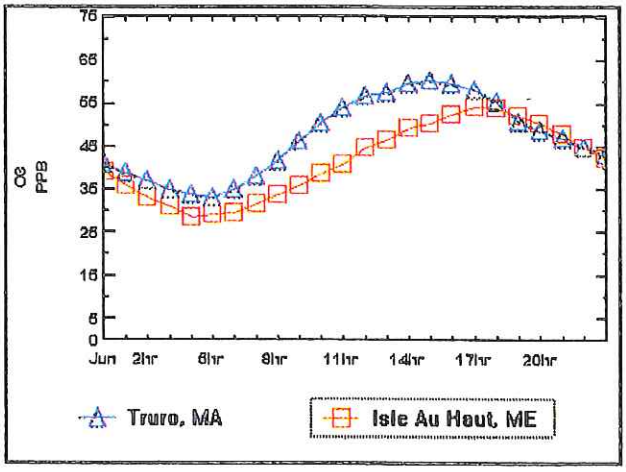


The average summer 1991 values for the high elevation sites are quite similar throughout the region, exhibit virtually no diurnal variation, and range from 40 to 60 ppb (on average) even

during the nighttime hours when ozone production is insignificant. The urban sites - where ground level ozone destruction mechanisms frequently reduce concentrations to near zero levels at night - are also subject to the influence of these upper level nocturnal plumes, as thermally induced mixing occurs during the daylight hours. In effect, these transported background levels aloft cut the federal ozone standard by one third to one half - requiring incremental ozone contributions of only 60 to 80 ppb to exceed standards under average summer conditions.

A similar nocturnal ozone transport phenomena also occurs over water, where NOx scavenging and physical removal processes are minimal. Unfortunately, there are no ozone monitoring sites sufficiently far out into the Atlantic Ocean to be free from the scavenging influences from on-shore NOx sources, especially at night when the wind is generally off-shore.

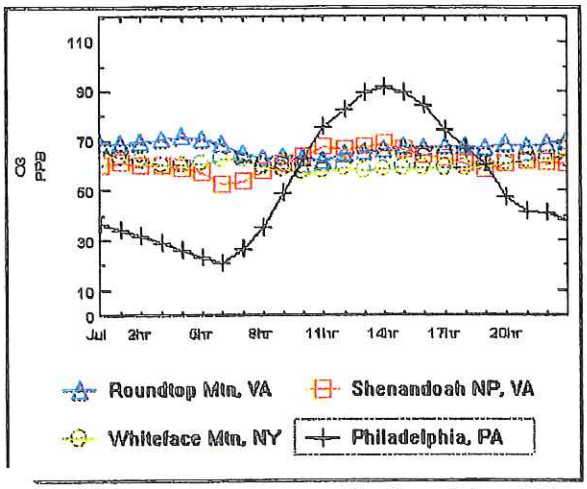
The most isolated coastal monitoring sites in the region include Truro, MA - at the northern tip of Cape Cod, and Isle Au Haut, ME - an island in Acadia National Park. The average Summer (June - August, 1991) diurnal cycles for these sites are displayed at the right. While these near-coastal sites exhibit more of a diurnal cycle than the high elevation sites, the magnitude of the average daily variation is much less than at the urban sites in the region (see preceding page). The average ozone levels at the near-coastal sites range from about 30 to 45 ppb at night, compared to average nighttime values of 0 to 20 ppb at the urban sites. Note also, that while the urban sites tend to peak at 1 PM, Truro tends to peak at 3 and the more northerly Isle Au Haut site tends to peak at 6 PM.



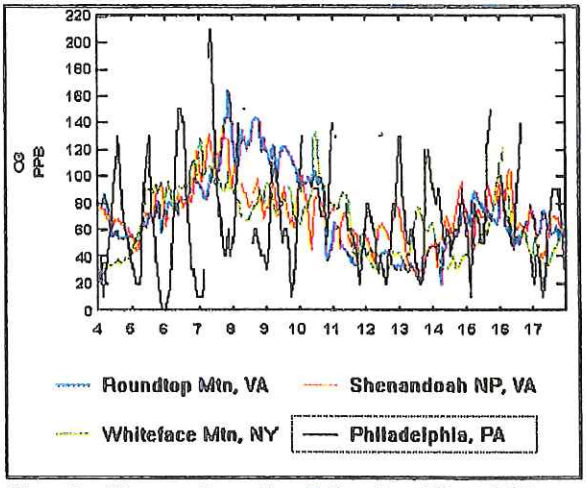
D. OZONE PATTERNS AND AIR TRAJECTORIES: JULY, 1988

As discussed in the preceding section, ozone levels aloft during a moderately clean Summer like 1991 average from 40 to 60 ppb during the nighttime hours when ozone production is minimal. During a more extreme episode period like July 1988, the average nighttime values at mountain top sites (and in an elevated layer often spanning the entire region) are even higher.

The figure at the lower left displays the average diurnal ozone levels for July, 1988 for 3 high elevation sites - Roundtop Mtn., VA, Shenandoah NP, VA and Whiteface Mtn. in northeastern NY- as well as for an urban site in Philadelphia, PA. In this case, the average nighttime levels at the mountain sites ranges from 60 to 70 ppb (and appear to be remarkably consistent over the entire OTC region). The figure on the right shows the actual hourly data for these sites during the period: July 4 through July 18, 1988 - a prolonged episode period assessed in detail by EPA ("Regional Ozone Modeling for Northeast Transport", EPA-450/4-91-002a, June 1991). The hourly values for the (widely scattered) high elevation sites display minimal diurnal variation, exceed 80 ppb for several days, and rise to levels in excess of the federal standard on several occasions. The Philadelphia site tracks the upper level sites to a certain extent, but exhibits a strong diurnal pattern and exceeds standards on most days during this 2 week period.



Average Diurnal Ozone Cycles: July 1988

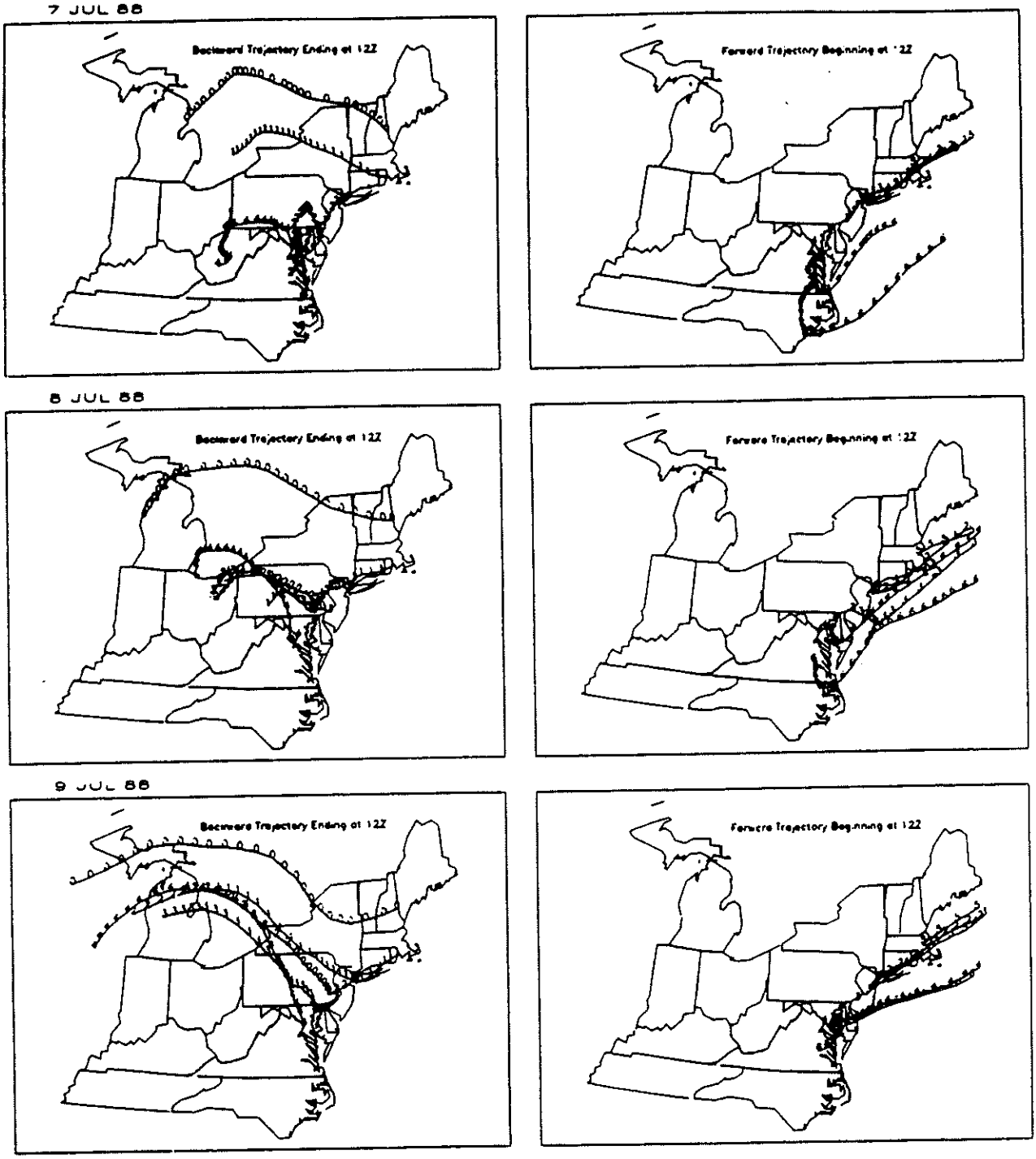


Hourly Ozone Levels: July 4 - 18, 1988

The EPA ROMNET report includes an exhaustive analysis of the July 1988 (and several other) episodes. It amply demonstrates the effects (and benefits of upwind controls) of transport a) from areas to the South and West of the Coastal urban corridor, and b) from Southwest to Northeast within (and to the North of) the corridor. The overall flow regime for the July 1988 episode period was characterized by EPA as dominated by "a persistent trough along the Corridor. Flow into the corridor was generally from the West to Southwest on most days. Within the Corridor, along-Corridor flow occurred on 10 of the 15 episode days with weak westerly or recirculation flow on other days."

The period July 7-9, 1988 provides a particularly good example of these characteristics of transport from West/Southwest into the corridor and from Southwest to Northeast along the corridor and beyond. A dominant feature of this 3-day period was a surface high pressure system which had built in from the Carolina Coast over the preceding few days and was centered over the Shenandoah Valley on the 7th and 8th. Skies were partly cloudy over much of the region on the 7th and 8th, and overcast with showers in several sections on the 9th - bringing temporary relief from the extreme and widespread ozone levels on the preceding and following days.

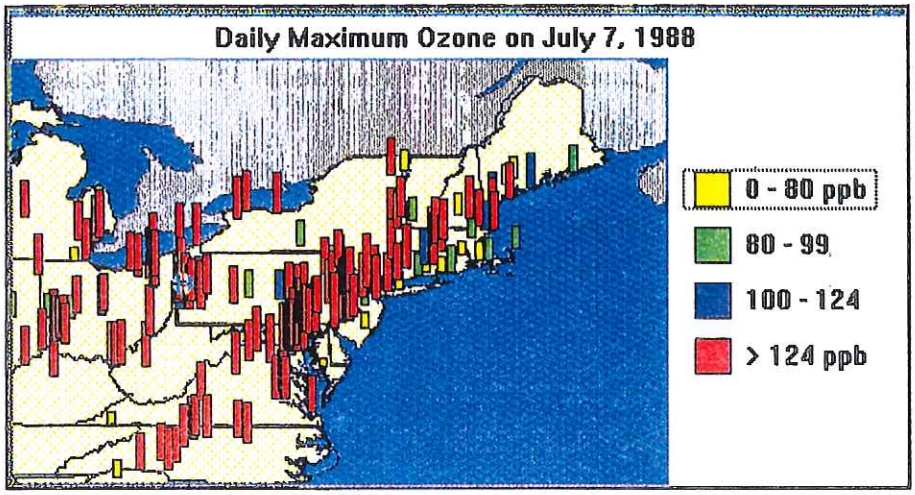
Backward and forward air trajectories, to and from sites in the coastal corridor on July 7 - 9 are displayed on the following page. These trajectories were calculated by the Hefter (1980) ARL ATAD model, and presented in the EPA ROMNET report. They clearly illustrate transport from Western sections of the OTC region (and beyond) to Eastern regions as well as Southwesterly flows along the East coast urban corridor (and beyond). Although temperatures were unusually high, and these flow conditions were generally more prolonged during this episode than in "typical" years, similar conditions - slightly less extreme and persistent are relatively typical of the most severe regional ozone episodes in most years.



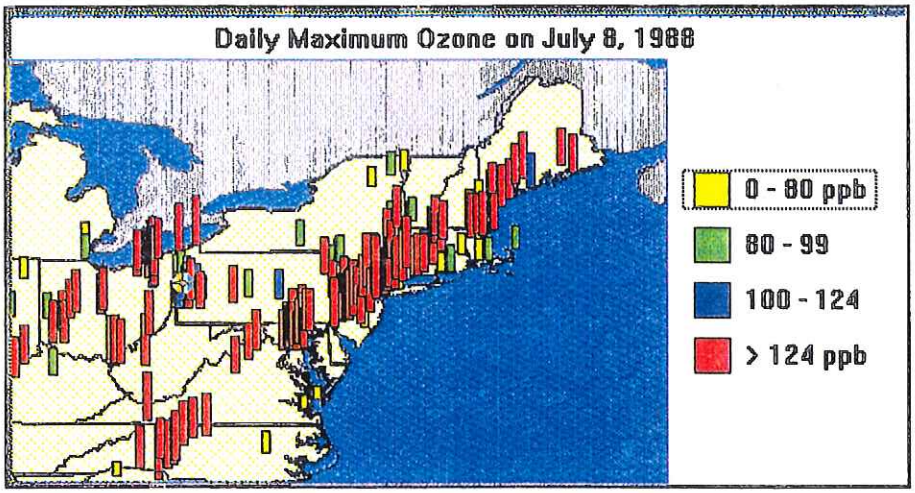
Backward and Forward Air Trajectories to and from East Coast Sites on July 7, 8 and 9, 1988

Calculated by ARL ATAD model (Heffter, 1980) as presented in ROMNET report (EPA, 1991)

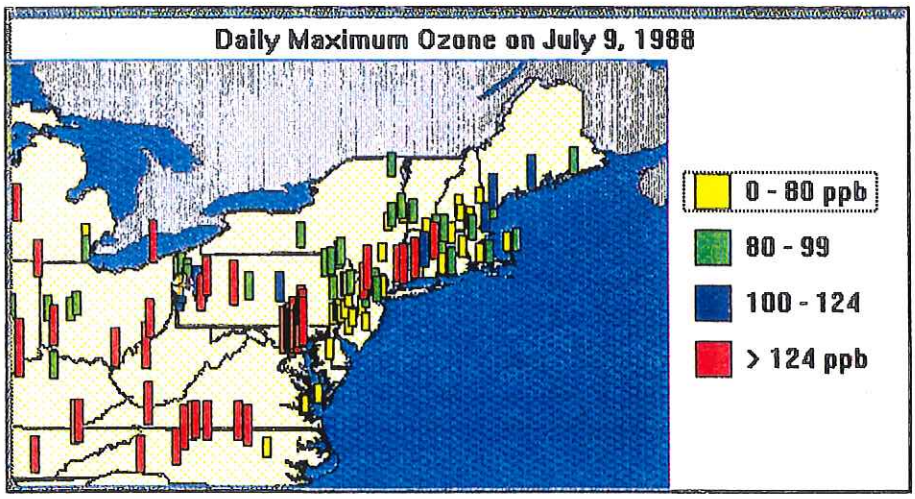
The maximum daily ozone levels in the Northeast on July 7th, 8th and 9th are displayed at the right.



