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The Effects of NOx Emission Reductions from Power Plants over the Eastern United States

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Abstract

The effectiveness of NOx emission reductions from power plants to alleviate persistent ozone nonattainment in the eastern United States was investigated with a focus on the Northeast Corridor, centered on New York City. The 1995 ozone episode along with the 2007 base case emission scenario was used with the Variable-Grid Urban Airshed Model (UAM-V) to determine ozone concentrations. Several scenarios based on EPA's proposal issued on October 10, 1997 were examined. Although it is widely recognized that the eastern United States includes a large NOx-sensitive region (e.g., Sillman, 1999), the study revealed that reducing NOx emissions from power plants beyond 500 miles (800 km) was not effective for reducing ozone exceedances in the region. It was also found that NOx emissions from power plants play an important role in local ozone exceedances.

Key words : NOx emission, power plant, ozone exceedances, emission control strategy, UAM-V model

1. BACKGROUND

On October 10, 1997, the United States Environmental Protection Agency (U.S. EPA) issued a proposed rule for reducing ground-level ozone resulting from regional transport in the eastern half of the U.S. The proposed rule builds on the findings of the Ozone Transport Assessment Group (OTAG), which deliberated on this issue for more than two years (OTAG Air Quality Analysis Workgroup, 1997). The EPA action is designed to mitigate ozone pollution due to transport by reducing the emissions of one of its main precursors, nitrogen oxides (NOx). Transported ozone can significantly contribute to nonattainment of the ozone National Ambient Air Quality Standard (NAAQS) in downwind locations. EPA's proposal specifies reductions in the levels of NOx emissions in 22 of the 37 states of the OTAG region and in the District of Columbia, under authority of the Clean Air Act, Sec. 110.

Although ozone nonattainment exists in many parts of the eastern U.S., this study primarily addresses the issue of ozone concentrations in the northeastern U.S. for the following reasons. First, the major region of ozone nonattainment is the Northeast Corridor from Washington to Boston, and second, the Northeast Corridor is the only part of the eastern U.S. where regional transport can be considered a major contributor to nonattainment (Husar and Renard, 1997).

The NOx emission reductions prescribed by EPA are relative to expected emissions in the year 2007, after implementation of all existing laws and regulations - a so-called "2007 Clean Air Act (CAA) Base." EPA generally used baseline information from the

OTAG analysis as to what the inventory of sources and emissions would be in 2007. These were devel-oped by E.H. Pechan & Associates' EMS-95 model (EHPA, 1997). However, EPA substituted growth projections developed with ICF's Integrated Planning Model (IPM) system (U.S. EPA, 1999), which called for significantly higher growth in electricity demand between 1996 and 2007. This has generated some discrepancies between OTAG analysis and the parameters of the EPA State Implementation Plan (SIP) call.

In this study, we concern ourselves only with emission reductions from utility power plants for three reasons: (a) because many studies point out the necessity of NOx emission reductions to control high ozone concentrations in the eastern U.S., except for one or two urban centers (NRC, 1991; Sillman, 1999); (b) because OTAG research suggests the possibility that occurrences of high ozone concentrations in the eastern U.S. result from transport of emissions from the Ohio River Valley where many NOx point sources are located; and, primarily, (c) because EPA has selected large stationary sources of NOx as the first targets for emission control.

Table 1 lists the 2007 state-level NOx emission baselines and budgets for utility and nonutility point sources, as specified in the EPA proposal. The ozone-season (May through September) total SIP-call budget for point sources is 0.96 million tons, or an average 58% reduction from the baseline level of 2.29 million tons. The utility budget is 0.49 million tons, representing an average 69% reduction from the baseline level of 1.60 million tons, while the nonutility budget is 0.47 million tons, an average 33% reduction from the baseline level of 0.70 million tons. A large reduction is

Table 1. SIP-call emission requirements for point sources in 2007. (unit: tons/ozone season from May to September)

