Journal of the Air & Waste Management Association
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/uawm20

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Version of record first published: 27 Dec 2011

To cite this article: Mike Barna, Brian Lamb & Hal Westberg (2001): Modeling the Effects of VOC/NO_x Emissions on Ozone Synthesis in the Cascadia Airshed of the Pacific Northwest, Journal of the Air & Waste Management Association, 51:7, 1021-1034

To link to this article: http://dx.doi.org/10.1080/10473289.2001.10464330

TECHNICAL PAPER

ISSN 1047-3289 *J. Air & Waste Manage. Assoc.* **51**:1021-1034

Modeling the Effects of VOC/NO_x Emissions on Ozone Synthesis in the Cascadia Airshed of the Pacific Northwest

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ABSTRACT

A modeling system consisting of MM5, Calmet, and Calgrid was used to investigate the sensitivity of anthropogenic volatile organic compound (VOC) and oxides of nitrogen (NO_x) reductions on ozone formation within the Cascadia airshed of the Pacific Northwest. An ozone episode that occurred on July 11–14, 1996, was evaluated. During this event, high ozone levels were recorded at monitors downwind of Seattle, WA, and Portland, OR, with one monitor exceeding the 1 hr/120 ppb National Ambient Air Quality Standard (at 148 ppb), and six monitors above the proposed 8 hr/80 ppb standard (at 82–130 ppb). For this particular case, significant emissions reductions, between 25 and 75%, would be required to decrease peak ozone concentrations to desired levels. Reductions in VOC emissions alone, or a combination of reduced VOC and NO_x emissions, were generally found to be most effective; reducing NO_x emissions alone resulted in increased ozone in the Seattle area. When only VOC emissions were curtailed, ozone reductions occurred in the immediate vicinity of densely populated areas, while NO_x reductions resulted in more widespread ozone reductions.

IMPLICATIONS

Photochemical grid modeling of ozone formation along the Interstate 5 corridor of western British Columbia, Washington, and Oregon was conducted to examine the sensitivity of ozone formation to changes in precursor emissions. Although the anthropogenic and biogenic emission signatures for this region are different from other U.S. urban areas, model sensitivity studies show that reducing NO_x emissions causes an increase in ozone in urban areas and reduced ozone on the regional scale. This is similar to results for other U.S. locations. Reducing anthropogenic VOC emissions yields a linear reduction in peak ozone concentrations downwind of each major metropolitan area.

INTRODUCTION

Ozone, the chief constituent of urban smog, remains a serious air quality problem in many regions of the United States. It is believed that demonstrating compliance with federal ozone standards will become even more difficult with the adoption of the 8 hr/80 ppb National Ambient Air Quality Standard (NAAQS), as compared with the existing 1 hr/120 ppb standard.[1] Photochemical grid models are often used to simulate regional ozone, which is formed through a complex series of chemical reactions that involve oxides of nitrogen (NO_x), volatile organic compounds (VOCs), and sunlight. One question frequently posed to a grid model asks what the response of predicted ozone concentrations is to changes in anthropogenic VOC or NO_x emissions. The answer has serious implications with regard to possible control strategies. For example, it is known that for some conditions, ozone formation is almost entirely controlled by the NO_x concentration and is not affected by an increase in the VOC concentration. In other cases, ozone production increases with an increasing concentration of VOC but does not increase (or will sometimes decrease) with an increase in the NO_x concentration. These two cases are referred to as NO_x-sensitive and VOC-sensitive, respectively. Implementing a regional control strategy may be extremely costly; therefore, modeling the ozone response to changes in VOC/NO_x emissions is important to develop an understanding of the photochemistry within an airshed. Examples of VOC/NO_x sensitivity studies using a grid model are numerous.[2-4]

A region of the United States that is receiving increased scrutiny with regard to photochemical air pollution is the Cascadia area of the Pacific Northwest, which is defined as the portions of western Washington, Oregon, and southwestern British Columbia bounded by the Pacific Coast to the west and the Cascade Range to the east.

The major metropolitan centers within this area are Vancouver, BC; Seattle, WA; and Portland, OR. The Cascadia region has a history of exceeding both the 1 hr and 8 hr ozone NAAQS almost every summer, and in recent years was declared a nonattainment area for ozone (although it has recently regained attainment status). A related problem is the occurrence of regional haze,[5] which can greatly obscure vistas of the peaks of the Cascades. These problems may be exacerbated by the continued rapid population growth in the region.

To investigate photochemical air pollution in the Cascadia region, a modeling system consisting of MM5[6] and the Calmet/Calgrid package has been assembled.[7,8] MM5 is a prognostic, mesoscale meteorological model. The Calmet/Calgrid system is designed to simulate photochemical air pollution on a regional scale. The first application of this modeling system was the simulation of an ozone episode that occurred in the Cascadia region during July 11–14, 1996.[9] During this episode, high levels of surface ozone were measured downwind of Seattle and Portland. Observed 1 hr and 8 hr ozone maxima downwind of Seattle were 118 and 92 ppb, respectively; 1 hr and 8 hr ozone maxima downwind of Portland were 145 and 130 ppb, respectively.

The purpose of this paper is to investigate the sensitivity of predicted ozone levels in the Cascadia airshed with respect to changes in anthropogenic emissions. In particular, a suite of Calgrid simulations with reduced anthropogenic VOC or NO_x emissions (specified at 25, 50, 75, and 100% of the base case emissions) is presented, and peak 1 hr and 8 hr ozone concentrations are compared with the NAAQS. Although photochemical grid models represent the best tool for simulating regional air quality, it should be emphasized that predictions for a specific event and region are uncertain, and that currently there is no direct method to test whether the predicted ozone response to changes in the VOC/NO_x emissions is accurate using this type of modeling study.[10] However, this type of exercise is useful for elucidating general trends in the Cascadia ozone/VOC/NO_x system and represents an initial attempt to model VOC/NO_x sensitivity in this region of the United States.

METHODOLOGY

Overview of the MM5/Calmet/Calgrid System

A brief overview of the configuration of the modeling system is given below, and a more detailed description can be found in Barna et al.[9] and Barna and Lamb.[11] A combination of MM5 and Calmet was used to generate a fine-scale wind field for the July 11–14 episode. The MM5 domain consisted of three nested grids with resolutions of 45, 15, and 5 km. Data assimilation, which applied analysis nudging to the outer grid and observational nudging with available surface measurements to the inner grid, was used to improve the wind field prediction. Thirty-two sigma layers were specified in the vertical dimension, extending from the surface to 100 mb, and the model was run in nonhydrostatic mode. The horizontal wind field from the inner MM5 grid was interpolated to the Calmet/Calgrid domain, which also had a 5-km resolution. Using available surface and upper air observations, Calmet was used to develop various boundary parameters required by Calgrid.

The Calmet/Calgrid domain extends 370 km east–west by 660 km north–south, yielding a 74 × 132 grid that covers southwestern British Columbia, western Washington, and northwestern Oregon, as shown in Figure 1. Figure 1 also shows the locations of the nine surface ozone monitors in Washington and the three monitors in Oregon; these monitors are primarily sited along the Interstate 5 (I-5) corridor, which links the major urban centers. The origin of the domain, defined at the southwest corner, is located at 350 km E and 4900 km N in UTM Zone 10. Calmet and Calgrid employ a terrain-following coordinate system; 10 vertical layers were specified, extending from the surface to 5000 m above ground level (AGL). Calgrid was used to predict the hourly, three-dimensional concentration fields for ozone, NO_x, and various explicit and lumped VOCs for the July 1996 episode.