Federal standards were exceeded over the entire OTC region (and further South and West) on the 7th and 8th, including the most northerly Maine sites on the 8th.

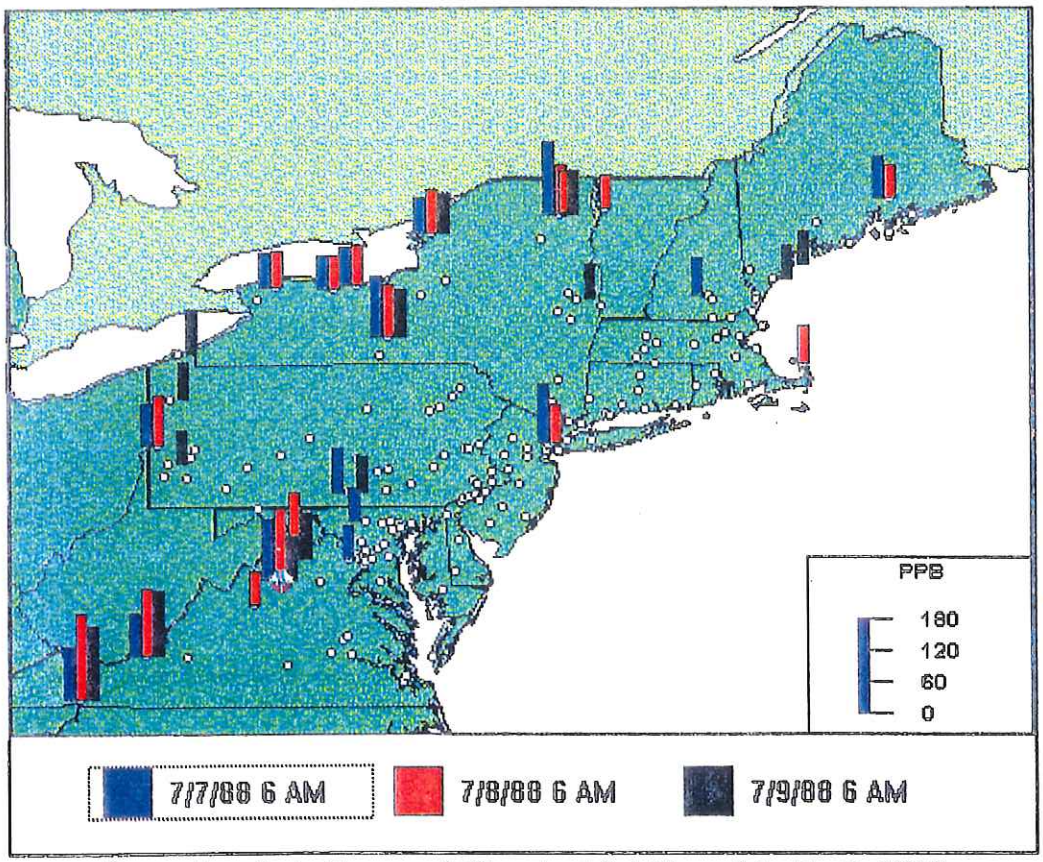


Overcast skies and showers on the 9th temporarily reduced levels in most Eastern sections with the exception of the NY and DC metropolitan areas.



Recall from previous discussions that the region's high elevation sites were recording continuous levels in excess of 80 ppb through this 3-day period (including over night). The figure below displays the 6 AM values on each of these 3 days at sites where these early morning levels were in excess of 60 ppb. Note that not only the high elevation sites, but a large number of low elevation sites - particularly in Southwestern and Northwestern sections - were experiencing sunrise ozone concentrations from 60 to 120 ppb (or higher) on one or more of these mornings.

When the day begins with these kind of obviously transported baseline levels, and the winds are from the Southwest, a relatively minor local contribution is all that's needed to exceed federal health standards. When local daytime production rates are also substantial, the standard has been, and will continue to be, exceeded by a wide margin over broad spatial domains.



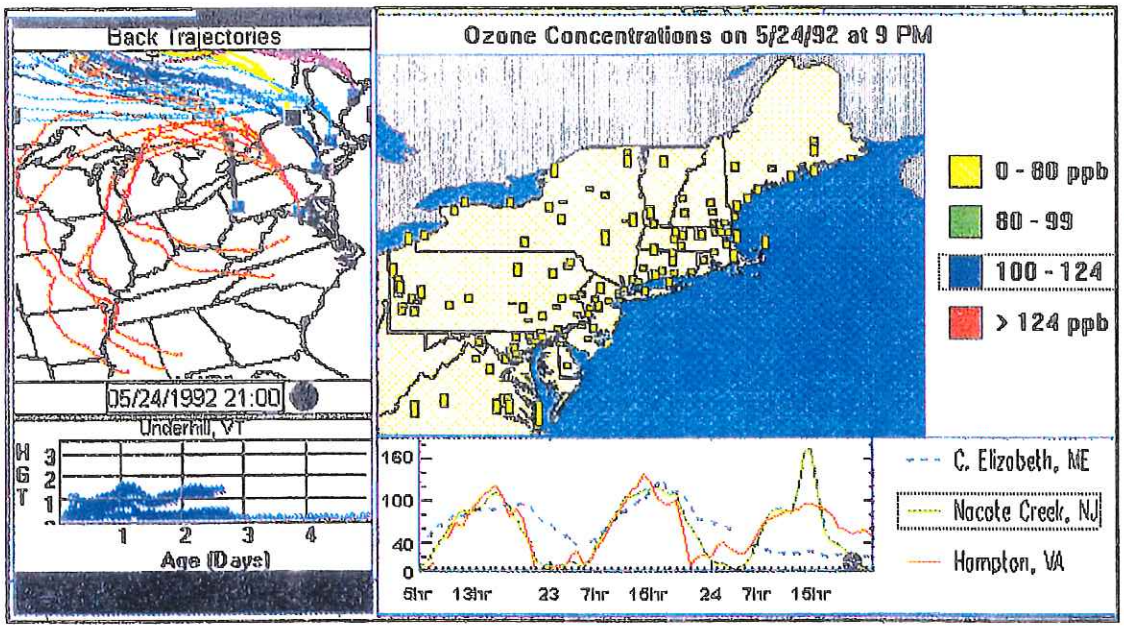
Ozone Levels in Excess of 60 ppb at 6 AM on July 7 - 9, 1988

E. TRAJECTORY ANALYSIS OF MAY, 1992 REGIONAL EPISODE

Backward air trajectory calculations provide a useful means for examining the spatial and temporal histories of air pollution episodes at discrete receptor locations. These trajectories are generally driven by various combinations of upper air and/or surface meteorological data, and can be calculated for specific layers in the atmosphere, or for mixed layers - which more realistically represent the characteristics of multi-day, multi-state pollutant episodes over synoptic scales. A number of current generation mixed layer trajectory models, such as the NOAA HY-SPLIT Model (Draxler, 1988) and the CAPITA Monte Carlo Regional Model (Patterson et al., 1971 et seq.) are driven by NOAA's recently developed Nested Grid Model (NGM) meteorological data set.

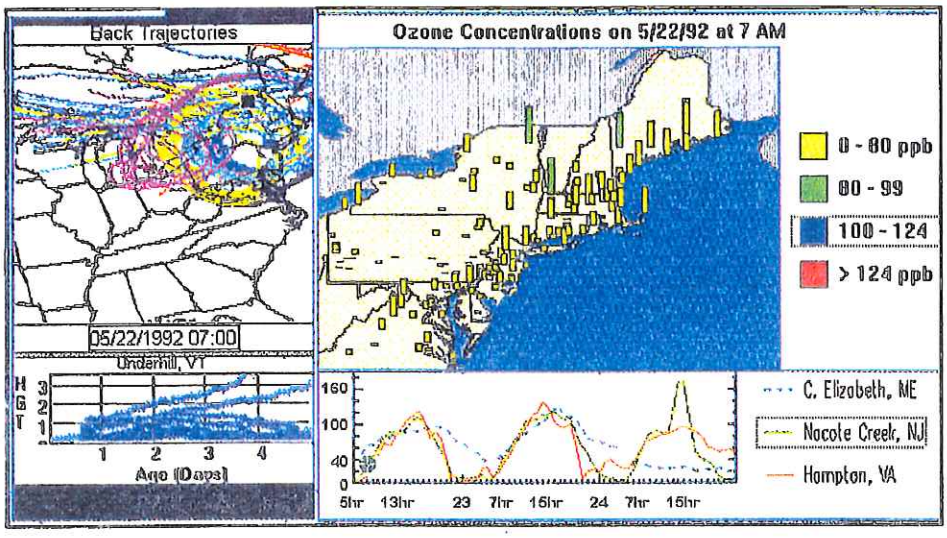
A recent evaluation of "*1992 Regional Ozone Concentrations in the Northeastern United States*" (NESCAUM, 1993), included back trajectory calculations for several 1992 episodes in the NESCAUM region (see NESCAUM, 1993, pp. 13-18). The "air mass histories" were calculated by the CAPITA Regional Model, developed and run by the Center for Air Pollution Impact and Trend Analysis (CAPITA). One of these 1992 episode periods during late May, 1992 provides a good illustration of several different aspects of the ozone transport phenomena, and has been re-assessed for the larger OTC region. Hourly ozone data are combined with CAPITA air mass histories in the form of an animated (Voyager) computer movie (5_23_92z.MOV) which can be reviewed using readily available commercial software. Several example frames are pasted on the following pages.

Ambient ozone concentrations are displayed in the map view at the upper right. A time view at the lower right shows the temporal variations in ozone levels at three coastal sites - Cape Elizabeth, ME, Nacote Creek, NJ and Hampton, VA. The CAPITA model "releases" 10 hypothetical particles at selected receptor sites and traces their "histories" backward in time for 4 days. The horizontal airmass histories are displayed at the upper left for receptor sites at Acadia NP, ME (purple); Underhill, VT (yellow); Ware, MA (light blue); Ringwood, NJ (dark blue); Washington, DC (red); and Pittsburgh, PA (black). Elevational air mass histories for the Vermont receptor are displayed at the lower left. The movie displays changing hourly ozone and (every second hour) airmass histories over the 3 day period.



The above figure shows conditions at 9 PM EST on 5/24/92 - just after a cold front had passed through the region. Strong northwesterly flows (and rain) swept the region with relatively cool, clean Canadian air, dramatically reducing the high ozone levels which had characterized the preceding 3 day period.

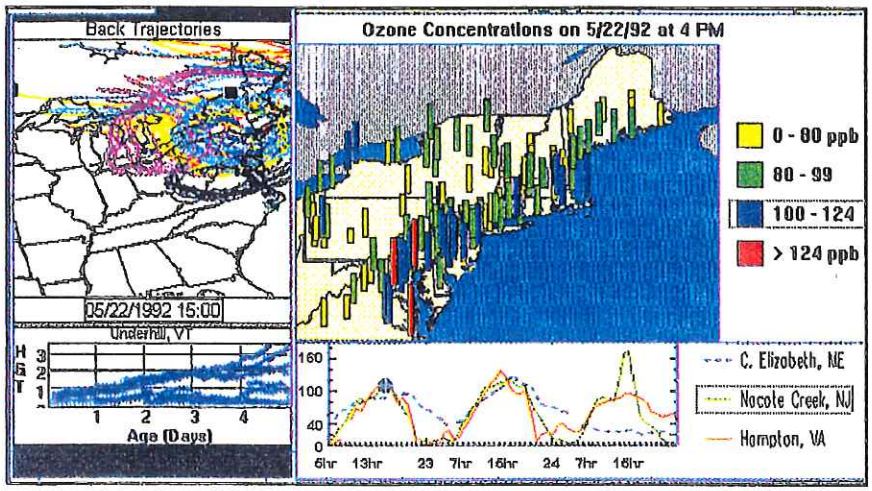
Several days earlier, at 6 AM on the morning of 5/22/92, ozone levels were also generally low throughout the region, with the exception of several rural sites in the Northeast of the OTC region, where concentrations at sunrise were already in excess of 80 ppb. These high over-night levels are essentially "left over" from the previous day.



Given the relatively remote nature of these northern sites, the dependence of ozone production on solar radiation, and the light to moderate wind speeds during this period, these high early morning ozone levels provide a clear indication of transport of the previous day's (or earlier) ozone production from relatively distant upwind regions of higher emissions densities. The airmass histories suggest that this polluted air mass had previously circulated over (was subject to emissions from) virtually the entire OTC region. A similar phenomenon of high over-night levels at northern rural sites is also evident for the next several days of the episode, as illustrated by the time trend at the Cape Elizabeth, ME site.

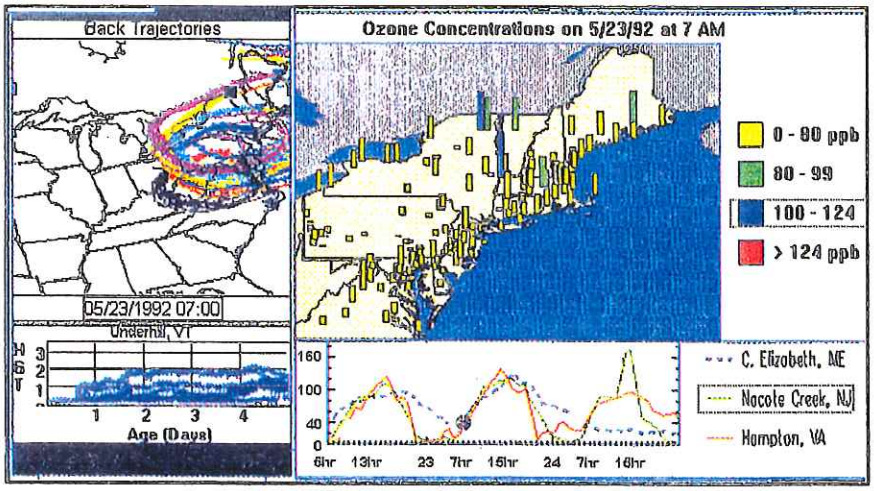
Trajectories throughout the region display the classic slow, clockwise flow around a high pressure system centered over Springfield, MA on the morning of 5/20/92, and drifting slowly to the southwest over the following few days. The elevational histories show a pronounced

subsidence under the influence of the high pressure. These are relatively common circulation patterns for ozone episodes in the Northeast.



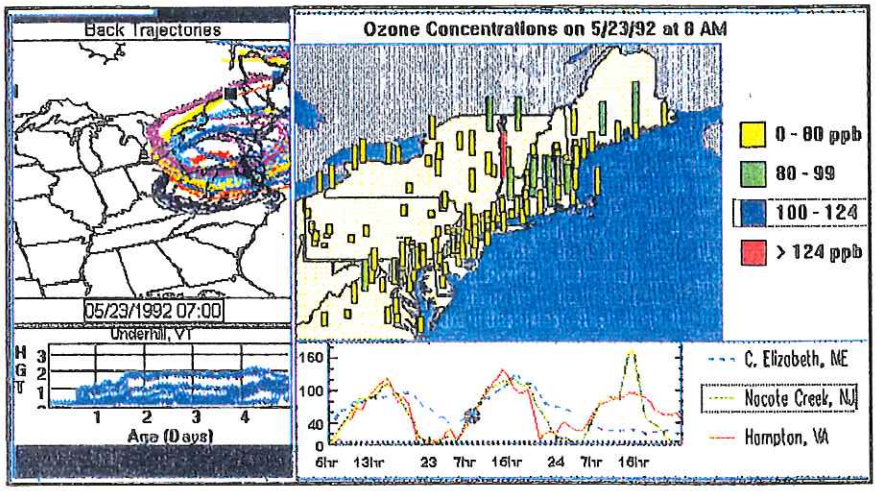
As the slow regional circulation pattern and low mixing heights persisted for several days, ozone levels climbed to greater than 80 ppb throughout the OTC region on the afternoon of 5/22/92. Exceedances were limited to the southern portion of the region, but levels in excess of 100 ppb were recorded along the coastal urban corridor as far north as Cape Cod, and in western NY and PA. Note that the western PA trajectories (black) appear to have initially stagnated over the DC/ Baltimore urban area prior to passing south of the OTC region and entering western PA via the Ohio River Valley.