	Utility Point			Nonutility Point			Total Point		
	Base	Budget	%	Base	Budget	%	Base	Budget	%
AL	81,704	26,946	67	47,182	25,131	47	128,886	52,077	60
CT	5,715	3,409	40	4,732	4,475	5	10,447	7,884	25
DE	10,901	4,390	60	5,205	3,206	38	16,106	7,596	53
DC	385	152	61	312	312	0	697	464	33
GA	92,946	30,158	68	34,012	20,472	40	126,958	50,630	60
IL	115,053	31,833	72	63,642	39,855	37	178,695	71,688	60
IN	177,888	48,791	73	51,432	35,603	31	229,320	84,394	63
KY	128,688	35,820	72	18,817	12,258	35	147,505	48,078	67
MD	35,332	11,364	68	6,729	4,825	28	42,061	16,189	62
MA	28,284	12,956	54	10,683	7,590	29	38,967	20,546	47
MI	82,057	25,402	69	57,190	35,317	38	139,247	60,719	56
MO	92,313	22,932	75	12,248	8,174	33	104,561	31,106	70
NJ	14,553	5,041	65	32,663	26,741	18	47,216	31,782	33
NY	39,639	24,653	38	19,889	16,930	15	59,528	41,583	30
NC	83,273	27,543	67	32,107	21,113	34	115,380	48,656	58
OH	185,757	46,758	75	50,946	32,799	36	236,703	79,557	66
PA	125,195	39,594	68	64,224	59,622	71	89,419	99,216	48
RI	773	905	**	328	328	0	1,101	1,233	**
SC	43,363	15,090	65	34,791	20,097	42	78,154	35,187	55
TN	71,994	19,318	73	65,051	32,138	51	137,045	51,456	62
VA	45,719	16,884	63	23,333	15,529	33	69,052	32,413	53
WV	83,719	23,306	72	41,510	31,377	24	125,229	54,683	56
WI	51,004	15,755	69	21,209	12,269	42	72,213	28,024	61
Total	1,596,255	489,000	69	698,233	466,158	33	2,294,488	955,158	58

** indicates emission increase by the SIP call.

made for the utility budget, and thus the budget ratio of utility to nonutility point source emissions changes from 2.29 to 1.05.

2. APPROACH

This study uses the same state-of-the-art computer model to determine ozone concentrations as OTAG used: the Variable-Grid Urban Airshed Model (UAM-V), developed by Systems Applications International, Inc. (SAI, 1996). The same 2007 baseline emission inventory was also used, in which power plant sources were identified by using the list for large elevated NOx sources (Koerber, 1997) and power generation unit list (U.S. DOE, 1996). For simulating ozone concentrations in the eastern U.S., the 1995-ozone episode was used. The effectiveness of NOx emission reductions from power plants was studied, first by comparing the results from several scenarios based on the SIP call, and next by investigating the influence of power plant emissions in terms of several selected metrics. For the scenario study, the five-day period (July 10~14) was simulated mainly to reduce the heavy computational burden, but for the subsequent investigation, the full nine-day period (July 10~18) was simulated. In any case, three days (July 7~9) were devoted to spin up periods in order to minimize the influence of assumed initial conditions.

Table 2 presents processed output from the UAM-V model for the OTAG domain for the base case. It was processed on the basis of 192×189 fine-grid cells, which corresponds to 64×63 coarse-grid cells including boundary cells for allocating space in calculating the advection scheme (SAI, 1996). It shows peak 1-h and 8-h concentrations, mean peak 1-h and 8-h concentrations over the domain, numbers of grid cells exceeding a specified concentration value, and numbers of grid-cell-hours exceeding a specified concentration value (GCHE). The information is provided by day and total for the duration of the episode. Table 2 shows that the numbers of grid-cell-hour exceedances increase up to 140 ppb for 1-h average and 120 ppb for 8-h average during the first 5 days and then decrease. But those exceeding 160 ppb still increase until the sixth day and sharply decrease thereafter. While mean peak 1-h and 8-h averages over the domain vary similarly with the numbers of grid-cell-hour exceedances, the peak 1-h and 8-h averages vary differently with other metrics.

For the analysis presented here, the GCHE metric was usually used as a measure of the severity of ozone pollution. Although 1-h exceedances for five specified concentration thresholds between 80 ppb and 160 ppb were calculated, the value of 120 ppb was chosen, denoted as GCHE/120. This was because it corresponds to the existing NAAQS.