The chemistry mechanism employed by Calgrid is based on the SAPRC90 system[12] and contains 54 chemical species and 129 reactions. Among the 54 species are two classes of lumped alkanes, three lumped olefins, and two lumped aromatics. The kinetic and mechanistic parameters of the SAPRC90 VOC were modified by the Canadian National Research Council (CNRC) to better reflect emissions within the Cascadia region.[13] In particular, the CNRC adjusted the default SAPRC90 VOC characteristics to better suit the emissions profile of the Lower Fraser Valley in southwestern British Columbia; this region is contained within the Calgrid model domain. Table 1 lists the SAPRC90 explicit and lumped VOCs.

Calgrid requires initial and boundary concentrations of the SAPRC90 species to be specified; these are shown in Table 2. Ambient VOC measurements collected on Washington's Olympic Peninsula, which is isolated from anthropogenic emissions, were used to develop these values.[14] The concentrations shown in Table 2 are quite low and are representative of clean, background air. It is reasonable to assume that these boundary concentrations can be applied along each edge of the modeling domain, which is bounded by the Pacific Ocean to the west and

Figure 1. The 370 × 660 km Cascadia Calmet/Calgrid model domain. Surface ozone monitors are shown in gray, and the interstate highway system is represented as a dashed line. Sites that recorded high ozone levels during the July 11–14, 1996, ozone episode include Enumclaw (EW), Lake Samammish (LS), Paradise (PA), Sauvie Island (SI), Mountain View (MV), Milwaukee (MH), and Carus (CA).

the sparsely populated regions along each of the inland sides. To minimize the influence of the initial concentration field, the first day of the simulation was regarded as a "spin-up" period for the model.

Preparation of the Emission Inventory

A detailed emission inventory was developed for the July 1996 ozone episode. The inventory consisted of both area source and point source emissions. Hourly gridded emission rates for 21 model species were specified: NO, NO_2, SO_2, and CO, plus various explicit and lumped VOCs. On-road mobile source emissions for Washington and Oregon were calculated with MOBILE5b.[15] Nonmobile

Table 1. Explicit and lumped VOCs included in the SAPRC90 chemistry mechanism.

SAPRC90 Model Species Name	Description
ETHE	Ethene
MEOH	Methanol
ETOH	Ethanol
MTBE	Methyl *t*-butyl ether
HCHO	Formaldehyde
CCHO	Acetaldehyde
RCHO	Propionaldehyde and higher aldehydes
MEK	Methyl ethyl ketone and higher ketones
CRES	Cresols and other alkyl phenols
MGLY	Methyl glyoxyl
ALK1	1st lumped group of alkanes (k_{OH} < 1.0 x 10^4/ppm/min)
ALK2	2nd lumped group of alkanes (k_{OH} > 1.0 x 10^4/ppm/min)
ARO1	1st lumped group of aromatics (k_{OH} < 2.0 x 10^4/ppm/min)
ARO2	2nd lumped group of aromatics (k_{OH} > 1.0 x 10^4/ppm/min)
OLE1	1st lumped group of anthropogenic alkenes (k_{OH} < 7.5 x 10^4/ppm/min)
OLE2	2nd lumped group of anthropogenic alkenes (k_{OH} > 7.5 x 10^4/ppm/min)
OLE3	3rd lumped group of primarily biogenic alkenes (isoprene, terpenes)

anthropogenic area emissions were developed using a population surrogate and an appropriate activity factor taken from U.S. Environmental Protection Agency (EPA) source activity guidelines. Point source emission rates were either determined directly, using continuous emission monitoring data, or estimated using facility throughput or annual emissions data. A similar methodology was used to develop the anthropogenic area and point source

Table 2. Initial and boundary concentrations for Calgrid.

Model Species	Initial and Boundary Concentration (ppb)
O_3	30
NO	0
NO_2	0.2
ALK1	5.75
ALK2	0.97
ARO1	1.52
ARO2	3.17
ETHE	0.3
OLE1	0.33
OLE2	0
OLE3	0.86
HCHO	0.31
CCHO	0.32
MEK	0.39
HNO_3	0.1
CO	200
HO_2H	2

emissions for southwestern British Columbia; these data were provided by the CNRC.[16] Biogenic VOC emissions were estimated using a modified version of the Biogenic Emission Inventory System,[17] which incorporates new tree inventory data from the U.S. Forest Service and a simple forest canopy model.[18]

Figure 2 shows the spatial distribution of mid-afternoon emissions within the Cascadia domain. In Figure 2a, emissions of ARO1, a lumped aromatic VOC emitted entirely by anthropogenic sources, clearly show the signature of the population centers. The spatial pattern of anthropogenic NO_x emissions (not shown) is similar. In contrast, emissions of OLE3, a lumped olefin consisting of biogenic isoprene and terpenes, display a much more disperse pattern, as shown in Figure 2b. Higher biogenic emissions in the southern portion of the domain are due to the composition of vegetative species and the warmer temperatures that predominate in this area. Predicted maximum anthropogenic NO_x and total VOC emission rates are ~0.12 t/hr/grid and 0.30 t/hr/grid, respectively. Maximum biogenic VOC emission rates are higher, at 1.3 t/hr/grid; biogenic NO_x emissions are very small, at less than 0.002 t/hr/grid.

A summary of the average domain-wide daily VOC/NO_x emissions is given in Table 3, and the temporal distribution of VOC/NO_x emission rates, from early morning to late afternoon, is presented in Figure 3. Table 3 and Figure 3 clearly show the dominance of biogenic VOCs (primarily represented by OLE3) on the overall VOC budget, with biogenic emissions accounting for 85% of the total VOC loading within the Cascadia airshed. Although biogenic VOCs dominate the total VOC emission inventory on a domain-wide basis, it is important to note that they are much more disperse than the anthropogenic VOC emissions and are not accompanied by significant biogenic NO_x emissions. With regard to anthropogenic VOC emissions, area and mobile sources are the primary contributors, at 51 and 41%, respectively; point sources comprise 8% of the total anthropogenic VOC. In terms of anthropogenic NO_x emissions, mobile sources are the largest contributors, at 70%, and nonmobile area sources and point sources account for 12 and 18%, respectively. Biogenic NO_x emissions contribute less than 10% to the overall NO_x budget.

Configuration of VOC/NO_x Sensitivity Runs

Calgrid was used to generate a set of VOC/NO_x sensitivity simulations. These simulations shared the same configuration as the base case run, except for a 25, 50, 75 or 100% reduction in the anthropogenic VOC or NO_x emissions. Both anthropogenic area and point source emissions were reduced. Ozone predictions from these sensitivity runs