Levels declined through the morning of 5/23/92, again with a notable exception of rural sites in the northeast. Trajectories to these northern sites had resided over south-eastern sections of the region several days earlier, prior to passing over western PA and NY on route to northern New England. By sunrise, remote sites at Whiteface Mtn., NY and Adams, MA were well in excess of 100 ppb.

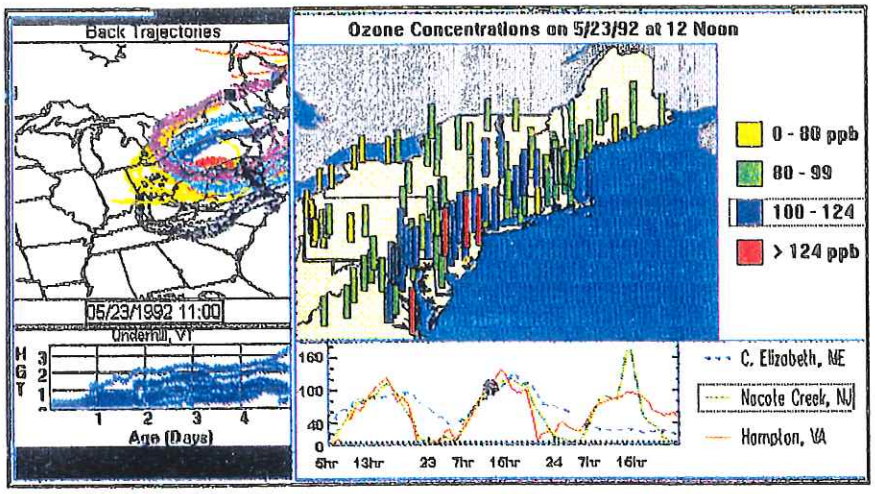


Given the high, and obviously transported background levels at these sites, only a relatively minor local ozone contribution (less than 20 ppb) would be sufficient to cause exceedances at these rural sites.

In fact, the days first exceedance was recorded at Adams, MA at 8 AM on May 23 - quite probably the result of a small incremental contribution from the Albany, NY area.



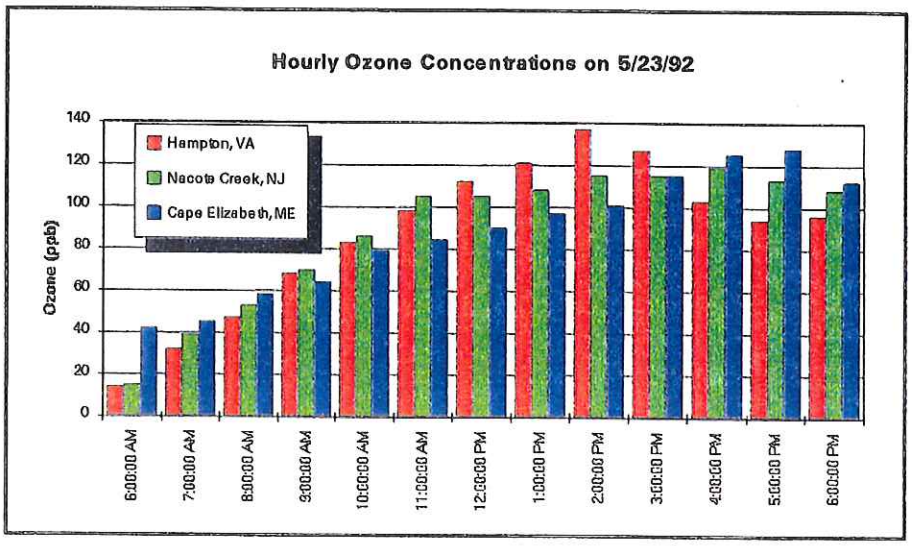
By noon on the 23rd, most of the Northeast was experiencing levels in excess of 80 ppb, with exceedances constrained to the southeast portion of the OTC region. Trajectories to these southeastern sites were looping tightly over a region extending from Western, PA to southern NJ.



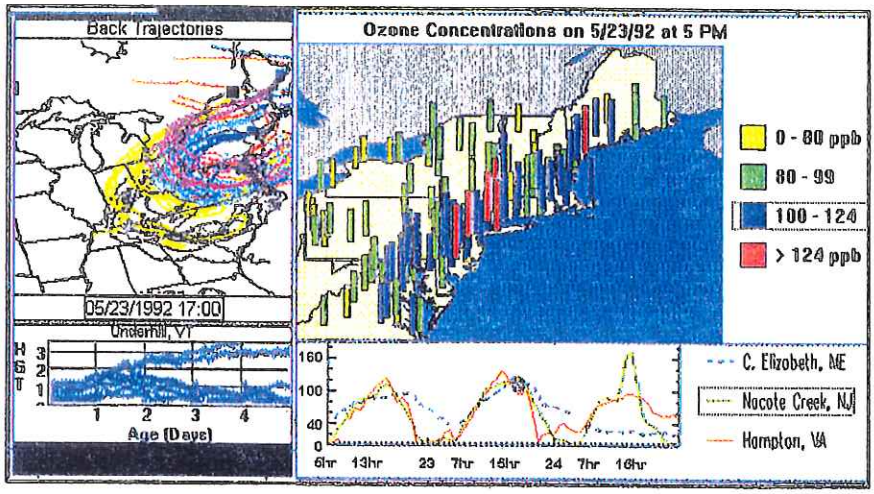
Note also, the progression in time of peak concentrations at the coastal sites from Hampton, VA to Nacote Creek, NJ to Cape Elizabeth, ME.

The hourly ozone values at these 3 coastal sites are displayed in additional detail on the following page.

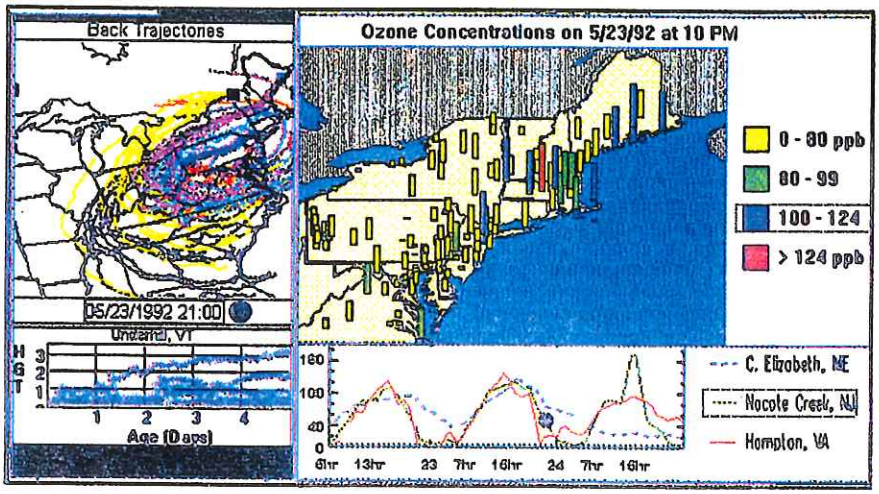
Concentrations start out highest at the ME site (transported from the previous days' production). The most southerly VA site peaks and exceeds standards at 2:00 PM. Further north, the NJ site peaks 2 hours later. While the standard is not exceeded here, the NJ site also experiences the most prolonged exposure to high levels, with 8 continuous hours in excess of 100 ppb. The most northerly ME site exceeds standards and peaks an hour after the NJ site - at a time when sunlight-driven ozone production rates have been declining for several hours, and when transport from the South/ Southwest is implicated.

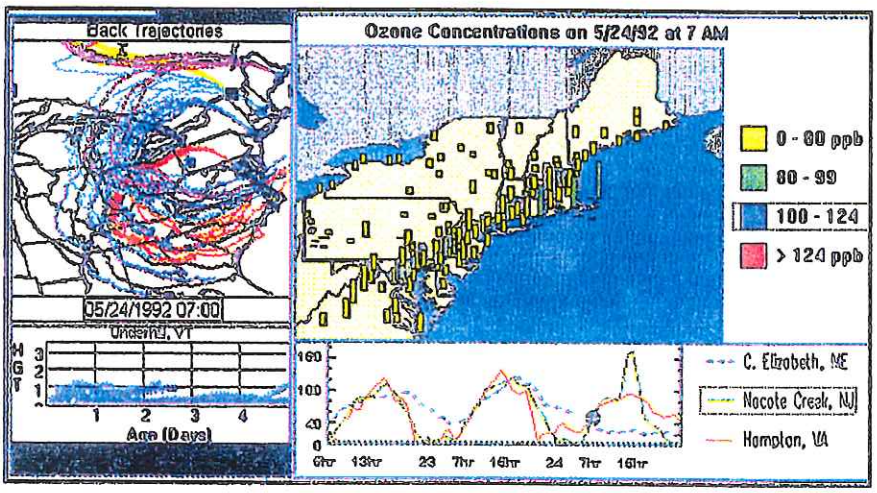


By 5 PM, there are no longer exceedances in the far South, but levels remain in excess of 80 ppb throughout the region; in excess of 100 ppb throughout the coastal corridor (as they've been for the preceding 8 hours); and in excess of the standard as far North as the coast of ME. Once again, trajectories had circulated over the entire region (including urban areas in the Southeast and West of the OTC Region.



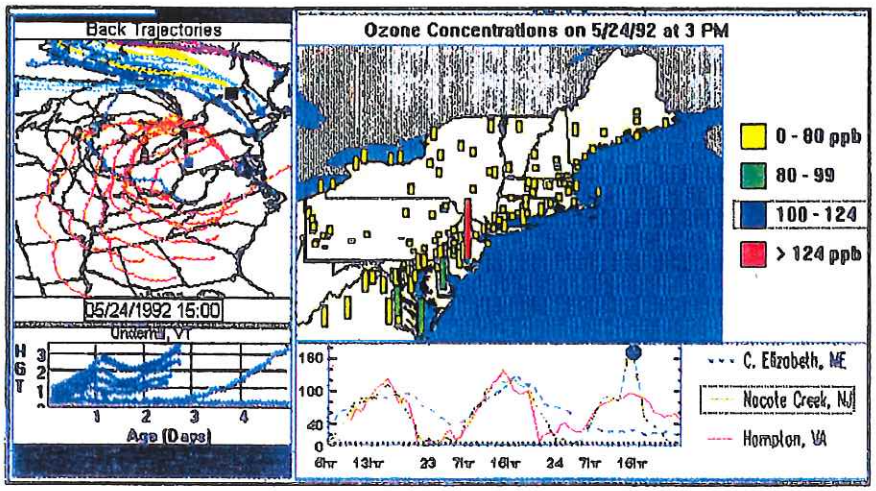
Later that evening, the highest levels are primarily limited to northern New England, with an exceedance as late as 10 PM in Central MA. The relatively tight circulation of the preceding few days is now beginning to loosen slightly, under influence of an approaching cold front from the Northwest. Sites in the West and Northwest of the region are now experiencing flows from further South and West of the region.





By sunrise on the morning of May 24, there is again evidence of transported high ozone in the North from preceding days' emissions. In this case, under northwesterly flows, the high levels are limited to eastern CT and Cape Cod, MA. High ozone levels are relatively rare under this kind of flow regime, and it would appear that ozone which had accumulated and moved to the north during the previous few days is now washing back to the southeast. Given these high early morning levels, only a small incremental local ozone contribution is required to exceed standards.

Despite the approaching cold front and strengthening flows from the Northwest, a value of 172 ppb was recorded at Nacote Creek on the southeastern coast of NJ at 3 PM on May 24th (the highest value recorded in the entire OTC region during the atypically cool and clean summer of 1992).

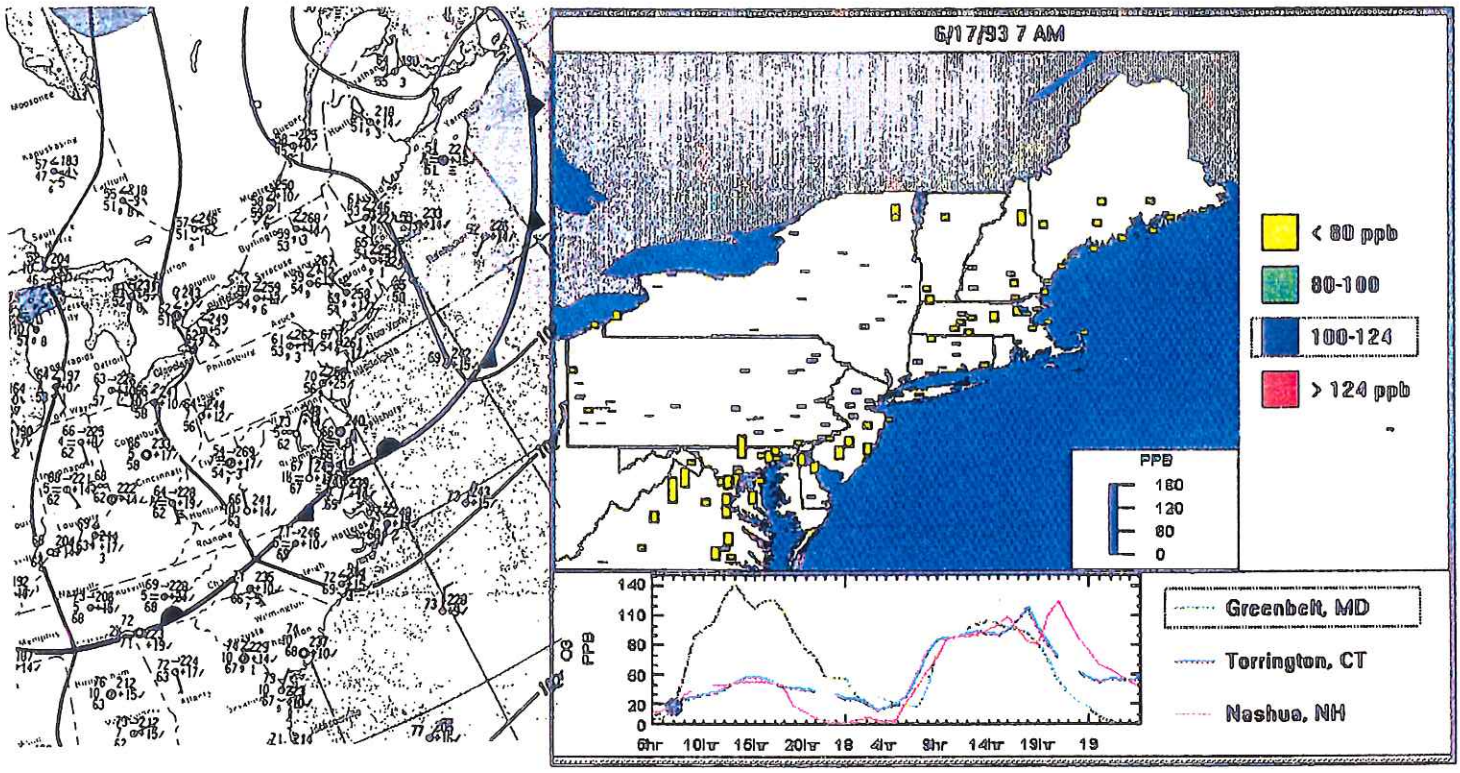


It appears that ozone produced, accumulated and transported to the North on preceding days is now being transported back to the Southeast, combined with emissions from urban and rural areas to the north of the Jersey coast, combining with local emissions, and producing one of the years highest concentrations just in advance of the cold front and associated showers which reduced levels throughout the region to the near-natural-background levels displayed on the first page of this discussion.