The OTAG domain extends from 26°N to 47°N latitude and from 67°W to 99°W longitude. Fig. 1 shows the distribution of NOx emissions from utility power plants in the OTAG domain in the present analysis. As is well known, many large power plants are located along the Ohio River; they are considered to contribute to high ozone levels in the Northeast

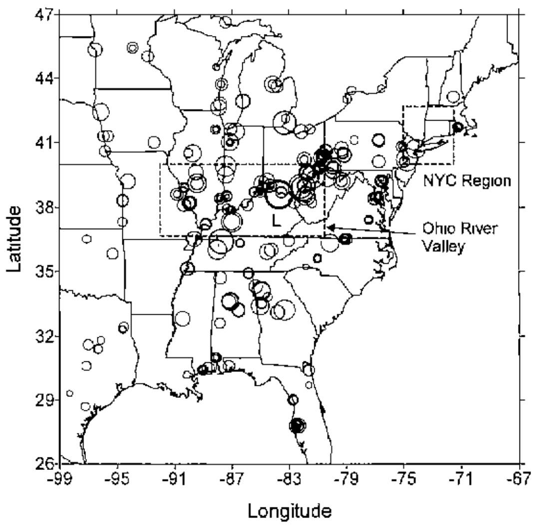


Fig. 1. Distribution of NOx emissions from power plants in the OTAG domain with locations of the NYC Region and the Ohio River Valley. The largest emission source, denoted L in the middle, is 170 tons/day.

Table 2. UAM-V output for the OTAG domain for the base case.

Scenario name : BASE CASE (07bas1cD2)
Domain name : OTAG DOMAIN
SW & NE corners : SW=(1, 1) NE=(192,189)

	071095	071195	071295	071395	071495	071595	071695	071795	071895	Total
Peak 1-h average (ppb)	191	186	165	180	187	198	159	145	152	198
Mean peak 1-h average over the domain (ppb)	51	53	57	60	59	56	51	50	49	54
Total # of grid cells										
> 80 ppb	1792	2485	4048	6258	6460	5127	3717	2751	2284	34922
>100 ppb	246	445	965	1500	1651	1634	672	361	446	7920
>120 ppb	47	89	229	386	600	505	146	40	94	2136
>140 ppb	12	21	41	084	247	208	23	5	6	647
>160 ppb	5	6	2	022	77	114	0	0	0	226
Total # of cell-hours										
> 80 ppb	8351	15452	25750	40537	46089	38794	23984	14984	13409	227350
>100 ppb	940	2247	4553	7534	10402	9245	2717	1322	2035	40995
>120 ppb	188	389	821	1680	3480	2886	535	150	317	10446
>140 ppb	54	79	108	365	1081	1008	53	7	22	2777
>160 ppb	23	27	3	61	246	337	0	0	0	697
Peak 8-h average (ppb)	176	172	147	154	165	169	140	133	144	176
Mean peak 8-h average over the domain (ppb)	48	50	53	56	56	52	48	48	46	51
Total # of grid cells										
> 60 ppb	7465	8585	10795	13713	14265	10932	8878	8618	7214	90465
> 80 ppb	823	1539	2572	4283	4498	3593	2365	1640	1427	22740
>100 ppb	83	238	459	813	1044	969	244	99	208	4157
>120 ppb	16	35	67	165	426	314	50	15	26	1114
>140 ppb	6	7	6	40	121	138	0	0	1	319

Corridor (OTAG Air Quality Analysis Workgroup, 1997). Thus, we defined two regions: the "NYC Region" centering around New York City, stretching approximately from northern Massachusetts to southern Pennsylvania, and the "Ohio River Valley" as a potential source region of the NYC Region. Statistics presented in Table 2 were calculated for three regions, the aforementioned two regions and the entire OTAG region.

3. SCENARIOS BY SIP CALL

Three scenarios were run: (1) a base case, which corresponds to the year 2007 OTAG base-case inventory; (2) a scenario in which all utility NOx emissions are reduced to zero; and (3) the SIP-call case, corresponding to EPA's proposed reductions from the electric utility sector. Six additional scenarios were then run, in which selected groups of states were removed from the SIP-call reductions, one group at a time. Fig. 2 shows a combination of states representing four "east-west" slices and two "north-south" slices. The effects of eliminating these emissions on exceedances in each of the three regions were estimated, although the analysis focused on effects in the NYC Region. Fig. 3 summarizes grid-cell-hour exceedances (GCHE) above 120 ppb in each case. Because the size of the region is different, mean values over the region are presented.