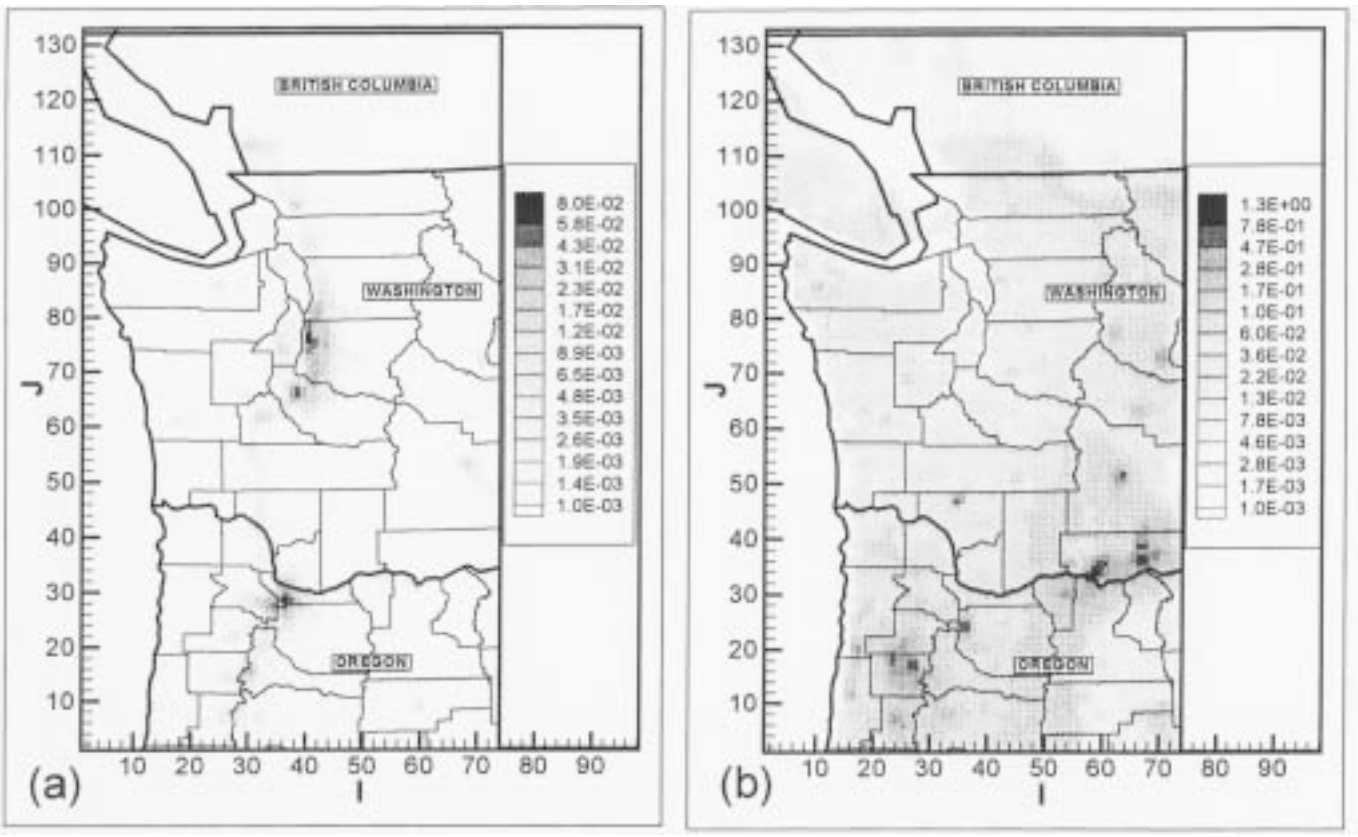


Figure 2. Example spatial patterns of area VOC emissions from (a) anthropogenic sources (represented as ARO1) and (b) biogenic sources (represented as OLE3) at 1400 LST, July 14, 1996; units are t/grid, with each grid measuring 5 × 5 km.

Table 3. Summary of anthropogenic and biogenic emissions (t/day) summed over the entire modeling domain.

Model Species	Point Sources (mT/day)	Area Sources (mT/day)	Mobile Sources (mT/day)	Total Anthro Emissions (mT/day)	Bio Emissions (mT/day)	Total Emissions (mT/day)	Percent Anthro (%)
ALK1	21	198	188	407	81	489	83.4
ALK2	11	107	49	167	0	167	100.0
ARO1	9	61	55	125	0	125	100.0
ARO2	6	52	46	104	0	104	100.0
CCHO	9	2	3	14	374	388	3.5
CRES	1	0	0	1	0	1	100.0
ETHE	2	13	21	35	0	35	100.0
ETOH	2	32	1	35	217	253	14.0
HCHO	3	4	7	15	510	525	2.8
MEK	3	21	3	27	324	351	7.6
MEOH	2	4	2	8	0	8	100.0
MGLY	0	0	0	0	0	0	100.0
MTBE	6	0	0	6	0	6	100.0
OLE1	3	16	25	44	176	219	19.9
OLE2	1	15	27	43	70	113	37.8
OLE3	6	0	0	6	4117	4124	0.2
RCHO	2	2	1	6	55	61	9.5
Total VOCs	86	528	428	1042	5926	6968	15.0
SO_2	641	10	36	687	0	687	100.0
NO_x	162	105	629	896	94	990	90.5
CO	616	1651	4252	6519	0	6519	100.0

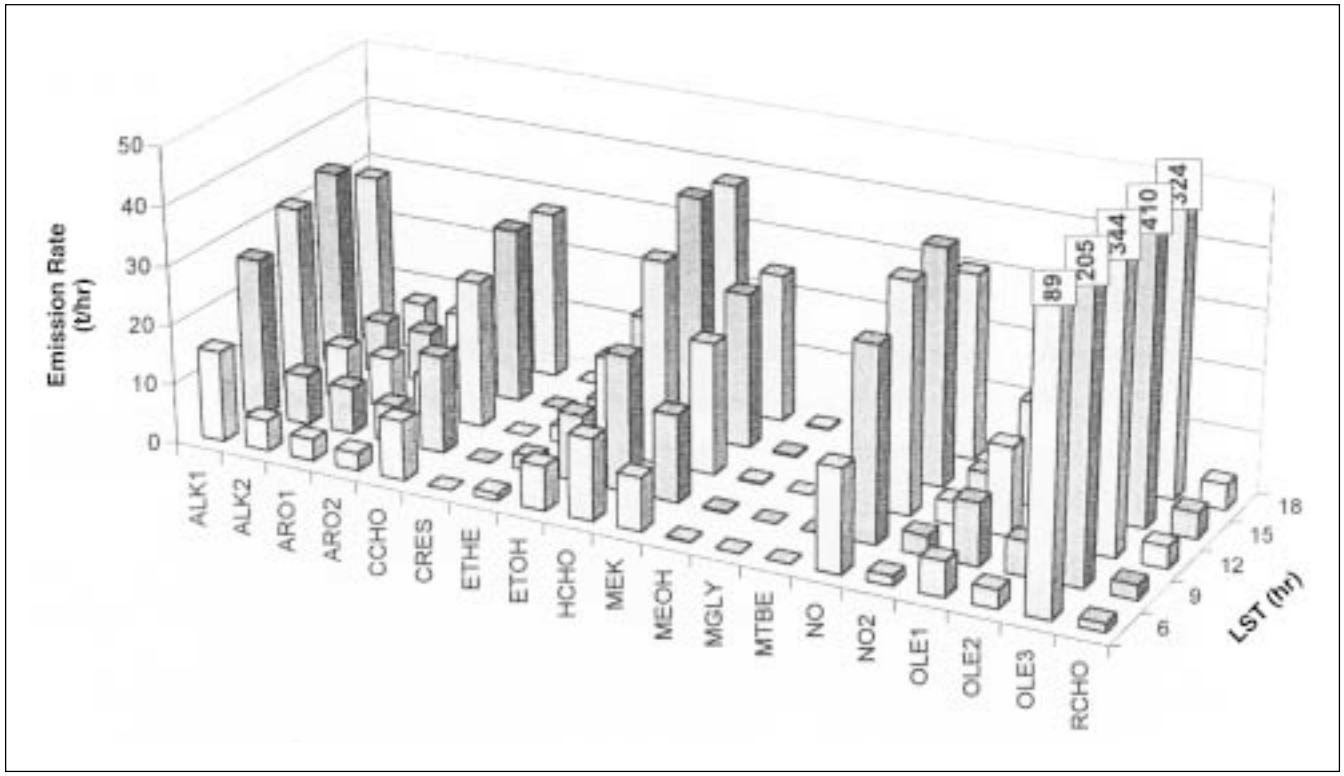


Figure 3. Temporal distribution of the total domain-wide emission rates for NO_x and SAPRC90 VOC species for July 14, 1996.

were then evaluated against the base case ozone levels, and the changes in the peak 1 hr and 8 hr ozone concentrations were determined. During this event, both the observed and predicted peak ozone levels occurred mid-afternoon on July 14; this is the period presented in the results.

RESULTS AND DISCUSSION

Overview of the July 11–14 Base Case Simulation

High levels of summertime ozone in the Cascadia region are generally associated with the building of an upper-level ridge of high pressure over the west coast of North America and a thermal trough that develops from California northward along the Pacific coast.[19] These synoptic features can result in elevated surface temperatures, stagnant winds, and suppressed mixing heights. These were the conditions during the July 11–14 episode.