It should be emphasized the these back trajectory calculations indicate only the general paths of airmass movements. They cannot in themselves provide definitive proof of specific contributions from specific urban or rural emissions to standards violations at specific receptors. On the other hand, the ambient concentrations and airmass histories during this episode provide a number of relatively clear cut examples of transported emissions from sources in the North, South, East and West of the OTC region contributing to elevated concentrations and multiple exceedances throughout the region.

F. JUNE 1993 REGIONAL OZONE EPISODE

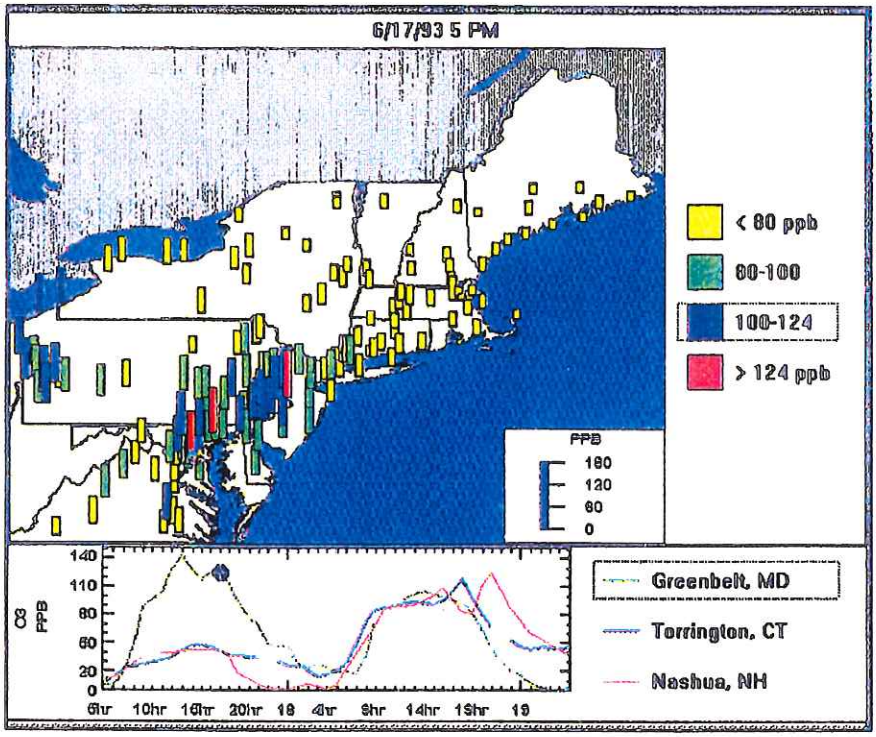
Ambient ozone data for the entire OTC region are currently available for periods as recent as the 2nd quarter (through June) of 1993. A multi-state, multi-day episode on June 17th and 18th helps illustrate several relatively common aspects of the ozone transport phenomena, and also helps demonstrate that the current nature of ozone non-attainment in the OTC region does not differ substantially from many episode periods analyzed in more detail in previous years. Changing hourly ozone levels during this 2-day period are displayed in a computerized *(Voyager)* Movie (6_18_93.MOV) which can be viewed on a PC using readily accessible software. The movie displays color coded hourly ozone levels in a map view, and a time view of the hourly data for 3 sites (Greenbelt, MD; Torrington, CT and Nashua, NH) located in southern, central and northern sections of the OTC region respectively.

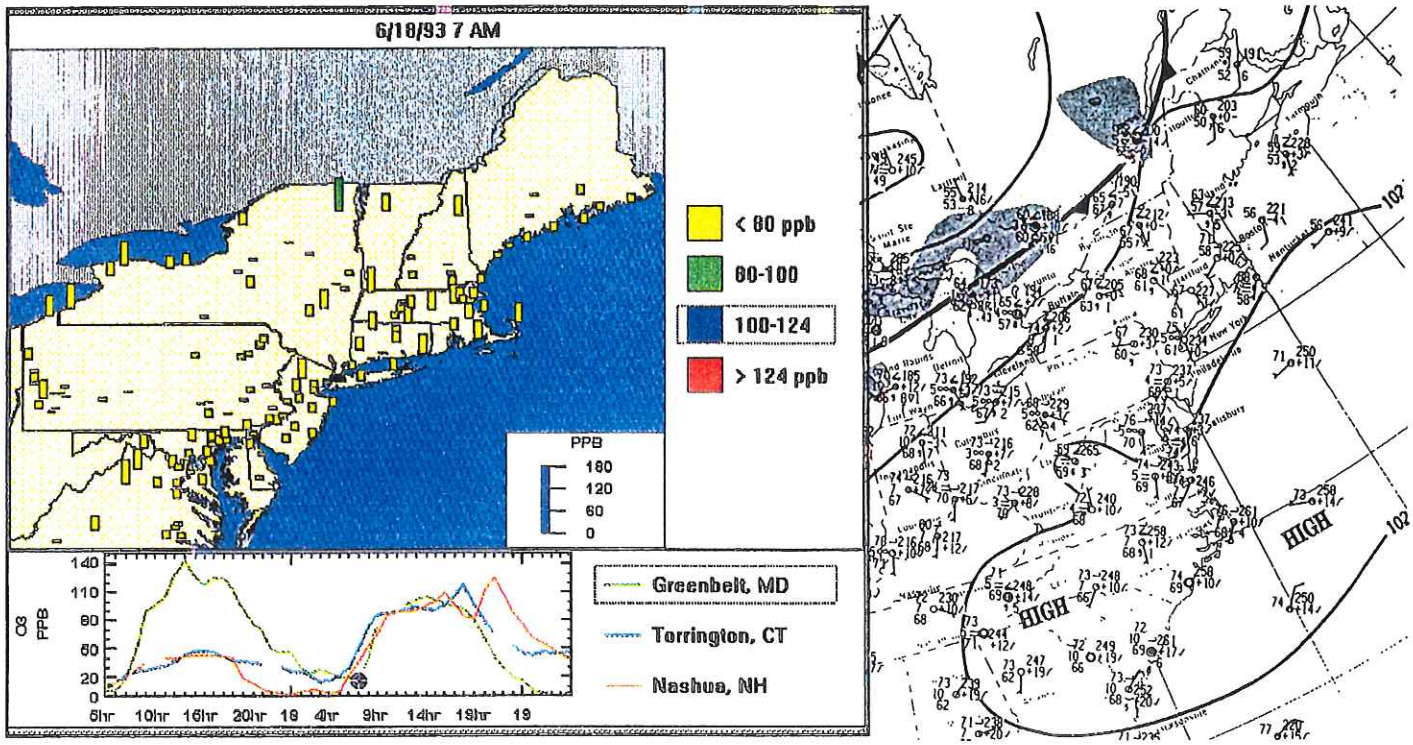


A weak cold front and light precipitation had passed through northern and western sections of the region on June 15 and 16, resulting in very low ozone levels on the morning of 6/17/93 throughout most of the region. There are some moderately high levels (40-60 ppb) in the extreme southeast of the region. The surface weather map indicates weak, but increasing high pressure over the region, with light winds approaching the southeast corner of the OCT region (southern NJ, MD, DE, DC, northern VA) predominantly from the North, and suggesting that these early morning ozone levels are left over (and transported) from previous day' production in portions of the OCT region further North.

As the high pressure continued to build and move to the South of the region on June 17th, flows to northern sections of the OTC region were still predominantly from the Northwest, and ozone levels remained low in northern sections.

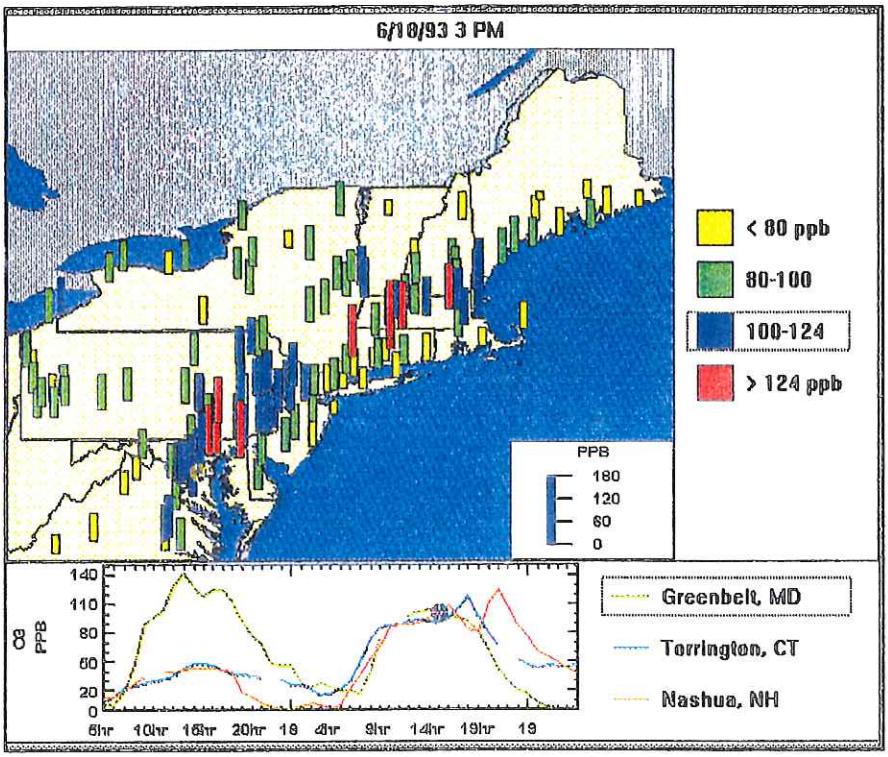
By 5 PM, ozone in excess of 100 ppb had accumulated in western NY and PA and in southeastern OTC sections. Exceedances of the federal standard recorded in MD and Western NJ appear to have resulted largely from local emissions in combination with transport from the North and Northeast.





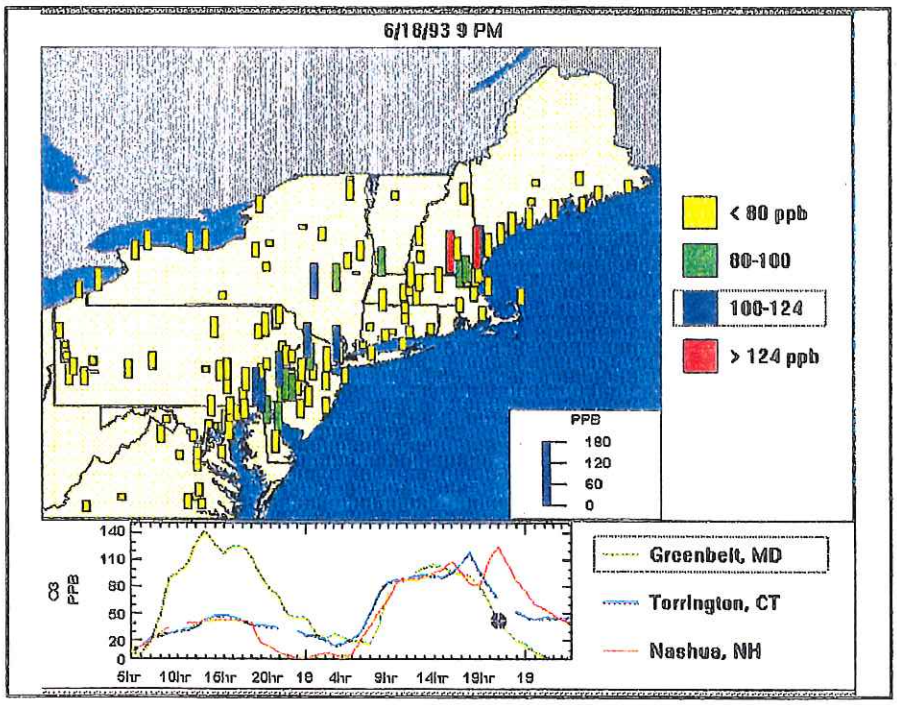
By the morning of June 18th, the high pressure system had intensified and moved to the SSE of the region. A cold front was approaching slowly from the Northwest. Light surface winds were shifting to a more Southwesterly flow, around the backside of the high, and channeled by the approaching front from the northwest. Moderately high early morning ozone levels (transported form previous days production) are apparent in several sections of the region. Most notable is a 7 AM value in excess of 80 ppb at the remote Whiteface Mtn., NY site in the northern end of the region.

Southwesterly flows continued throughout the day on the 18th, and by 3 PM, concentrations throughout the region were in excess of 80 ppb (where Whiteface Mtn. had started out that morning), and exceedances were occurring at sites in MD, PA, NJ, CT and MA.



Note also the clear progression of peak levels at the 3 sites displayed in the Time view. The southern Greenbelt, MD site peaks at 2 PM; further north, Torrington, CT peaks at 6 PM.

The most northern Nashua, NH site peaks (exceeds standards) at 9 PM - a time when ozone production rates have been declining for over 6 hours and when transport from relatively distant sources to the Southwest is clearly implicated.



In summary, this episode began with moderately elevated ozone levels in the southeast corner of the OTC region on the morning of 6/17/93. These early morning background levels appear to have been transported from the previous day's production from states further North in the region. As high pressure built to the Southwest of the region local emissions stagnated and combined with the transported baseline levels to cause high afternoon concentrations in the West and Southeast, with exceedances limited to the Southeastern sections. By the morning of the 18th, surface flows were shifting toward the Northeast, and moderately high early morning concentrations were present throughout the region. Clear skies, high temperatures, low mixing heights and persistent Southwesterly flows resulted in a Southwest to Northeast progression of ozone exceedances throughout the day and evening of 6/18/93, ultimately resulting in exceedances as far north as New Hampshire after sunset at a time when transport is the only possible explanation.

G. RESIDENCE TIME ANALYSIS: 1989 - 1991

A number of receptor-oriented ensemble trajectory techniques have been developed and employed to examine the long-term space/time characteristics of multiple air trajectory calculations and associated air pollution concentrations. One of the simplest most straightforward of these techniques is known as "residence time analysis" (Ashbaugh, 1983; Poirot and Wishinski, 1985). Multiple back trajectories are calculated for one or more receptor locations, sorted by resultant pollutant characteristics (such as high or low concentration); and aggregated and plotted on a gridded map projection. In the current application, 3 summers (April - September, 1989-1991) of 3-day back trajectories were calculated 4 times a day for each of three receptor sites: Underhill, VT; Ringwood State Park, NJ and Shenandoah National Park, VA. The trajectory model employed was the Hybrid Single-Particle Lagrangian Integrated Trajectories (HY-SPLIT), developed at the NOAA Air Resources Laboratory (Draxler, 1988) and run by the Vermont Air Pollution Control Division (Wishinski, 1993).

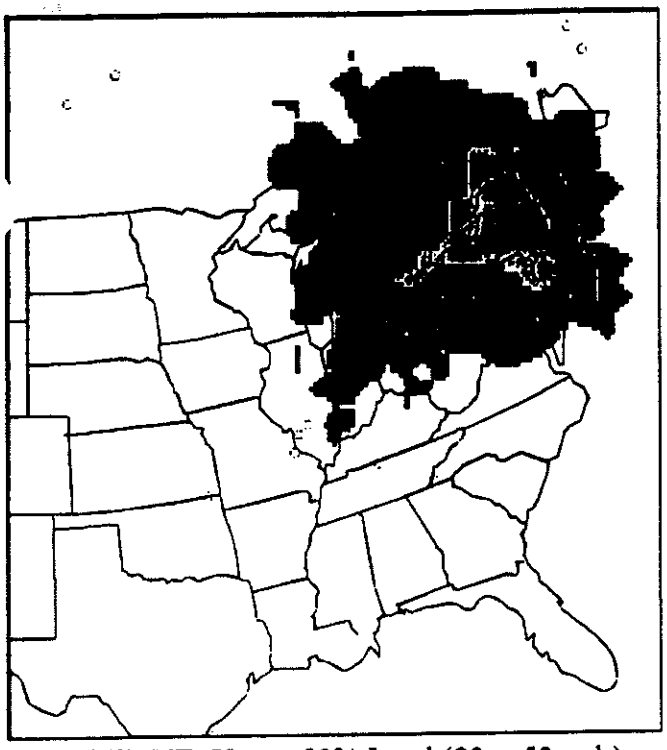
Daily maximum ozone concentrations for each of the receptor locations were ranked and summed to form a cumulative long-term ozone dose, and sorted into 4 subsets representing different percentiles (lower 50 %, upper 50%, upper 25% and upper 10%) of the total cumulative dose. At the Underhill, VT site, for example, there were a total of 373 dates when both trajectories and ozone data were available. Ozone concentrations were less than 53 ppb on 220 of these days. When ozone concentrations on these 220 days are summed, they represent the lower 50% of the long-term ozone dose at this site. The remaining 152 days with concentrations above 53 ppb represent the upper 50% of the dose. The upper 25% of the dose was contributed on 69 days with ozone greater than 64 ppb; while the upper 10% of the dose was contributed on 26 days with ozone greater than 73 ppb.