From Fig. 3 (a), the UAM-V analysis shows that the 2007 base case causes more than one GCHE/120 per grid-cell in the NYC Region during the first 5 days of the episode. Eliminating all power-plant emissions in the OTAG domain decreases mean GCHE/120, but it is still close to one due to the contributions of other point and area sources. The SIP-call reductions result in about one hour exceedance on the average. Fig. 3 (a) also shows the number of exceedances for the six variant scenarios. Only excluding NY/PA/MD and OH/

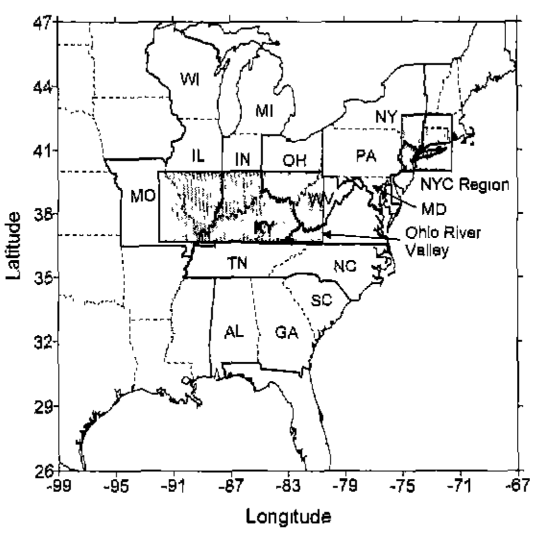


Fig. 2. Combinations of states chosen to study the effect of exclusion from the EPA SIP call.

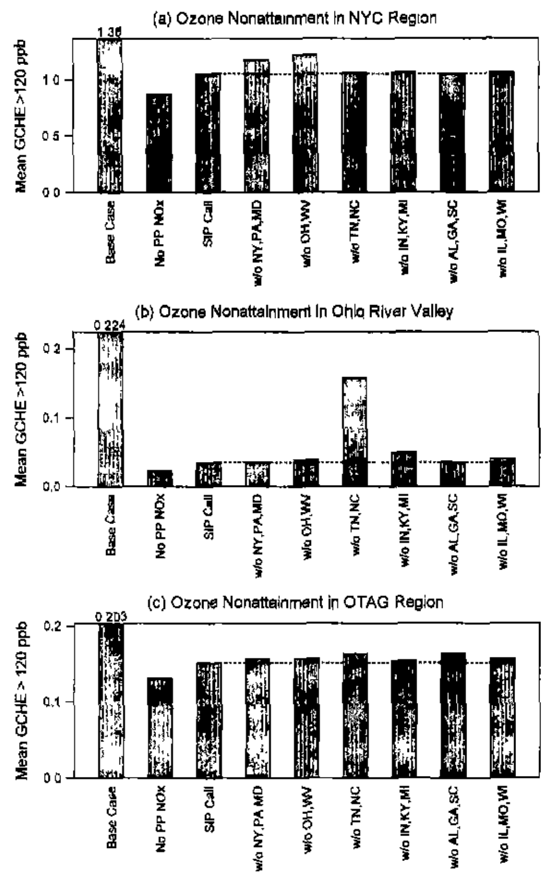


Fig. 3. Grid-cell-hour exceedances (GCHE) above 120 ppb for various scenarios in three regions.

WV, the two groups closest to the NYC Region, shows a noticeable effect. Effects of other groups on the NYC Region are not distinguishable. However, inclusion of AL/GA/SC in the SIP-call reduction package has no effect on ozone exceedances in the NYC Region.