On the afternoon of July 14, high ozone levels were evident along the I-5 corridor and downwind of the metropolitan areas, as shown in Figure 4. Maximum predicted ozone concentrations occurred 40 km southeast of Seattle, near the Enumclaw monitor (103 ppb), and 50 km south of Portland (145 ppb). Peak observed ozone concentrations recorded at the surface monitors also occurred during this period, with 118 ppb reported at the Enumclaw monitor and 145 ppb recorded at the Milwaukee monitor, 10 km south of Portland. Two monitors in the Seattle area (Enumclaw and Lake Sammamish) and all four monitors in the Portland area (Sauvie Island, Mountain View, Milwaukee, and Carus) measured peak 8 hr ozone levels that were in excess of the 8 hr/80 ppb standard; the Milwaukee monitor (and very nearly the Enumclaw monitor) also exceeded the 1 hr/120 ppb standard. Calgrid was generally able to reproduce the observed time series at the monitors, as shown in Figure 5; a detailed model evaluation for this episode can be found in Barna and Lamb.[11] Although Calgrid underpredicted Sunday's observed peak concentration at the Milwaukee monitor near Portland (Figure 5d), ozone levels of this magnitude were predicted 20 km further south. At the Paradise monitor, located in a Class I wilderness area on the slopes of Mt. Rainier (100 km southeast of Seattle, 1650 m above sea level), the peak observed 8 hr ozone level was 69 ppb.

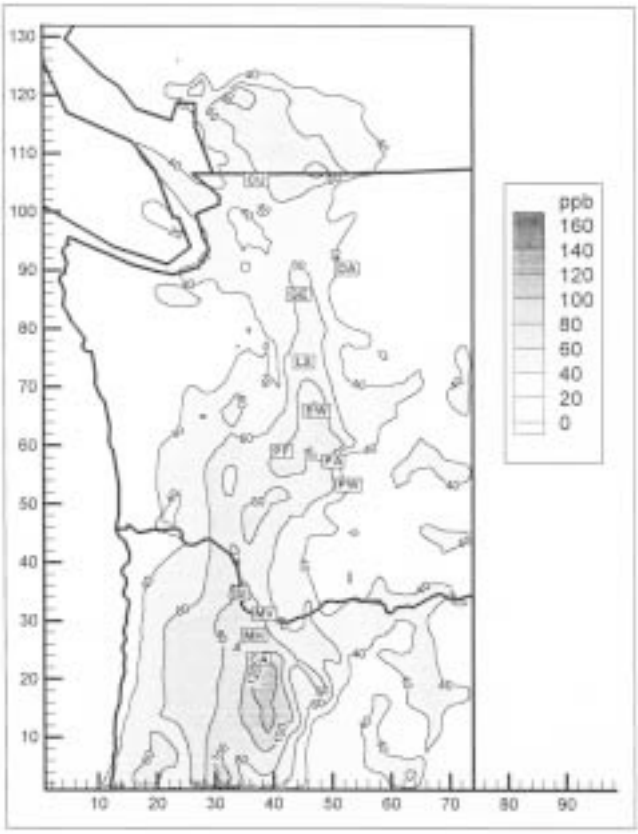


Figure 4. Base case surface ozone contours (ppb) at 1600 LST, July 14, 1996.

Given the inflow of clean maritime air into the Cascadia region and the fact that the predominant winds during this event were from the north or northwest, ozone boundary concentrations were set to 30 ppb. To assess the model's sensitivity to these conditions, ozone levels were raised and lowered by 50%, resulting in boundary concentrations of 45 and 15 ppb, respectively. The impact of this change on the peak predicted concentrations is shown in Figure 6. Generally, the model's response to modified ozone boundary concentrations was quite small, with the 1 hr and 8 hr maxima in the Portland area changing by only a few ppb. In the Seattle area, the peak 1 hr and 8 hr maxima varied by 6–7 ppb.

Results of VOC/NO_x Sensitivity Runs for July 14

The change in the ozone concentration field was calculated for each VOC/NO_x sensitivity simulation. Figure 7 shows examples of mid-afternoon surface ozone difference contours for the –50% VOC/NO_x runs, where the base case concentration field is subtracted from the sensitivity case concentration field as follows:

$$\Delta O_3 = (\text{sensitivity case } O_3) - (\text{base case } O_3) \qquad (1)$$

Hence, negative concentrations in Figure 5 indicate ozone reductions that result from reduced emissions, while positive concentrations indicate ozone enhancements that result from reduced emissions. The simulation in which both the anthropogenic VOC and NO_x emissions were reduced by 50% is shown in Figure 7a. Ozone reductions between 5 and 15 ppb are evident downwind of the population centers along the I-5 corridor, with larger reductions, between 20 and 25 ppb, apparent 80–100 km downwind of the Seattle and Portland urban cores. Also,