Ozone characteristics and sample sizes of the 4 plotted scenarios for all 3 sites are as follows:

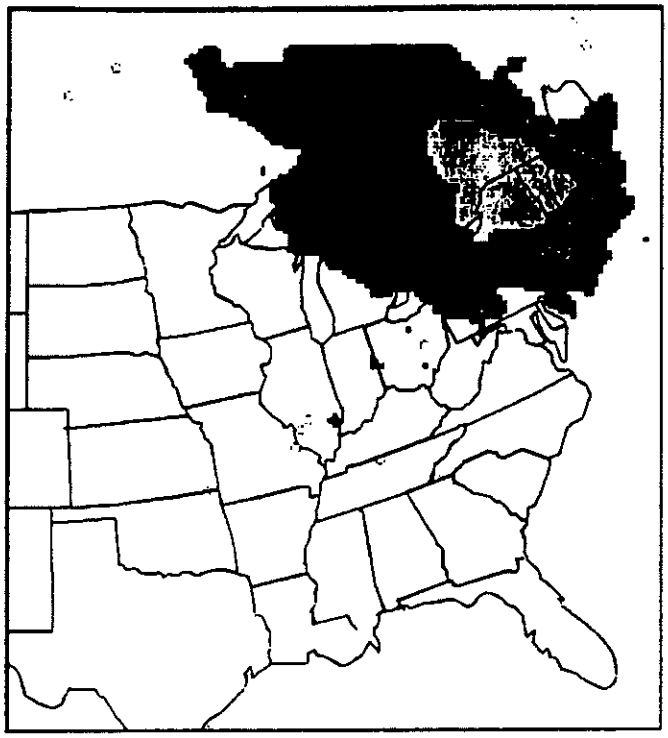
	Underhill, VT		Ringwood St. Park, NJ*		Shenandoah NP, VA	
	# of Days	Ozone	# of Days	Ozone	# of Days	Ozone
Lower 50%	220	< 53 ppb	262	< 71 ppb	233	< 65 ppb
Upper 50%	152	> 53 ppb	153	> 71 ppb	160	> 65 ppb
Upper 25%	69	> 64 ppb	65	> 91 ppb	76	> 74 ppb
Upper 10 %	25	> 73 ppb	23	> 111 ppb	27	> 84 ppb
Total Dates	372		415		393	

* Trajectories are for Ringwood State Park, NJ; ozone data are from nearby Chester, NJ

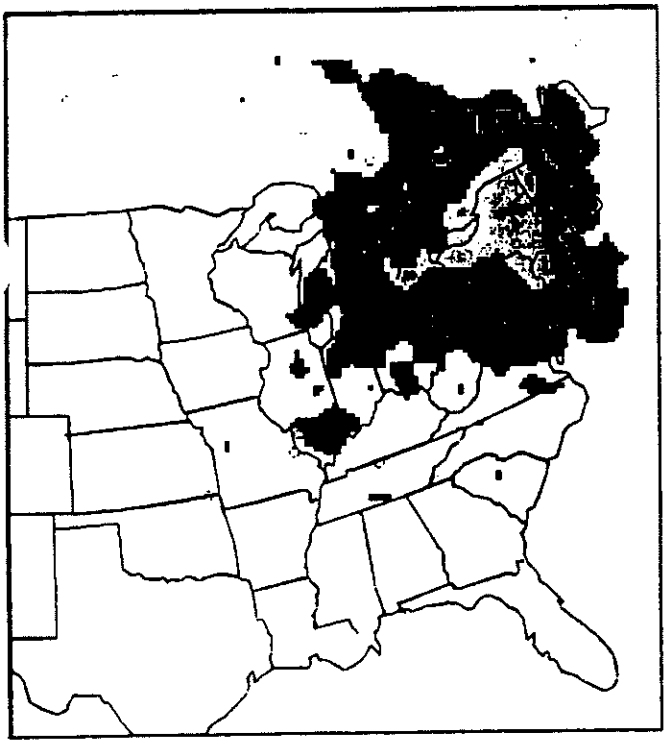
A grid of 80 x 80 km squares is super-imposed on a map of eastern North America, and the "residence times" of each trajectory are calculated for each grid square in its path. For each scenario, the residence times of all trajectories are aggregated for each grid square, and the total of the scenario's residence time hours is determined. Isopleths bounding the separately shaded areas are plotted to bound the smallest areas which account for 25%, 50% and 75% of the total scenario residence time hours respectively. The resulting patterns show the areas where an airmass is most likely to have previously resided if the subsequent ozone concentration at the receptor is low, or high, or very high, etc. The technique does not identify quantitative contributions from specific sources or source regions, but does indicate the directional tendencies or predominant pathways of pollution transport to each receptor.



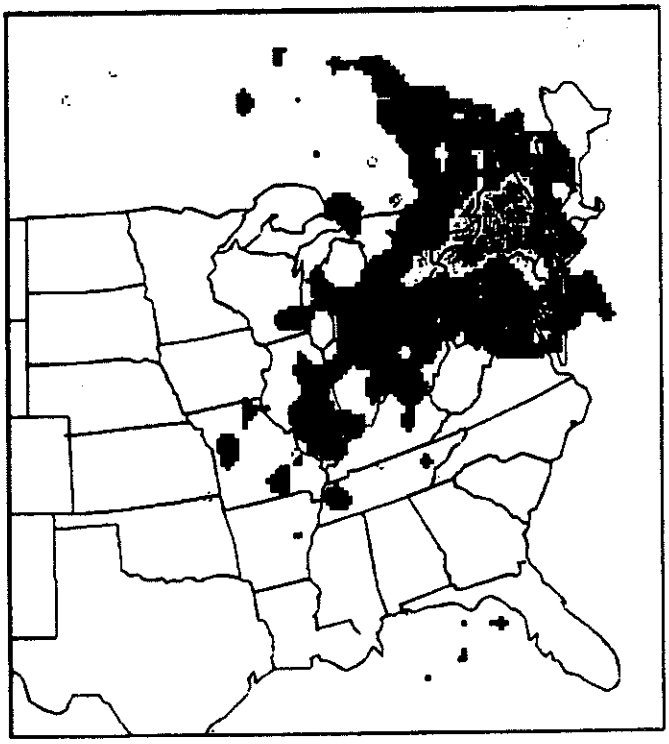
Underhill, VT; Upper 50% Load (03 > 53 ppb)



Underhill, VT; Lower 50% Load (O3 < 53 ppb)

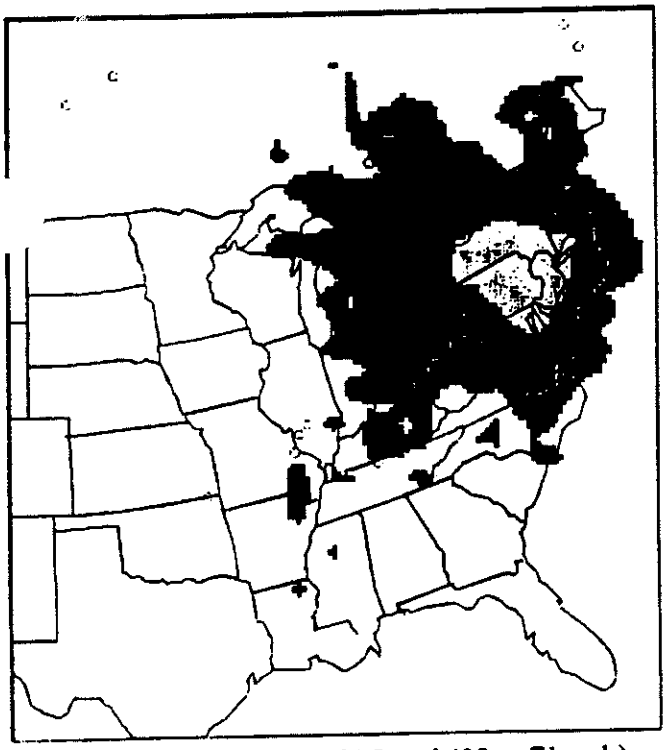


Underhill, VT; Upper 25 % Load (O3 > 64 ppb)

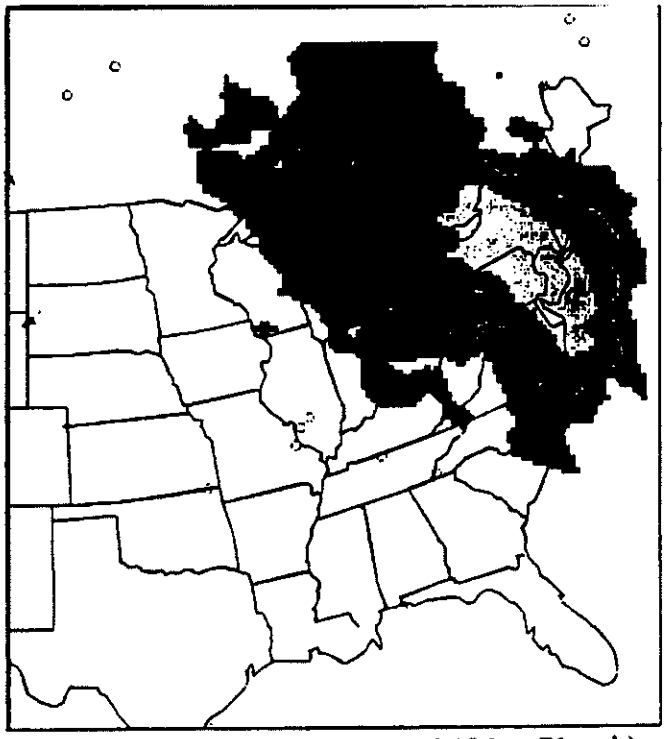


Underhill, VT; Upper 10% Load (O3 > 73 ppb)

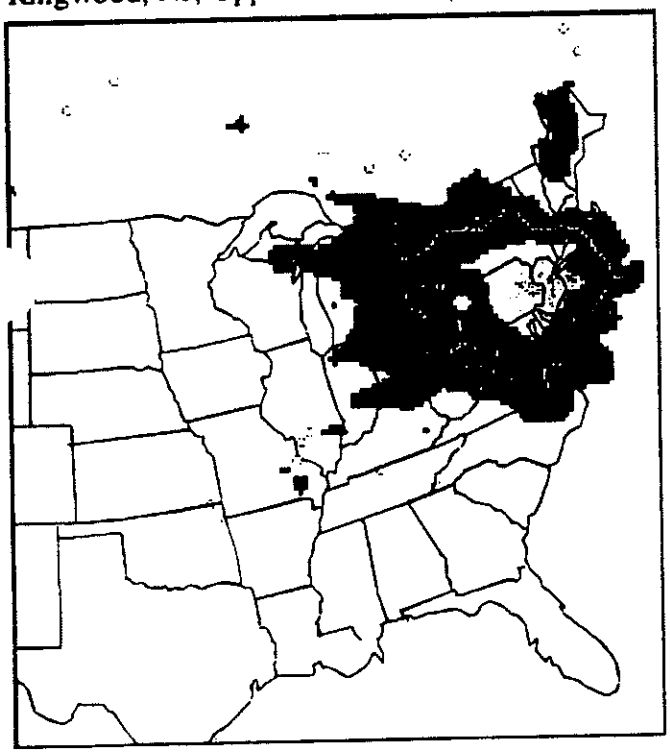
Underhill, VT is is the most northerly of the 3 receptor sites (lowest temperatures and solar radiation), is farthest from major source regions and experiences the lowest ozone levels. Underhill's lowest ozone concentrations (upper right) tend to occur in air that has previously resided locally - over VT, NH and northern NY - and to the northwest over western Quebec. For higher ozone concentrations, there is a relatively minor lobe to the NNW in the direction of the nearby Montreal urban area, and 2 more prominant lobes - one to the south along the Hudson River Valley toward the New York metropolitan area, NJ and Eastern PA - and one to the WSW toward the western portion of the OTC region, and toward Midwestern and Canadian regions of higher emissions densities along the lower Great Lakes.



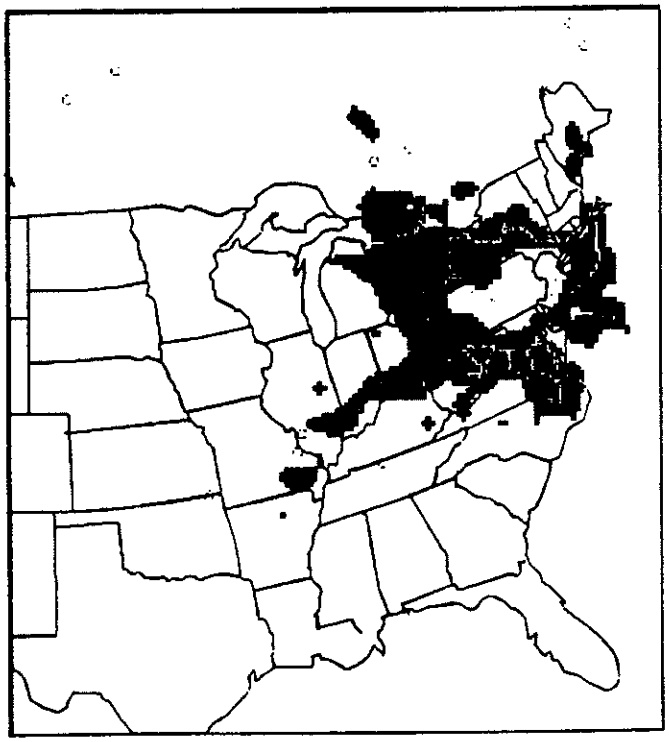
Ringwood, NJ; Upper 50% Load (03 > 71 ppb)



Ringwood, NJ; Lower 50% Load (O3 < 71 ppb)

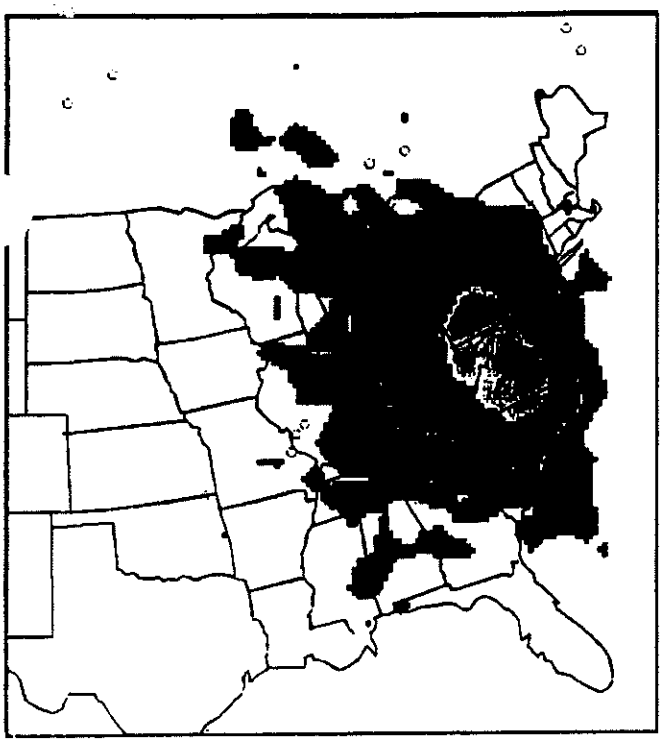


Ringwood, NJ; Upper 25% Load (03 > 91 ppb)