On the other hand, eliminating all power-plant emissions substantially reduces GCHE/120 in the Ohio River Valley, although mean GCHE/120 is low, slightly over 0.2 even for the base case, as shown in Fig. 3 (b). The SIP-call reductions also exert a comparable effect. Effects of excluding OH/WV, IN/KY/MI, and IL/MO/WI from the SIP call are nearly proportional to their area portions included within the Ohio River Valley. However, emission reductions in TN/NC-group are essential for reducing ozone exceedances in the Ohio River Valley, probably because this area is located in the upstream side during the 1995-ozone episode.

The mean GCHE/120 over the OTAG domain is even lower than that in the Ohio River Valley for the base case, in Fig. 3 (c). Eliminating all power plant emissions reduces about one third of ozone exceedances on the whole, which means, emissions from other sources are responsible for the remaining two thirds. Different from the aforementioned two regions (NYC Region and Ohio River Valley), excluding AL/GA/SC has some effects on reducing ozone exceedances, as in the case of excluding TN/NC. This can be interpreted either by the fact that these southern regions were still located in the upstream side of other regions besides the above two regions, or by the fact that ozone exceedances in these south regions were reduced by emission reductions from co-located power plants, or both.

Since the NYC Region is located in the downwind side, the clear effects of the closest two groups on ozone nonattainment in the NYC Region in Fig. 3 (a) may indicate a dependency of effectiveness of emission reductions on the distance. Fig. 4 shows decrease in GCHE/120 per kiloton reduction of NOx emissions as a function of average distance from the NYC Region. It reveals that greater effect of excluding OH/WV

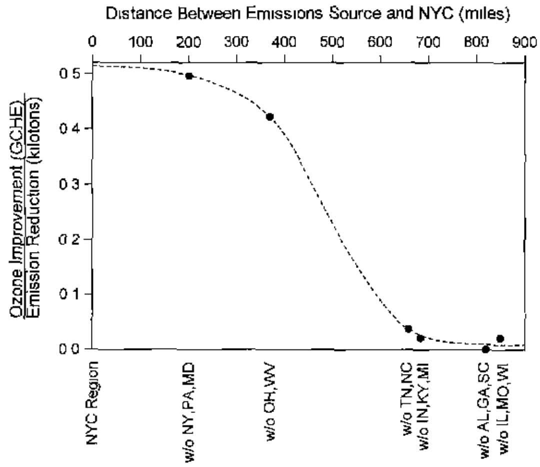
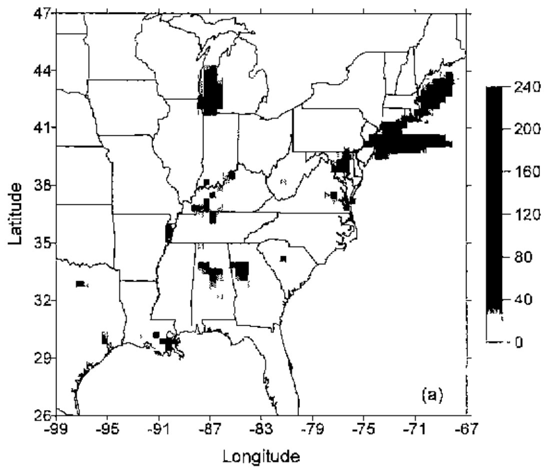
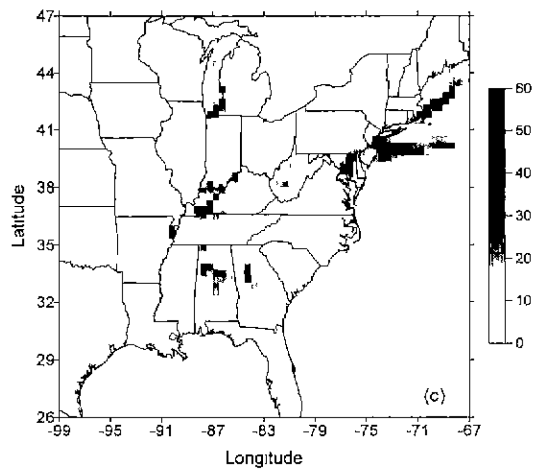


Fig. 4. Improvement in ozone per kiloton reduction in emissions during the ozone season as a function of average distance from the region where emission controls are applied.

than that of excluding NY/PA/MD in Fig. 3 (a) appears to result from the much larger emission reductions in OH and WV. As a consequence, the effect of emission reduction gradually decreases up to OH and WV, but follows a sharp drop-off beyond about 500 miles from the NYC Region. This is consistent with the findings of the OTAG modeling: spatial and temporal scales of ozone transport derived from various air quality analyses range up to about 2 days and 500 miles (OTAG Air Quality Analysis Workgroup, 1997).