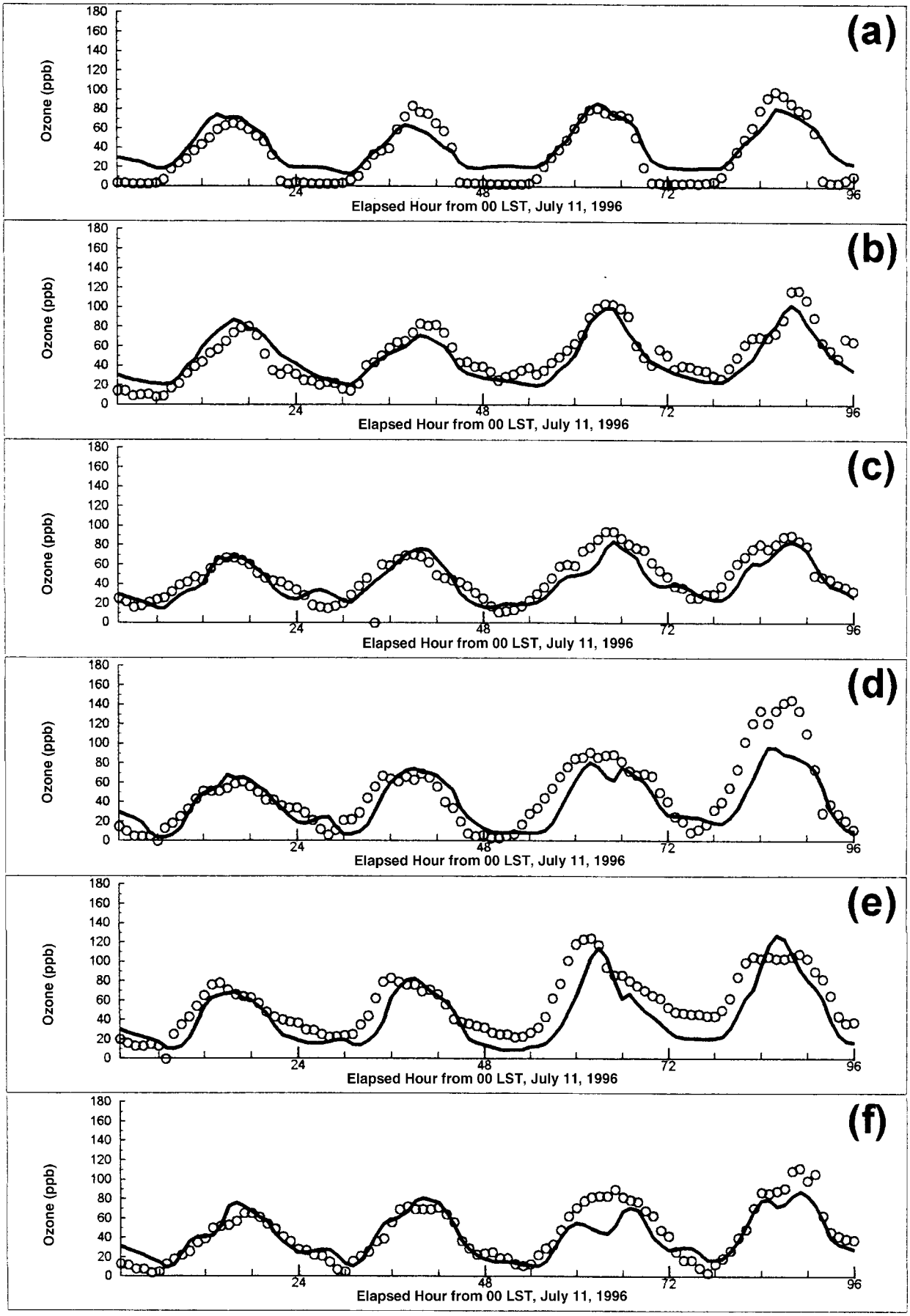


Figure 5. Predicted and observed ozone time series for July 11–14, 1996, at (a) Lake Sammamish, (b) Enumclaw, (c) Sauvie Island, (d) Milwaukee, (e) Carus, and (f) Mountain View.

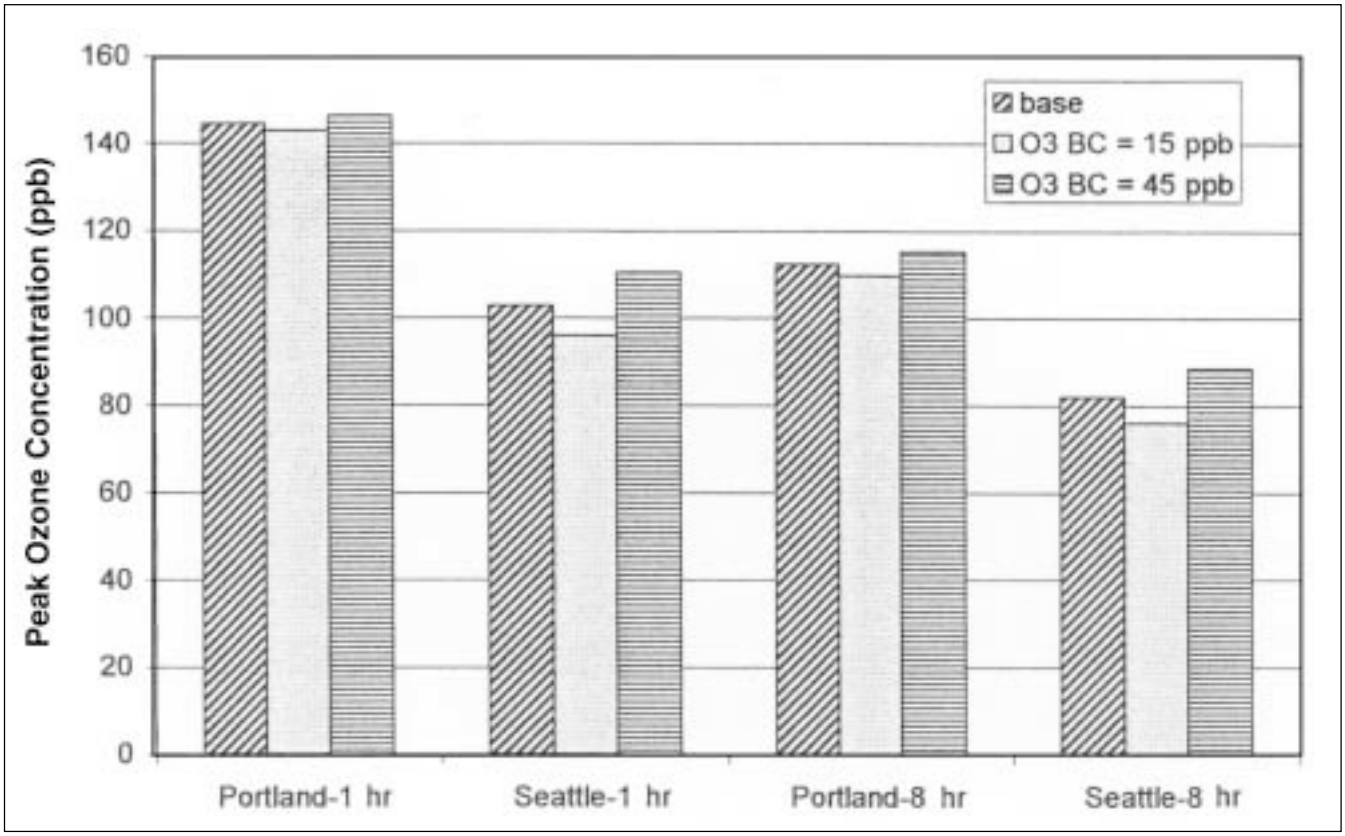


Figure 6. Effect of increased (45 ppb) and decreased (15 ppb) ozone concentrations at the domain boundaries on peak 1 hr and 8 hr ozone levels.

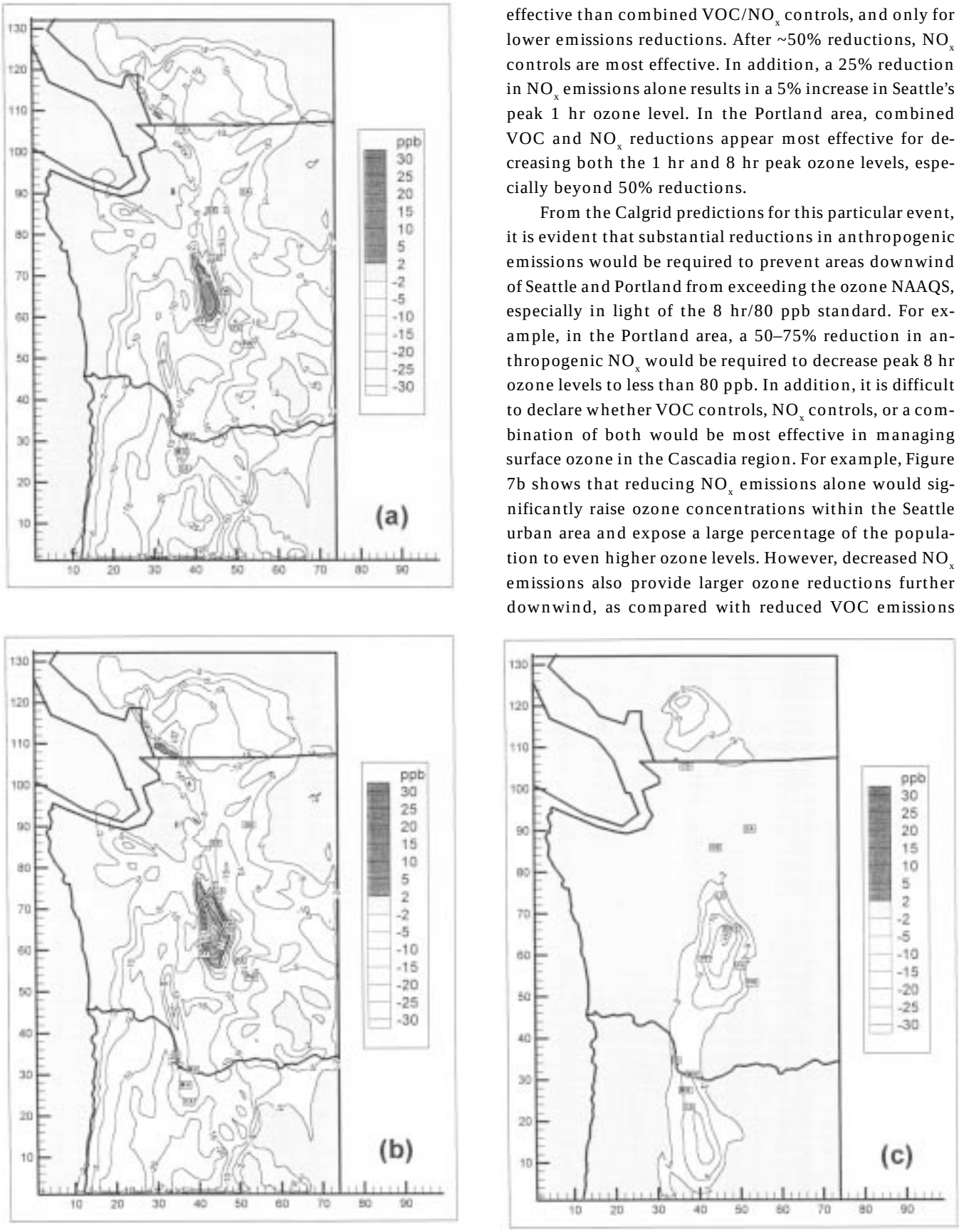
due to reduced NO scavenging, ozone enhancements between 5 and 10 ppb are predicted in the vicinity of Seattle.