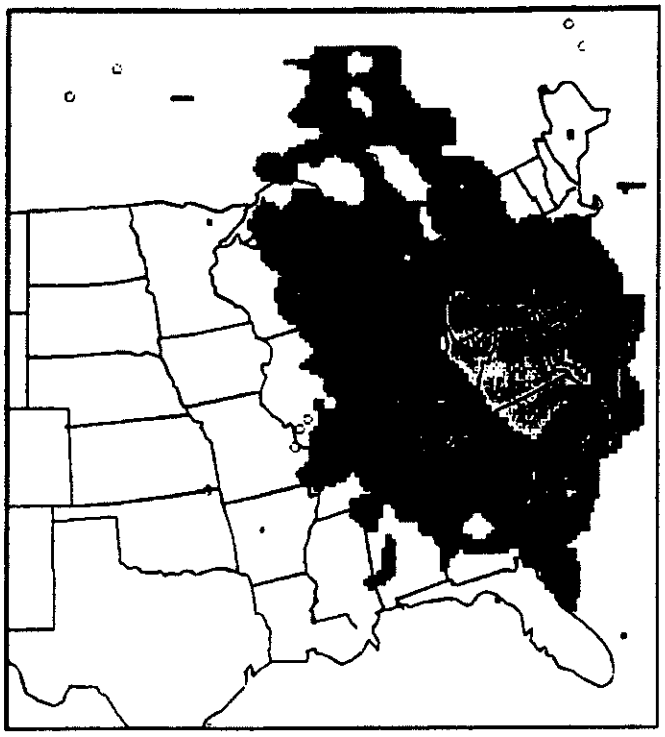


Ringwood, NJ; Upper 10% Load (O3 > 111 ppb)

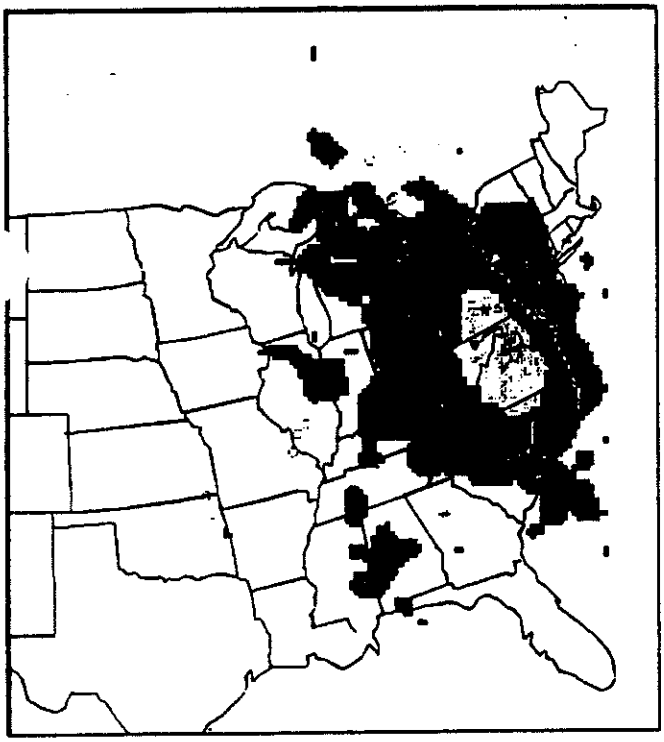
Ringwood State Park (and Chester) in northern NJ are rural sites in relatively close proximity to large urban centers to the East and South. Ringwood's lowest ozone concentrations tend to occur in air which had previously resided to the Southeast - over the Atlantic Ocean - or to the Northwest - over central NY and Canadian areas to the East of the Great Lakes. Ringwood's (Chester's) highest ozone levels tend to occur in air that has previously resided slightly to the East - over the NY metropolitan area;) the South - over other urban centers in NJ, eastern PA, MD, DE, DC and northern VA; and to the West - toward western NY and PA (and most probably beyond the OTC borders to areas as distant as the lower Great Lakes and Ohio River Valley).



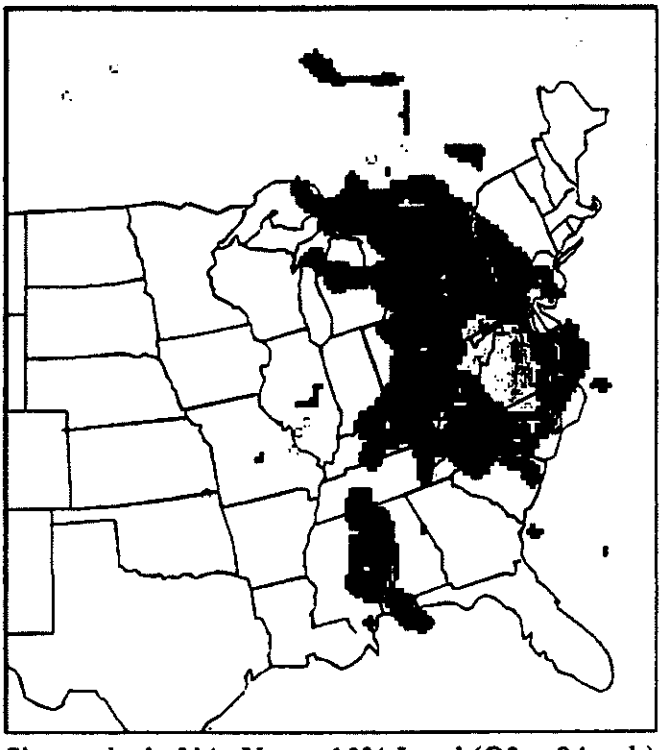
Shenandoah, VA; Upper 50% Load (03 > 65 ppb)



Shenandoah, VA; Lower 50% Load (O3 < 65 ppb)



Shenandoah, VA; Upper 25% Load (03 > 74 ppb)



Shenandoah, VA; Upper 10% Load (O3 > 84 ppb)

Shenandoah National Park is further South, more remote, and at a much higher elevation than the Underhill and Ringwood sites. These factors tend to exert a moderating influence on its ozone levels which exhibit a minimal diurnal cycle and a relatively small range between the 50% and 10% ozone load levels (65 - 84 ppb). While there are relatively large nearby source regions to its Northeast, flows from this direction are infrequent. Conditions most conducive to ozone formation and accumulation (high temperatures and stagnation) would tend to occur in air arriving from the South. Perhaps for ıese reasons, there do not appear to be dramatic differences between the residence time areas resulting .n low vs. high ozone at this site. The highest ozone levels tend to occur when air has previously resided to the NNW - over northern VA and western PA, and to the SSE over South-Central VA.

H. Conclusions from Analysis of Ambient Ozone and Meteorological Data

Based on the analysis of the selected episodes reviewed here, the multi-year Residence Time Analysis, and short and long-term evaluations of high ozone levels which have been reported in the literature of the past several decades, it is clear that the transport of ozone and its precursors can and does contribute to exceedances of Ozone health standards over large regions of the Northeastern US (and Eastern Canada). This transport phenomena also contributes to even more widespread occurrences of somewhat lower chronic exposures which are known to adversely affect sensitive terrestrial ecosystems, in a region where such ecosystems are already subject to a variety of other air pollution-related stresses. The following conclusions may be drawn from this review and from the recent literature:

- Two major source regions contribute to high local and transported ozone concentrations in the OTC region: the "East Coast Urban Corridor" - extending from South of Washington DC to North of Boston, MA; and a "Midwestern" region - including Western PA in the OTC region and areas further West along the Ohio River Valley and lower Great Lakes.

- The atmospheric transformation and transport process does not distinguish between emissions originating from urban and rural areas. As the air moves over both urban and rural areas, the emissions from a poorly tuned motor vehicle or point source will contribute to the formation and accumulation of ozone downwind regardless of the point of origin.

- Multi-state, multi-day ozone episodes in the OTC region (and elsewhere) are commonly associated with the passage of slowly moving high pressure systems over or near to the region during Summer. These systems are frequently characterized by subsiding airmasses (low mixing heights), light winds, clear skies, high temperatures and slow clockwise circulation - conditions conducive to the formation, accumulation and transport of ozone (and ozone precursor) pollution over scales of several hundred kilometers or more.

• When one of these high pressure systems stagnates approximately over the OTC region for several days, ozone or ozone precursor pollutants can circulate (and recirculate) over virtually the entire region. If one of these systems stagnates or moves slowly to the Southeast of the OTC region, the resultant southwesterly flows around the backside of the high can initially enhance transport from the Midwest to the Northeast, and later (as the high moves further East) produce flows which align directly along the East Coast urban corridor, enhancing ozone accumulation along and to the Northeast of the corridor.

• High ozone concentrations, transported over night from areas of precursor emissions and/or ozone formation on preceding days are often delivered to relatively remote sections of the OTC region. This nocturnal transport is particularly efficient in higher levels of the atmosphere, decoupled from NOx scavenging and physical ozone destruction mechanisms at the earth's surface. When mixed downward - after sunrise on the following morning - these early morning levels are often sufficiently high (> 80-100 ppb) that only a small local contribution is needed to exceed standards.

• Given this nocturnal transport above the surface layer (and a similar lack of NOx scavenging during transport over water), emissions of ozone precursors from nearly every section (North, South East and West) of the OTC region can potentially contribute to exceedances of standards in nearly every other section of the region (and in Eastern Canada). There is also frequent evidence of transport into the OTC region from adjacent areas of high emissions density to the South and West.

• It does not require a sophisticated meteorological analysis to observe that the winds generally blow from West to East in Eastern North America. During the Summer ozone season, these flows are predominately from the Southwest. The kinds of meteorological conditions most conducive to ozone formation (particularly high temperatures) are most likely to occur with airmasses approaching and moving through the OTC region from the South or Southwest. Consequently the effectiveness of specific control measures is likely to be greater for reductions in Southern and Southwestern sections of the region than for equivalent controls in far Northeastern sections.

I. RESULTS OF ROMNET ANALYSIS

The previous analyses based on wind trajectories, ambient ozone concentrations, and residence time estimates clearly make a convincing case for the significant role of long-range transport in regional, elevated ozone concentrations. Additionally, results of ROMNET effort from 1988 through 1993, including the analysis done in 1992 (presented at the June 1992 meeting of the OTC) show that the 1990 CAAA-mandated controls alone will not be sufficient to attain the ozone standard in the Northeast. The same analysis also demonstrates that additional controls will still be needed in most nonattainment areas (including even the marginal and moderate areas) before the OTR will be able to demonstrate attainment of the ozone standard. The ROMNET protocol, as outlined by EPA, does recognize limitations in its use in SIP planning (in determining specific levels of controls required). For example, the relatively large grid size in ROM limits the ability of the model to accurately predict peak concentrations in urban plumes, and its results can not be relied upon to demonstrate attainment in specific grids or at individual monitoring sites. In spite of its limitations, ROMNET may still be the most appropriate regional tool (on the scale of the whole OTR) currently available to provide a reasonable estimate of level of ozone precursor emission reductions which will be needed region-wide to reach attainment. This report, however, relies on the modeling results derived from ROMNET only in a qualitative sense in that the results of ROMNET are directionally correct and consistent with our understanding of atmospheric chemistry and transport in the Northeast, and more importantly, consistent with the overwhelming evidence based on analysis of ambient wind and ozone data on long-range transport presented earlier.

IV. CONCLUSIONS

The pattern and prevalence of ozone NAAQS exceedances in the northeast and mid-Atlantic states demonstrate the regional nature of the OTR's ozone pollution problem. While substantial strides have been made to improve air quality in the OTR, additional reduction strategies must be implemented in order to both provide for healthful air quality and avoid the imposition of economic sanctions required by the 1990 CAAA if attainment goals are not met.

The OTC is empowered to develop recommendations for additional control strategies whenever a majority of OTC members determines that such measures are necessary to bring about attainment of the ozone NAAQS anywhere within the OTR. The findings from the atmospheric transport analyses described above, and the conclusions from the ROMNET project, provide incontrovertible evidence that long-range transport of ozone and ozone precursor emissions plays a substantial role in perpetuating ozone nonattainment throughout the northeastern and mid-Atlantic states. Moreover, the ROMNET study indicates that aggressive application of the emission control strategies specified in the 1990 CAAA will be inadequate to bring about regional attainment for ozone.

Both the trajectory analyses and the ROMNET study demonstrate that, during the summer months, plumes of elevated ozone are often transported hundreds of miles during multi-day pollution episodes. During severe ozone episodes, the background levels of transported ozone themselves actually exceed the ambient health standard causing nonattainment violations everywhere the plume travels regardless of localized emissions.

Transported ozone has been shown to be a primary cause of nonattainment in both rural and urban areas. These studies indicate that regional ozone control strategies geared at diminishing ozone transport must be implemented in order to provide for attainment, as well as long-term maintenance, of the ozone NAAQS throughout the OTR.

Emissions originating from major metropolitan areas, smaller cities, and rural areas, all contribute to the ozone transport problem. As such, the most effective control strategies are those

that are applied to the transport region as a whole. An examination of the emission inventory for the OTR states indicates that the largest single category of ozone precursor emissions is light-duty motor vehicles. Motor vehicles are an appropriate target for regional pollution control strategies because, in addition to their significant contribution of emissions, the vehicles themselves move throughout the OTR. Thus, by their very nature, vehicles that are registered in less-polluted areas play a substantial causal role in the severe pollution problems that exist throughout the OTR.

THE RESPONSE OF REGIONAL OZONE TO VOC AND NO_x EMISSIONS REDUCTIONS: AN ANALYSIS FOR THE EASTERN UNITED STATES BASED ON REGIONAL OXIDANT MODELING

ME20

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ABSTRACT

The latest version of the Regional Oxidant Model (ROM 2.2) was applied to the July 2-10, 1988 episode to test the regional ozone response to different combinations of the across-the-board NO_x/VOC reductions in the eastern half of the United States. Given the current input and model accuracy, the ROM results suggest that reduction of NO_x emissions is a key factor in reducing regional ozone. The primary benefit of VOC reductions appears to be in reducing ozone peak values near NO_x-source-intensive areas, such as the large urban cores and/or large NO_x point sources. In these NO_x-source-intensive areas, a strategy featuring a combination of both NO_x and VOC reductions appears to be most effective in reducing the regional ozone.

INTRODUCTION

Unlike the other criteria pollutants, ozone is not emitted directly to the atmosphere. Instead, it is formed in the atmosphere as the result of chemical reactions among volatile organic compounds (VOC) and nitrogen oxides (NO_x) in the presence of sunlight. The relationships among VOC and NO_x and ozone concentrations are complex and highly nonlinear. Hence, the most effective combination of VOC and NO_x controls to reduce surface ozone is not obvious. Additional complexity is introduced by transport of ozone and its precursors and, in some parts of the country, by the proximity of cities to each other.

In recent years, tools for assessing effectiveness of strategies to reduce ozone have improved markedly. In this study, the latest version (version 2.2) of the Regional Oxidant Model (ROM)[1,2] has been applied to the eastern half of the United States to assess effects of VOC and NO_x reductions on predicted regional ozone levels. Results of the study are intended to provide insight to State agencies in selecting strategies to simulate with more detailed urban-scale models. The results are also intended to serve as one input to the USEPA in assessing usefulness of broad national policies.