The conclusion from this scenario study is that the control region for improving ozone exceedances in the NYC Region could be judiciously shrunk from the EPA SIP-call region or the full OTAG region to an area bounded by the OH/IN state line to the west and the NC/VA state line to the south. Although this conclusion was drawn from the first 5-day simulation, it was confirmed by the full 9-day simulation by defining the "Core Region" (CT, DE, DC, MD, MA, NJ, NY, OH, PA, RI, VA, and WV), where controls would be effective as suggested by Fig. 4 (Streets *et al.*, 1998). Accompanying economic analysis also showed that applying the SIP call only in the Core Region would be about three times cost-effective in





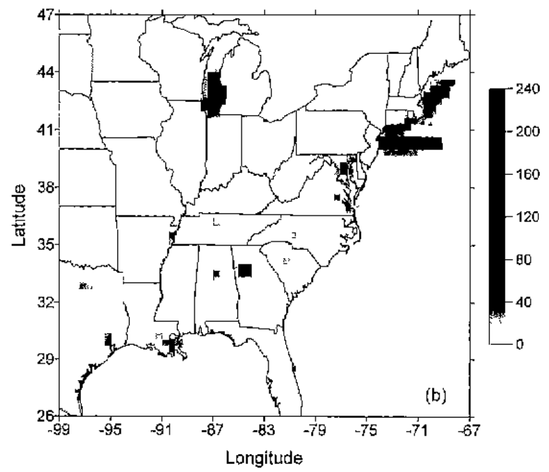


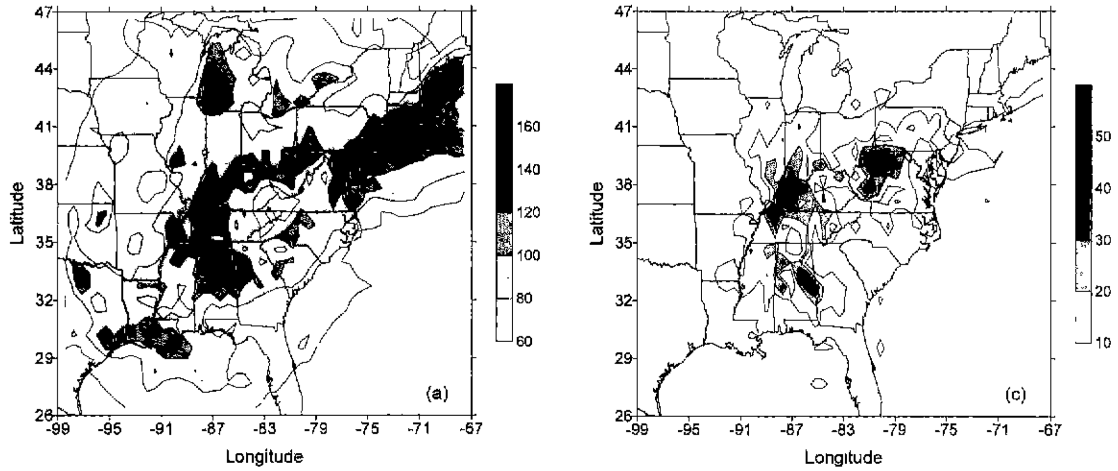
Fig. 5. Distributions of the number of grid-cell-hour exceedances over the OTAG domain for the base case and with elimination of all NOx emissions from power plants, and their differences. (a) Grid-cell-hour exceedances above 120 ppb in the base case. (b) Grid-cell-hour exceedances above 120 ppb with elimination of all power-plant NOx emissions. (c) Differences in grid-cell-hour exceedances between the base case and elimination of all power-plant NOx emissions.

terms of GCHE avoided per $billion spent.