The effect of NO scavenging is even more apparent in Figure 7b, which shows the difference contours for the –50% NO_x emissions case. Surface ozone levels increased substantially within and near downtown Seattle, with ozone enhancements of up to 25 ppb immediately southeast of the urban core. A more modest enhancement of less than 5 ppb is shown for Vancouver, and no enhancement is evident for Portland. The spatial patterns of the ozone difference contours are similar between the reduced NO_x case and the reduced NO_x plus VOC case.

Finally, the –50% anthropogenic VOC case is shown in Figure 7c. Ozone reductions are evident downwind of the urban cores and along the I-5 corridor between Seattle and Portland, with peak reductions of ~20 ppb south of the Enumclaw monitor. The areal extent of the ozone difference contours for the –50% VOC case is much smaller than the other –50% sensitivity runs, with changes in ozone levels limited primarily to the densely populated urban centers.

Figure 7 indicates that reduced anthropogenic VOC emissions have a larger impact near the urban centers (indicating regions of VOC-sensitive chemistry), while the influence of reduced NO_x emissions is apparent further downwind in rural areas (indicating regions of NO_x-sensitive chemistry). These results are broadly consistent with a typical ozone/VOC/NO_x system, in which newly emitted pollutants evolve from a VOC-sensitive regime to a NO_x-sensitive regime as the air mass ages.[2,20,21] The predicted ozone enhancements from reduced NO scavenging which occur in close proximity to Seattle and, to a lesser extent, Vancouver, are also consistent with a VOC-sensitive regime.[10] The spatial patterns of the surface ozone difference contours for the other VOC/NO_x sensitivity cases (not shown) are similar to those in Figure 7, with the exception of the simulation in which all anthropogenic NO_x emissions are removed. For this case, ozone concentrations fall to background levels of ~30 ppb.

The impact of the reduced anthropogenic emissions on the peak predicted 1 hr and 8 hr ozone levels is shown in Figure 8 and Table 4 for Seattle and Figure 9 and Table 5 for Portland. For both Seattle and Portland, reducing VOC emissions alone results in a linear reduction of peak ozone levels, with each 1% decrease in VOC emissions yielding a 0.3–0.4 ppb drop in the 1 hr peak ozone level and a 0.2–0.3 ppb drop in the 8 hr peak ozone level. In the Seattle area, VOC controls appear to be most effective for reducing peak 1 hr concentrations in the range of 0–75% reductions. However, when the 8 hr ozone standard is considered, VOC controls alone are only marginally more



effective than combined VOC/NO_x controls, and only for lower emissions reductions. After ~50% reductions, NO_x controls are most effective. In addition, a 25% reduction in NO_x emissions alone results in a 5% increase in Seattle's peak 1 hr ozone level. In the Portland area, combined VOC and NO_x reductions appear most effective for decreasing both the 1 hr and 8 hr peak ozone levels, especially beyond 50% reductions.

From the Calgrid predictions for this particular event, it is evident that substantial reductions in anthropogenic emissions would be required to prevent areas downwind of Seattle and Portland from exceeding the ozone NAAQS, especially in light of the 8 hr/80 ppb standard. For example, in the Portland area, a 50–75% reduction in anthropogenic NO_x would be required to decrease peak 8 hr ozone levels to less than 80 ppb. In addition, it is difficult to declare whether VOC controls, NO_x controls, or a combination of both would be most effective in managing surface ozone in the Cascadia region. For example, Figure 7b shows that reducing NO_x emissions alone would significantly raise ozone concentrations within the Seattle urban area and expose a large percentage of the population to even higher ozone levels. However, decreased NO_x emissions also provide larger ozone reductions further downwind, as compared with reduced VOC emissions

Figure 7. Surface ozone difference contours (ppb) at 1600 LST, July 14, 1996, for (a) the 50% reduction of both anthropogenic VOC and NO_x emissions, (b) the 50% reduction of anthropogenic NO_x emissions, and (c) the 50% reduction of anthropogenic VOC emissions.