STUDY DESIGN

A total of 25 ROM simulations are planned to test the regional ozone responses to across-the-board reduction of anthropogenic NO_x and VOC in the eastern U.S. Twelve of them have been completed. The anthropogenic emission inputs to the model are based on the 1985 National Acid Precipitation Assessment Program (NAPAP) inventory[3]. The ROM modeling domain spans from 26° N to 47° N and from 99° W to 67° W (Figure 1). The period simulated, July 2-10, 1988, was one of the most wide-spread ozone episodes in this region for the last 10 years. During this episode, surface ozone concentrations above 120 ppb were observed in many places over a large area stretching from Birmingham, Alabama to Manitowoc, Wisconsin and from St. Louis, Missouri to Cape Cod, Massachusetts. Ozone over 200 ppb was recorded in New York, Chicago, Philadelphia, Detroit and Baltimore. The episode lasted more than a week. Preliminary results of the 12 ROM simulations are

compared for the episode maximum ozone concentrations (as predicted by the model) between different precursors reduction strategies and the base case.

METEOROLOGICAL CONDITIONS

The meteorological conditions of this episode are extremely ozone-conducive both photochemically and dispersively. A strong blocking high pressure system which was centered over the Ohio River Valley, dominated two-thirds of the eastern U.S. from July 5-10, 1988. The axis of the jet stream was displaced far north of the continental U.S. away from its seasonally averaged location. Hence, the active frontal and low pressure systems were blocked outside this region. An approaching frontal system stalled just west of the Great Lakes and an enhanced mountain lee trough, which was embedded in the high pressure system, lay just east of the Appalachian Mountains. During the episode, high temperatures above 90° F were observed as far north as the U.S./Canadian border. The influence of summer blocking high pressure systems on regional ozone episodes are discussed in previous papers[4,5].

MODELING SYSTEM

The ROM is a three-dimensional Eulerian model. It is designed to simulate most of the important chemical and physical processes that are responsible for the photochemical production of ozone in the planetary boundary layer over a domain of 1000 km or more. ROM is capable of simulating ozone episodes ranging from a few days to well above two weeks. The physical processes simulated by the model include (1) horizontal transport, (2) atmospheric chemistry, (3) the effects of cumulus clouds on vertical mass transport and photochemical reaction rates, (4) mesoscale vertical motions induced by terrain and large scale flow, 5) terrain effects on advection, diffusion and deposition, (6) emissions of natural and anthropogenic ozone precursors, and (7) dry deposition. The horizontal grid resolution of ROM is currently set at (1/4)° longitude by (1/6)° latitude, or about 18.5 km x 18.5 km. In the vertical, however, there are only three dynamic layers to simulate the planetary boundary layer and the capping inversion or cloud layer. These dynamic layers are free to expand and contract locally in response to changes in the physical processes occurring therein.

The chemical kinetic mechanism embedded in ROM is the Carbon Bond Mechanism IV (CB-IV)[6]. This mechanism simulates the significant reaction pathways responsible for gas-phase production and destruction of photochemical smog constituents on regional scales. The mechanism consists of 83 reactions including 33 individual species.

Model Inputs

Initial and Boundary Conditions.

The model is initialized with the daytime background concentrations, computed with the CB-IV mechanism and mean tropospheric concentrations of gases, for each model grid cell. The simulations presented here begin on a day with relatively clean air. Because of the effects of meteorology and chemistry, the effects of the initial conditions are considered to be insignificant after the first day or so.

For this study, the background values, described above, are also used to specify the lateral boundary conditions for all four sides of the modeling domain. The justification for this selection is that the four lateral boundaries chosen were remote from any big anthropogenic source area. Relatively clean tropospheric air is assumed to exist above layer 3 (i.e., the capping inversion or cloud layer) at all times, and therefore background values equilibrated with an O_3 level of 40 ppb are used for the top boundary condition.

Meteorological Data.

Standard surface and upper air meteorological observations, as well as data from buoys were

processed for the July 2-10, 1988 episodic period. Many levels of data preprocessing occur in preparing these data for the model, along with quality assurance procedures at each level to filter out erroneous data. Surface and buoy data are merged and subjected to objective analysis to obtain gridded values for various meteorological parameters. Hourly upper air profiles are produced by interpolating upper air data between observation times and by adjusting the interpolated profiles to account for hourly surface conditions. Objective analysis is then used to grid horizontally other derived meteorological parameters based on these hourly profiles. In addition to the standard meteorological parameters required by the model, turbulence parameters are computed using the observed meteorological data and provided to the model.

Emissions Data.

The anthropogenic point and area emissions input to the model for the July 2-10, 1988 base case run are derived directly from the 1985 NAPAP inventory. This inventory consists of annual major point source and area source data for VOC, NO_x, CO, SO2, TSP.

Unlike the point and area source data, the mobile source emissions are not based on the 1985 NAPAP inventory. These data are derived from 1986 vehicle miles travelled (VMT) data derived from Federal Highway Statistics projected to 1988 using motor vehicle gasoline consumption data for each State and average roadway fuel economy data. The fuel consumption data are multiplied by the roadway miles per gallon to estimate State level VMT. The growth rate for each State is then determined using the following formula[7]:

$$GROWTHRATE = [(\frac{1988\,VMT}{1986\,VMT})^{1/2} - 1] * 100$$

Once the VMT are projected to 1988, the MOBILE 4.1 Emission Factor Model is run for 1988 to generate the appropriate emission factors which are then applied to the corresponding VMT. The resulting mobile emission estimates are then temperature adjusted using the daily average temperatures and range of temperatures for each day of the 1988 episode.

The biogenic emissions data are derived from the Biogenic Emissions Inventory System (BEIS)[6] and are based on county-level biomass data and standard emissions factors. A simple canopy model is also incorporated to estimate profiles of leaf temperature and sunlight within forested area. Unlike stationary source emissions data, the biogenics data are generated using the actual meteorology data for the episode with the final output being hourly emissions based on episode hourly meteorology conditions.

PRECURSORS REDUCTION STRATEGIES

In this study, a base case model simulation is performed using the emissions and meteorological data discussed in previous sections. Then, a series of uniform NO_x/VOC emissions reduction runs have been performed. These across-the-board NO_x/VOC reductions apply only to the anthropogenic emissions. Biogenic emissions, initial and boundary conditions and meteorological inputs are kept the same for all simulations. A total of 25 precursor reduction strategies are planned, with 12 ROM simulations having been completed thus far. They are:

1. Base case;
2. 25% NO_x and 25% VOC reductions, referred to as 25%/25%;
3. 25% NO_x and 50% VOC reductions, referred to as 25%/50%;
4. 25% NO_x and 75% VOC reductions, referred to as 25%/75%;

5. 50% NO_x and 25% VOC reductions, referred to as 50%/25%;
6. 50% NO_x and 50% VOC reductions, referred to as 50%/50%;
7. 50% NO_x and 75% VOC reductions, referred to as 50%/75%;
8. 75% NO_x and 25% VOC reductions, referred to as 75%/25%;
9. 75% NO_x and 50% VOC reductions, referred to as 75%/50%;
10. 75% NO_x and 75% VOC reductions, referred to as 75%/75%;
11. 0% NO_x and 100% VOC reductions, referred to as 0%/100%;
12. 100% NO_x and 0% VOC reductions, referred to as 100%/0%.

RESULTS AND DISCUSSION

Base Case Simulation and Model Performance

The ROM predicted maximum hourly-averaged ozone concentrations at each grid of the entire 9-day episode from July 2 to July 10, 1988, is plotted in Figure 1. The shading is used to denote the levels of ozone concentrations with light shading representing low concentrations and dark shading representing high concentrations. The advantages of choosing episodic maximum hourly concentrations at each grid for presentation are twofold: first, it makes it easy to identify areas with maximum predicted ozone concentrations greater than a certain level (e.g., > 120 ppb). Second, it gives an integrated picture of regions where the ROM has predicted high ozone impact. These features are particularly useful in the later comparisons with different control strategies.

The base case prediction (Figure 1) shows that high ozone concentrations (> 120 ppb) are predicted over a large area in association with a blocking high pressure system which prevailed over the eastern U.S. during this period. The model predicted most severe ozone impacts along the Northeast corridor (the extended overlapping urban areas from Washington, D.C. through Boston) and along Lake Michigan. Both areas were under the influence of the steady south-southwesterly flow that resulted in strong warm temperature advection and pollutant transport. The extremely high ozone concentrations predicted in these areas reflect interactions between the blocking high pressure system, local topography and orientation of major sources. Along the Northeast corridor, ozone concentrations above 180 ppb were predicted in Washington D.C., Philadelphia and New York. Along Lake Michigan, ozone above 180 ppb was predicted near Chicago and Lake Michigan. High ozone concentrations were also predicted near other big source areas: daily maxima greater than 180 ppb were predicted in southern Lake Erie while concentrations in excess of 150 ppb were predicted near Pittsburgh, Atlanta, Lake Ontario, Charleston (West Virginia) and along a small segment of the Ohio River. The highest predicted hourly ozone concentration was 262 ppb, which occurred over Lake Michigan.

Comparing predicted concentrations with observations suggests that the model did well in predicting the area of high concentrations over the Great Lakes, Ohio River Valley, Northeast Corridor, Mid-Atlantic, and part of the Southeast. Much of this area was observed to have concentrations above 120 ppb. The spatial extent of the area exceeding 120 ppb was smaller in the predicted data. The model extended the Chicago plume over Lake Michigan, while the observations showed that the plume moved further north. Despite the difference in positioning of the Chicago plume, maximum values predicted within the plume agreed well with observed data; both showed concentrations above 180 ppb. The predicted alignment and magnitude of the Northeast Corridor plume closely corresponds to the observations, with the exception that the model positioned the area with concentrations > 180 ppb further to the northeast. Modeled concentrations near Pittsburgh and Cleveland (150-180 ppb) agreed well with observed data. Several simulated urban plumes in Texas, Louisiana, and Oklahoma were also noted in the observations. Thus, overall it appears that the model performed reasonably well in predicting the spatial patterns in ozone, but had a tendency to underpredict the high concentrations by

10-20 ppb. Initial findings of the ROM performance agree with results from previous evaluations by Pierce et al. (1990)[9], and Roselle (1992)[10].

Sensitivity of Ozone to Changes in NO_x and VOC

Figures 2-4 are tile diagrams depicting predicted episode maximum ozone concentrations for each level 1 grid square in the domain corresponding with several different combinations of across-the-board NO_x/VOC reductions. Comparing these plots with the base case (Figure 1) indicates that, in general, daily maximum ozone concentrations decrease as NO_x/VOC reductions increase. However, significant differences exist between predominantly VOC reductions and predominantly NO_x reductions. This point is clearly demonstrated when comparing the 25%/75% (Figure 2) with the 75%/25% (Figure 3). Except at some NO_x-source-intensive areas (large urban cores and/or large NO_x point sources), regional ozone reductions appear to be more sensitive to NO_x than VOC reductions. Figures 5 and 6 compare sensitivity of predicted ozone to changes in NO_x and VOC respectively. It is clear that the ROM predicted sensitivity of regional ozone is greater to changes in NO_x than to changes in VOC even near the high end of the distribution of predicted ozone values. In similar tile plots obtained for the differences between precursor reduction scenarios and the base case (not included due to space limitations) we observe that, in NO_x-source-intensive areas, NO_x reductions (except for very large reductions) could result in increases of ozone by more than 10%. This is due to the fact that highly concentrated NO_x has a titration effect on ozone. When these highly concentrated NO_x emissions are reduced, the local titration of ozone decreases and the area of peak ozone downwind moves closer to the NO_x sources. The negative impact, however, was limited to less than 0.3% of the grid squares. In these areas, VOC reductions are found to be very effective in reducing the peak ozone values and a strategy featuring some combination of NO_x and VOC reductions would be most effective in reducing regional ozone.

Figure 7 plots a response matrix showing the number of occasions when daily maximum ozone concentrations exceed 120 ppb under different control strategies. The unit of the vertical bars is in grid-days. This graph illustrates a measure of the integrated spatial and temporal impact of different precursor reduction strategies on regional high ozones in the eastern U.S.. It is of interest to note the differences among the slopes of the bars plotted on the matrix. By comparing these slopes, it is clear that the reduction of NO_x emissions is much more effective than reduction of VOC emissions in reducing the number of occasions where predicted daily maximum ozone exceeds 120 ppb. Competing effects of the NO_x versus VOC reduction strategies are also observed. In particular, the effectiveness of reducing regional ozone through reduction of VOC emissions diminishes as the level of NO_x reductions increases. In contrast, the decrease in effectivness of NO_x reductions as the level of VOC reductions increases is much smaller. These effects are also clearly demonstrated in the tile maps by comparing Figure 3 (75%/25%) with Figure 4 (75%/75%) and by comparing Figure 2 (25%/75%) with Figure 4 (75%/75%). Figure 7 also suggests, however, that there are further reductions in highest regional ozone to be gained from reducing VOC emissions in the event it is not feasible to implement large reductions in NO_x needed to reduce predicted ozone to less than 120 ppb everywhere. The population exposure to ozone above 120 ppb is shown in Figure 8. The population exposure is calculated as a domain summation of population in each grid times predicted hours of ozone above 120 ppb in each grid. The results show that even the modest precursors reduction strategy (25%/25%) would make a big difference in improving the air quality.

Finally, it is also of interest to examine two extreme cases, i.e., the 100% reduction of anthropogenic VOC versus the 100% reduction of anthropogenic of NO_x. These are shown by the two rightmost points in figures 5 and 6. This information suggests that given the current model input of VOC and NO_x emissions and meteorological conditions, it is not possible to reduce regional ozone

episode maximum to levels below 120 ppb without any NO_x reductions. Another way to look at it, the modeling results imply that under meteorological conditions which are conducive to high ozone, biogenic VOC emissions alone are enough to convert existing anthropogenic NO to NO_2 and produce ozone above 120 ppb in the eastern U.S. The Figures also suggest that without anthropogenic NO_x emissions, regional ozone will be essentially at tropospheric background level.

SUMMARY AND CONCLUSIONS

The preliminary results of 12 ROM simulations of uniform NO_x/VOC reductions in the eastern U.S. suggest that ozone production in much of the eastern U.S. is limited by available NO_x emissions. The following summarizes key findings from the scenarios investegated these far:

1. The ROM modeling results suggest that reduction of NO$_x$ emissions is likely to be a key factor in reducing regional ozone levels across broad areas of the eastern U.S..

2. While there may be other benefits to reductions of VOC emissions that the study was unable to discern, the primary benefit appears to be in reducing ozone peak values near NO_x-source-intensive areas (large urban areas and/or major NO_x point source areas).

3. It appears that, in NO$_x$-source-intensive areas, a strategy featuring a combination of both VOC and NO$_x$ reduction would be most beneficial in reducing regional ozone.

4. Under meteorological conditions which are conducive to high ozone, it may not be possible to reduce regional ozone to 120 ppb or less everywhere in the eastern U.S. without substantial reduction of NO_x emissions.

Limitations

Like any numerical modeling study, there are inherent limitations that need to be addressed. First, only one very severe episode was considered. Sensitivity of ozone to VOC and NO_x reductions could differ for other meteorological conditions. Second, how close the results are to reality depends on the accuracy of the model, the accuracy of the model inputs and the representativeness of the episode. Recent studies[11,12] indicate that large uncertainties exist in the emissions inventories, in particular, the mobile source and biogenic components. A third important potential limitation is the ROM grid size. ROM's grid scale may be too coarse to adequately resolve the subgrid scale chemistry near large sources. The instantaneous mixing of all species within these large grid boxes may underestimate the ozone titration near large NO_x sources (i.e., the urban cores and large power plants). Finally, across-the-board reductions in VOC and NO_x emissions considered in this study are not realistic control strategies. Results could differ for more realistic strategies, depending on the spatial orientation of sources to one another. Thus, results of this study are most appropriately used to assist States in the initial design of control strategies to simulate with urban-scale photochemical grid models. Use of these higher resolution urban models to simulate realistic control strategies for several meteorological episodes is necessary to have confidence that a strategy will likely be effective in reducing ozone.