Suggestions given by Fig. 4 are manifest, but the following findings from this study call for further investigation in order to improve our understanding on the influence of NOx emissions from power plants. First, the total number of GCHE decrease by reducing NOx emissions from power plants is not large in the NYC Region, whatever the control strategies are. Second, the effects of reducing power plant NOx emissions are substantial in the Ohio River Valley. Third, up to now, the effectiveness of NOx emission reduction was investigated in terms of GCHE in that it represents a general feature of high ozone episode. However, it is difficult to decrease peak 1-h concentrations by reducing NOx emissions from power plants. Peak 1-h concentrations in the NYC Region are 187 ppb in the base case, 185 ppb with the SIP call, and 184 ppb with no NOx emissions from power plants for the full 9-day episode (Streets *et al.*, 1998). These facts are primarily due to source characteristics in the associated regions, which will be discussed later.

4. INFLUENCE OF POWER PLANT NOx EMISSIONS

The UAM-V model was run for a nine-day episode in July 1995 for the base case and the case with eliminating NOx emissions from all power plants. Fig. 5 (a) shows distributions of GCHE/120 over the OTAG domain under base-case conditions, i.e., the 2007 emissions inventory with no additional reductions. Ozone exceedances are concentrated on the east side of Lake Michigan and widely distributed along the Northeast



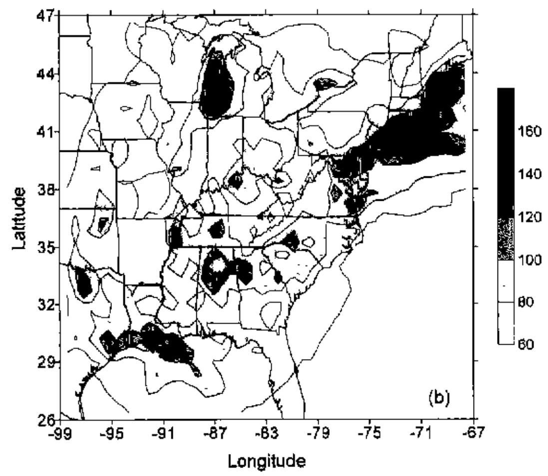


Fig. 6. Distributions of peak 1-h concentration (ppb) over the OTAG domain for the base case and with eliminating all NOx emissions from power plants, and their differences. (a) Peak 1-h concentration in the base case. (b) Peak 1-h concentration with elimination of all power-plant NOx emissions. (c) Differences in peak 1-h concentration between the base case and elimination of all power-plant NOx emissions.

Corridor. Exceedances are also found around Atlanta and Birmingham, the greater Houston area, and the Ohio River Valley. These observations are quite similar to distributions of ozone nonattainment areas in the eastern U.S. (NRC, 1991).

Fig. 5 (b) shows the same distribution but without NOx emissions from power plants, and Fig. 5 (c) shows the difference between the first two plots. Improvement in exceedances is noticeable in the Ohio River Valley, as was seen in Fig. 3 (b). Some improvement is also achieved in the Northeast Corridor by eliminating power-plant emissions, but the remaining exceedances are still considerable because of large number of exceedances in the base case. On the other hand, exceedances on the east side of Lake Michigan would not be much reduced, indicating those are mainly due to other local emissions.

Similar plots were prepared in Fig. 6, but in this case, in terms of peak 1-h concentrations. The general features of Figs. 6 (a) and (b) are analogous to Figs. 5 (a) and (b). However, Figs. 6 (a) and (b) clearly show the disappearance of high values of peak 1-h concentrations over the OTAG region by eliminating power plant NOx emissions.

Nevertheless, the influence of power plant emissions on peak 1-h concentrations is much different from that on grid-cell-hour exceedances. Fig. 6 (c) shows that NOx emissions from power plants slightly contribute to peak concentrations in the Northeast Corridor and cannot alter peak concentrations on the east side of Lake Michigan. This means that peak concentrations in the Northeast Corridor as well as those on the east side of Lake Michigan are mainly determined by local emissions. As far as peak concentrations are concerned, the influence of power plant emissions is exerted from the south to the east along the Ohio River. It is interesting to note that high concentration areas depicted in Fig. 6 (c) are quite similar to the distribution of power plant emissions in Fig. 1. This is probably because power plant emissions in these areas are dominant over other sources.