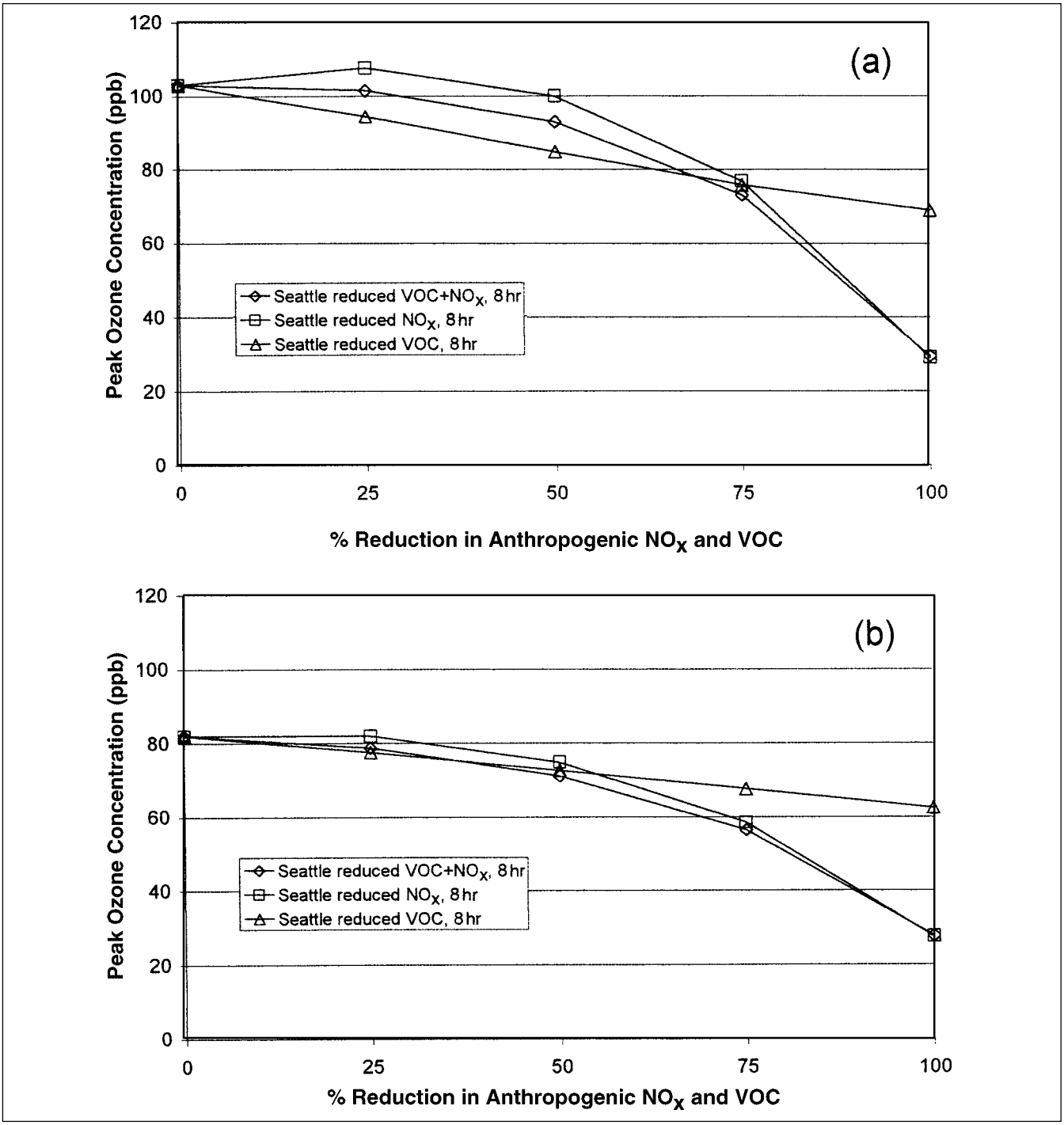


Figure 8. Peak 1 hr (a) and 8 hr (b) ozone concentrations vs. reductions in anthropogenic VOC or NO_x emissions downwind of Seattle.

only (Figure 7c). Although VOC controls appear to be most effective in reducing peak ozone levels within the urban centers, it is likely that relying on VOC controls alone would not reduce the total amount of ozone produced, but merely delay ozone synthesis until the urban air mass moved farther downwind.[10]

The location of the predicted Seattle and Portland ozone peaks for the base case run and each sensitivity run is shown in Figure 10. In the Seattle area (Figure 10a), the peak ozone levels tend to occur near the Enumclaw monitor for cases when NO_x or both NO_x and VOCs are reduced. When VOC emissions alone are reduced, the location of the peak ozone levels is shifted 40 km downwind to the southeast, resulting in maxima occurring in the vicinity of the Paradise monitor on Mt. Rainier. In the Portland region (Figure 10b), the peak ozone maxima are generally tightly clustered within 10 km of the base case maxima, which is predicted immediately south of the

Table 4. Peak 1-hr (left) and 8-hr (right) ozone levels in the Seattle area as a function of anthropogenic VOC/NO_X reductions.

		% Reduction VOC				
	(1-hr)	0	25	50	75	100
% Reduction NO_X	0	103	94 -8%	85 -18%	76 -26%	69 -33%
	25	108 5%	101 -1%	–	–	–
	50	100 -25%	–	93 -10%	–	–
	75	77 -25%	–	–	73 -29%	–
	100	29 -72%	–	–	–	29 -71%

		% Reduction VOC				
	(8-hr)	0	25	50	75	100
% Reduction NO_X	0	82	77 -5%	73 -11%	68 -18%	62 -24%
	25	82 0%	79 -4%	–	–	–
	50	75 -9%	–	71 -13%	–	–
	75	58 -29%	–	–	56 -31%	–
	100	28 -66%	–	–	–	28 -66%

Carus monitor. In both the Seattle and Portland areas, a complete elimination of anthropogenic NO_x emissions yields ozone concentrations at background levels; these peaks occur at locations far from the urban centers.

Other studies have shown that, during severe air pollution episodes, substantial cuts in anthropogenic emissions are required to reduce predicted ozone levels to acceptable levels. For example, Chock et al.[4] found that in southern California, reductions of anthropogenic NO_x emissions of greater than 75% were required to decrease 8 hr ozone levels to less than 80 ppb. Saylor et al.[3] discuss similar results for the Atlanta, GA, area. In addition to the challenge of managing anthropogenic emissions to meet prescribed ozone levels, the Pacific Northwest may face an additional problem in maintaining acceptable air quality. A recent study by Jacob et al.[22] suggests that by 2010, rising fossil fuel emissions from Asia may raise monthly average surface ozone levels in the western United States by 2–6 ppb, with the maximum increase occurring between April and June. Jacob et al. predict that this increase would more than offset the benefits that would be realized from a 25% reduction in anthropogenic VOC and NO_x emissions. Although it is not clear what the impact of Asian emissions would be during an extreme summertime ozone episode in the Pacific

Table 5. Peak 1-hr (left) and 8-hr (right) ozone levels in the Portland area as a function of anthropogenic VOC/NO_X reductions.

		% Reduction VOC				
	(1-hr)	0	25	50	75	100
% Reduction NO_X	0	103	94 -8%	85 -18%	76 -26%	69 -33%
	25	108 5%	101 -1%	–	–	–
	50	100 -25%	–	93 -10%	–	–
	75	77 -25%	–	–	73 -29%	–
	100	29 -72%	–	–	–	29 -71%

		% Reduction VOC				
	(8-hr)	0	25	50	75	100
% Reduction NO_X	0	82	77 -5%	73 -11%	68 -18%	62 -24%
	25	82 0%	79 -4%	–	–	–
	50	75 -9%	–	71 -13%	–	–
	75	58 -29%	–	–	56 -31%	–
	100	28 -66%	–	–	–	28 -66%