ACKNOWLEDGEMENT

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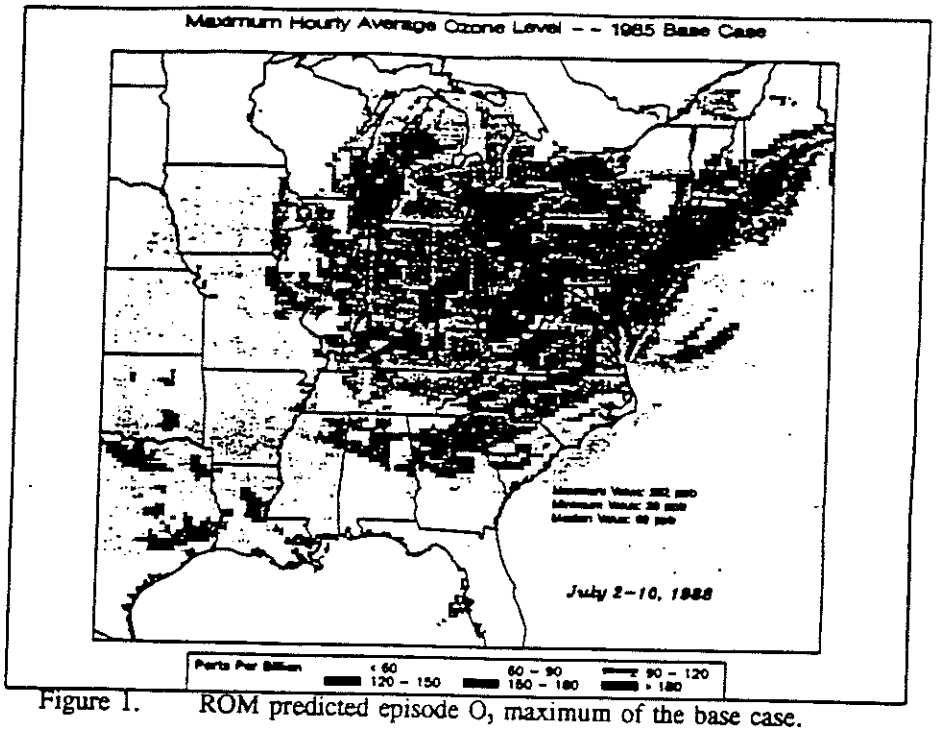

Figure 1. ROM predicted episode O, maximum of the base case.

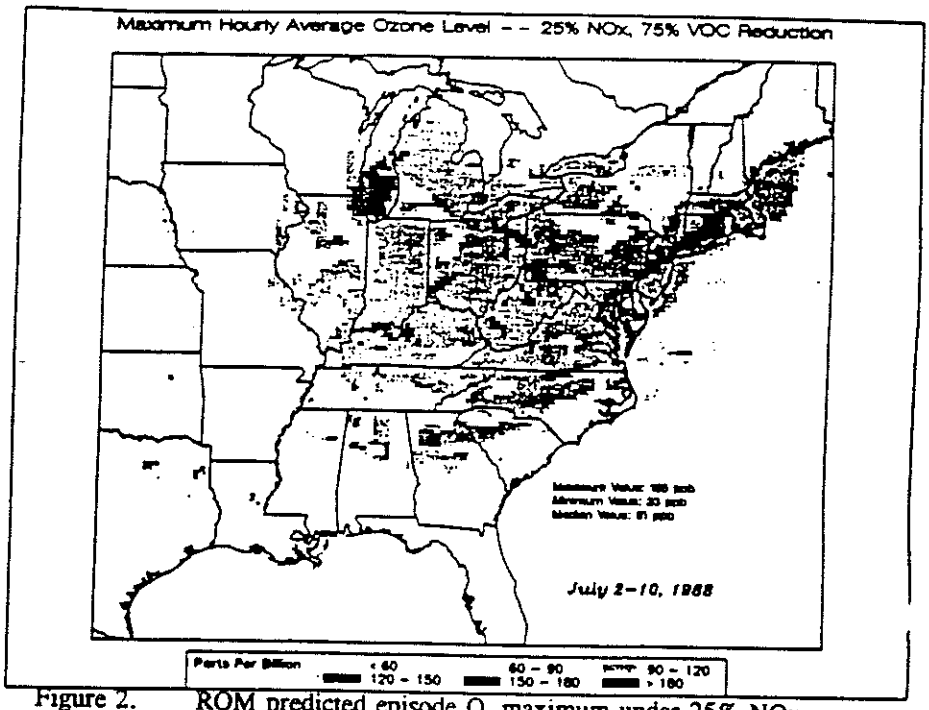

Figure 2. ROM predicted episode O, maximum under 25% NOx, 75% VOC reductions from base case emissions.

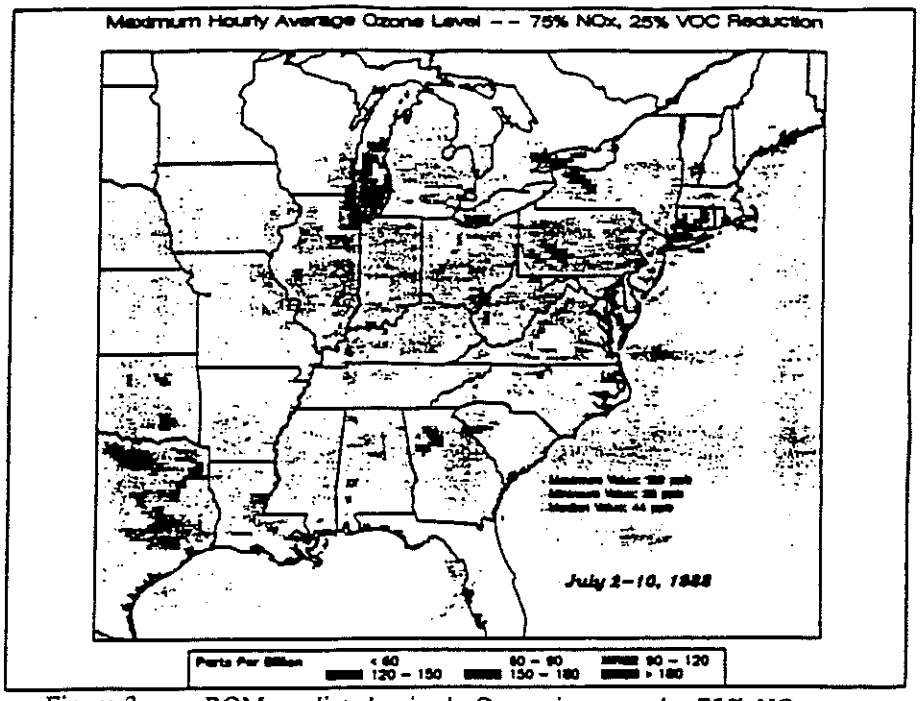

Figure 3. ROM predicted episode O_3 maximum under 75% NOx, 25% VOC reductions from the base case emissins.

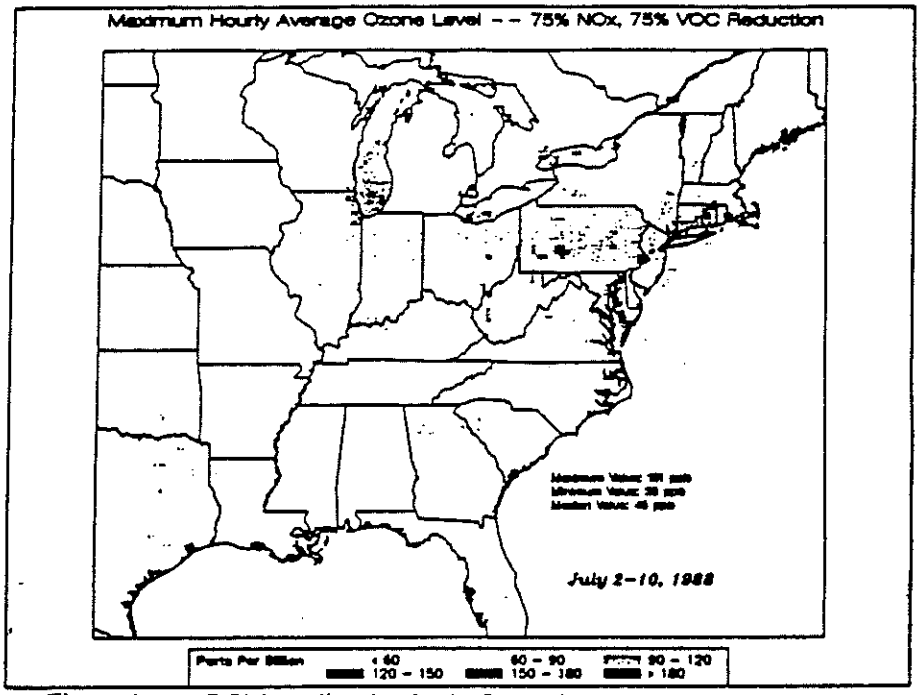

Figure 4. ROM predicted episode O_3 maximum under 75% NOx, 75% VOC reductions from the base case emissions.

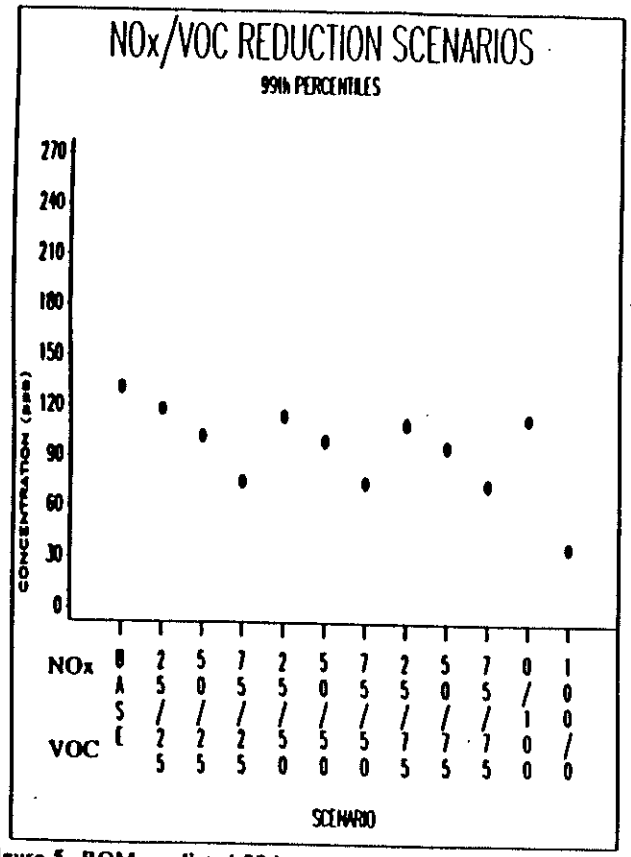

Figure 5. ROM predicted 99th percentile daily maximum 1-hour O_3 under increasing NOx reductions at different VOC levels.

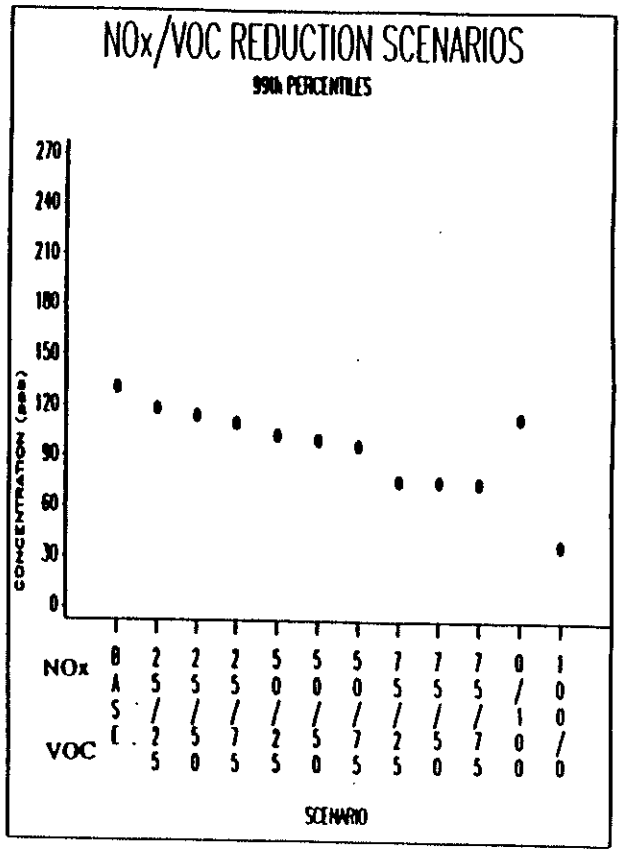

Figure 6. ROM predicted 99th percentile daily maximum 1-hour O_3 under increasing VOC reductions at different NOx levels.

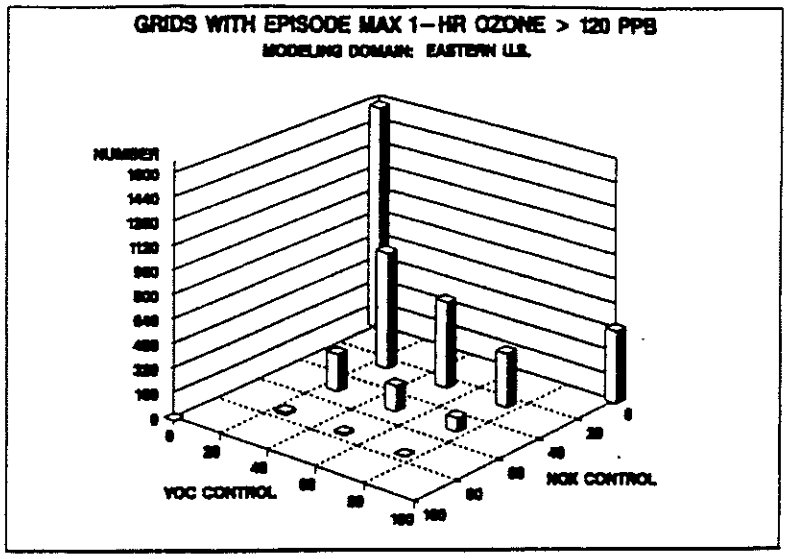

Figure 7. ROM predicted grids with episode maximum O_3 > 120 ppb.

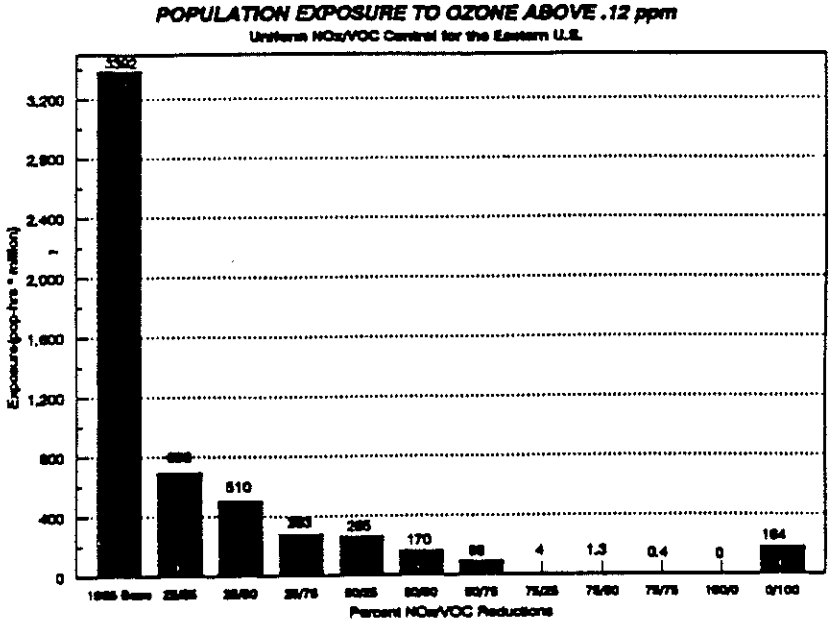

Figure 8. ROM predicted population exposure to O_3 > 120 ppb under different precursor reduction scenrios.