In order to clarify the problem, two more simulation experiments were performed, (1) with power plant NOx emissions in the Ohio River Valley eliminated, and (2) with power plant NOx emissions in the NYC Region eliminated. In both cases, the target area was the NYC Region. It should be noted that while only a few power plants are located in the NYC Region, the Ohio River Valley is crowded with power plants, about 500 miles from the NYC Region. Fig. 7 shows the results from simulations, together with the previous results in the base case and when eliminating all power-plant NOx emissions for comparison. Fig. 7 (a) shows that eliminating power plant NOx emissions in the Ohio River Valley reduces more GCHE/120, but eliminating power-plant emissions in the NYC Region more effectively reduces GCHE/160.

Fig. 7 (b) demonstrates how these kinds of results are obtained. With NOx emissions from the Ohio River Valley, fractions of lower concentrations below 60 ppb are gradually changed into higher concentrations above 60 ppb. On the other hand, NOx emissions in the NYC Region change middle range concentrations, for instance, between 40 ppb and 120 ppb into the fraction of the highest concentration above 160 ppb and also into the fraction of the lowest concentration below 40 ppb. This latter phenomenon is frequently found in the urban area where daytime production and nighttime scavenging of ozone simultaneously occur due to local emissions (Fuentes and Dann, 1994; Lefohn *et al.*, 1993). That is to say, power-plant NOx emissions in the NYC Region directly affect photochemical production of ozone in the same region. They are, however, not so direct as other emissions from point and area sources in that they cannot greatly change the peak 1-

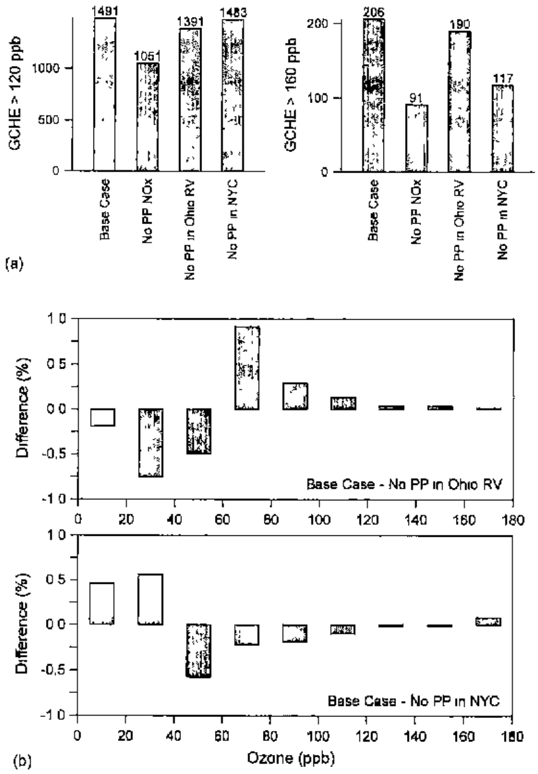


Fig. 7. (a) Grid-cell-hour exceedances for various scenarios in the NYC Region. (b) Difference in frequency distributions between scenarios in the NYC Region.

h concentration.

5. CONCLUSIONS

The purpose of the proposed regulatory action by EPA is to reduce long-range transport of ozone and NOx that contributes to persistent nonattainment of the ozone NAAQS. This paper addresses this subject with a focus on the Northeast Corridor, centered on New York City, located in the downwind side during the 1995-ozone episode. If we confine our interest to the NYC Region, NOx reduction of power plants in the region, east of the IN/OH line and north of the NC/VA line, is sufficient rather than the whole area suggested by the SIP call.

Although emissions from power plants are likely to be transported over long distances due to their large quanfities from tall stacks, their effects on peak 1-h concentrations are limited to around the Ohio River Valley because major power plants are located in that region. Contributions of emissions from other point and area sources to GCHE/120 in the NYC Region are far larger than those of NOx emissions from all power plants over the whole OTAG domain. Regarding GCHE in the NYC Region, eliminating a few power plants in the same region could effectively reduce GCHE/160, while eliminating large number of power plants in the Ohio River Valley could reduce only some of GCHE/120.

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