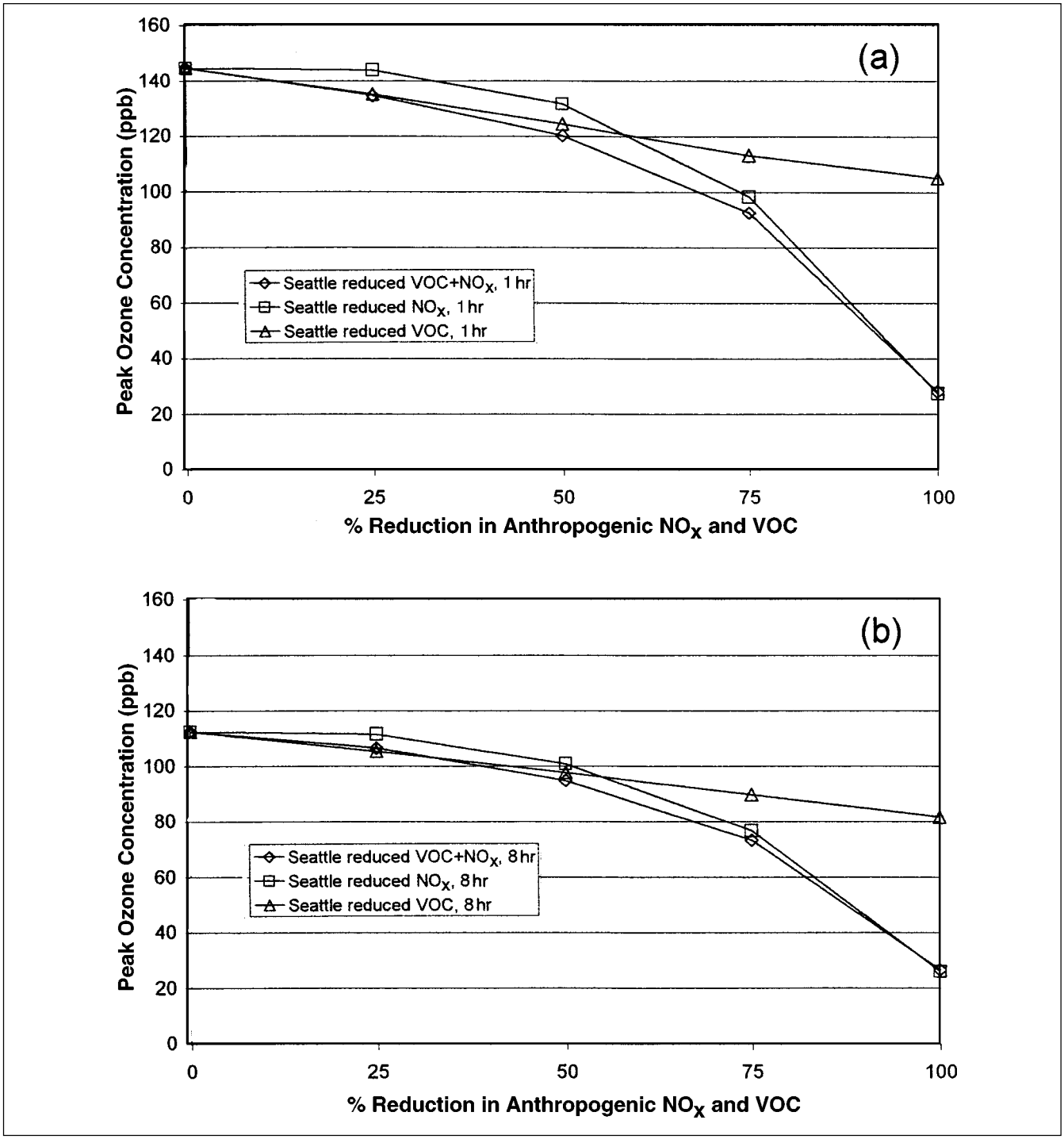


Figure 9. Peak 1 hr (a) and 8 hr (b) ozone concentrations vs. reductions in anthropogenic VOC or NO_x emissions downwind of Portland.

Northwest, these results indicate the need to apply both a global and local perspective to managing photochemical pollution in the Cascadia region.

SUMMARY

A modeling system consisting of MM5, Calmet, and Calgrid was used to evaluate the VOC/NO_x sensitivity of the Cascadia airshed for an ozone episode that occurred on July 11–14, 1996. Changes in ozone levels were evaluated as a function of reduced anthropogenic emissions. During this episode, high ozone levels were observed downwind of Seattle and Portland, with maximum observed concentrations of 118 and 145 ppb, respectively. Applying the 8 hr standard to this episode would result in more monitors reporting excessively high ozone levels (six sites above the 8 hr/80 ppb level vs. one site above

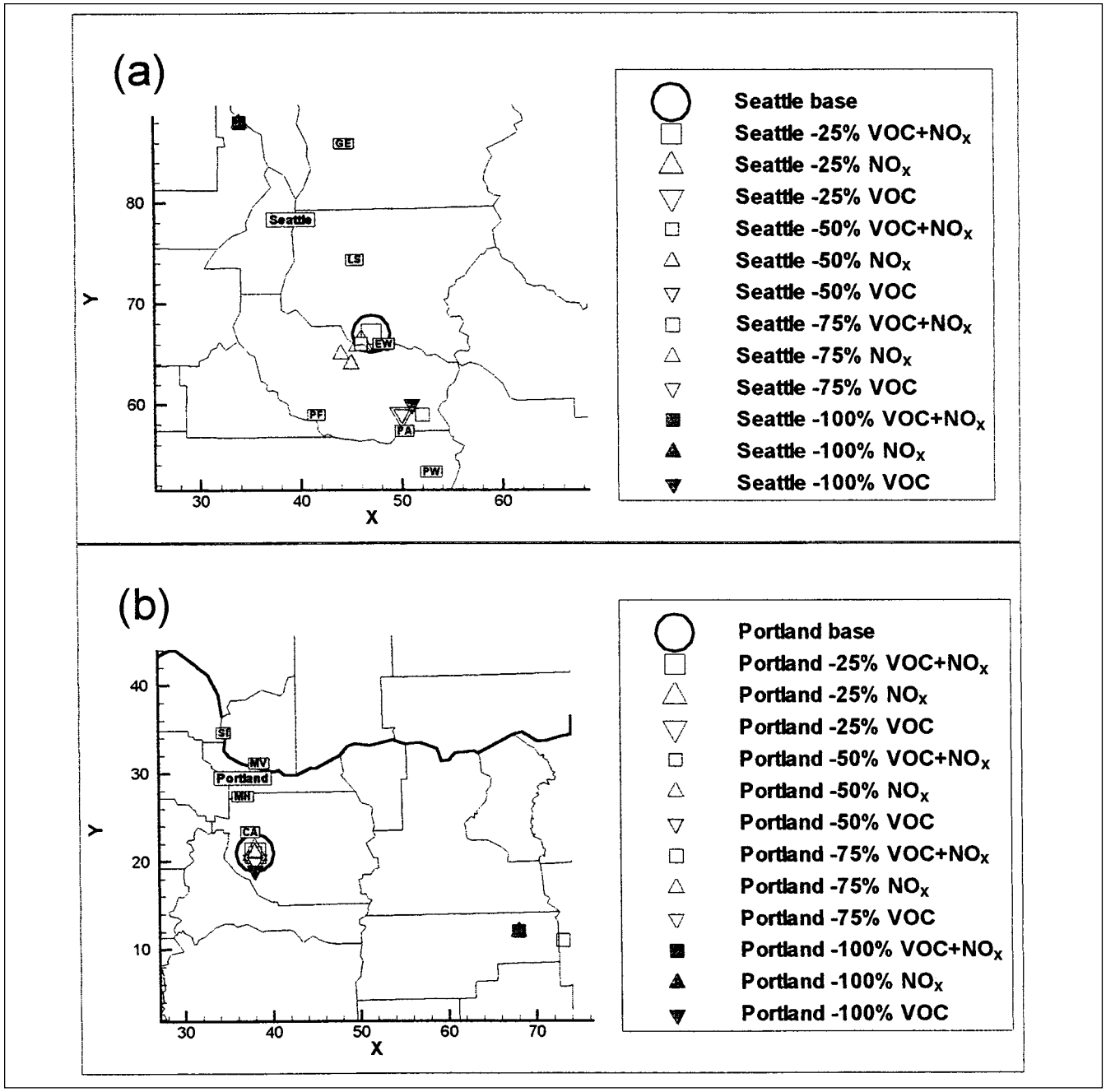


Figure 10. Locations of the predicted peak ozone concentrations in (a) the Seattle area and (b) the Portland area for the base case and each sensitivity test.

the 1 hr/120 ppb level), indicating that the new 8 hr standard would likely make it more difficult for the Cascadia region to remain in compliance with the NAAQS.

Changes in the ozone concentration field resulting from reduced anthropogenic VOC/NO_x emissions were restricted to areas downwind of the urban centers and the I-5 corridor and were not evident in the more sparsely populated regions toward the east (e.g., in the Cascade Range) or in the northwest portion of the Cascadia domain. In general, large emission reductions of 25–75% were required to decrease peak ozone concentrations to desired levels. The areal extent of the effects of reduced VOC emissions was limited to the urban cores, while the influence of decreased NO_x emissions was evident further downwind in the rural areas. Decreased NO_x emissions also yielded higher ozone levels in the Seattle area due to reduced NO scavenging. The locations of the predicted ozone maxima from the sensitivity simulations tended to occur in the same area as the predicted base case maxima. One exception to this, however, was the reduced VOC scenario for the Seattle region, where peak ozone concentrations were shifted downwind toward Mt. Rainier.

ACKNOWLEDGMENTS

The authors would like to thank Ms. Susan O'Neill of Washington State University for developing the MM5 simulation used in this study. The updated SAPRC90 chemistry mechanism was provided by Drs. Weimin Jiang and Don Singleton of the CNRC. Dr. Chris Geron of the EPA supplied updated forest cover data that were used in the creation of the biogenic emission inventory. The anthropogenic emission inventory was prepared by Ms. Sally Otterson, Ms. Cris Figueroa-Kaminsky, and Mr. Clint Bowman of the Washington State Department of Ecology, and Ms. Jennifer DeMay of the Olympia Air Pollution Control Authority of Washington State. This research was supported, in part, by Boeing endowment funds to Washington State University. Support for computer resources was provided by Grant No. 9508417 from the National Science Foundation.

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