GROUND-LEVEL OZONE:

OCCURRENCE AND TRANSPORT

IN EASTERN NORTH AMERICA

A Report by the

Canada-United States Air Quality Committee

Subcommittee 1:

Program Monitoring and Reporting

March, 1999

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* Note: Canadian spelling is used throughout.
"This is a policy document that provides a summary of information as a basis for decision by the Air Quality Committee."

1. INTRODUCTION

This report presents results of co-operative efforts set in motion in April 1997 to describe ground-level ozone[1] concentrations and transport in the border region of the eastern United States and Canada. It is intended to provide a foundation for a recommendation to governments on the means to jointly address the transboundary ozone issue.

Foundation for the Transborder Ozone Issue in Eastern North America

Ozone has long been recognised as an important health and ecosystem-related air quality concern in the United States and Canada. Recent health and environmental studies in both countries indicate that adverse effects result from ozone exposures at concentrations much lower than previously thought. The United States has recently revised the ozone air quality standards and Canada has a process underway to examine its ozone-related objectives and standards. Both countries have committed to addressing the ozone air quality problem within their own territories. The status of ambient air quality standards and objectives for ozone in Canada and the United States are summarised in Table 1.

TABLE 1. AMBIENT AIR QUALITY OBJECTIVES AND STANDARDS FOR OZONE

	United States	**Canada**	
Averaging time	National Ambient Air Quality Standards	National Ambient Air Quality Objective	Proposed Canada-wide Standard
1-hour	120 parts per billion (ppb) (std. being replaced by 8-hr)	82 ppb	--
8-hours*	80 ppb (Revised standard)	--	60-70 ppb

*4th highest 8-hours averaged over 3 years

Recognition of the effects of ozone has been accompanied by considerable monitoring and analyses of the spatial pattern of ozone in the two nations. Large-scale summertime smog episodes occur in the eastern half of both countries, with events that transcend political borders. In Canada, exceedences of the current 1-hour 82 ppb (parts per billion) air quality objective are regional in nature, with areas of concern in southern British Columbia in the West, and throughout the Windsor–Québec City Corridor and the Southern Atlantic Region in the East. A similar pattern of regionally elevated ozone occurs in the United States; nationally, a number of areas in California and the Gulf Coast, as well as numerous locations in the eastern portion of the nation exceed the U.S. standards.

The Canadian effort to address ozone exceedences began in 1990 with all governments co-operating to develop the first phase of a management program to reduce precursor emissions of ozone - nitrogen oxides (NOx) and volatile organic compounds (VOC) (CCME, 1990). Since 1990, while the management program has continued to be further refined and implemented, a comprehensive science assessment has defined the nature and extent of the ozone problem in Canada and established the scientific foundation for management options (Multistakeholder, 1990).

[1] The term ground-level ozone, which includes smog-related ozone found in the lower troposphere, is used to make a clear distinction from beneficial stratospheric ozone. Hereafter, the report refers to ground-level or smog ozone simply as ozone.

In the United States, the need to improve upon the effectiveness of ozone implementation programs led to the new classification system, mandatory requirements, and additional mobile source controls embodied in Titles I and II of the 1990 Clean Air Act Amendments. In the process of implementing these requirements, it became clear that expanded regional, as well as local control approaches were essential to meet clean air standards. As a result, 37 eastern states formed the Ozone Transport Assessment Group (OTAG). The OTAG effort produced substantial documentation on the nature of regional ozone transport and alternative strategies (OTAG, 1997). This led directly to promulgation of a major new regional regulatory program to reduce emissions responsible for such transport. The U.S. Environmental Protection Agency (EPA) promulgated this ozone transport rule on October 27, 1998 (EPA, 1998). Since it calls on states to develop implementation plans (SIPs) to address NOx emissions, the rule is known as the NOx SIP call.

Canadian and international studies have reached similar conclusions. In addition to the OTAG Air Quality Analysis Workgroup section of the OTAG final report (OTAG, 1997), the Canadian 1996 NOx/VOC Science Assessment reports (Multistakeholder, 1997) have demonstrated that ozone concentrations locally, sub-regionally, and regionally are influenced by background concentrations, locally generated ozone, and transported ozone. The contribution of transported ozone and its precursor emissions occurs over distances of many hundreds of kilometres in the eastern United States and Canada. Recent reports by the Commission on Environmental Cooperation (CEC, 1997) and the International Joint Commission (IJC, 1998) have also highlighted the significance of the transboundary transport of ozone and its precursors to air quality management programs in the United States and Canada.

Joint Plan of Action for Addressing Transboundary Air Pollution

In 1991, Canada and the United States signed the *Air Quality Agreement*, which codified the principle that countries are responsible for the effects of their air pollution on one another. While the *Agreement* initially addressed acid rain, it also confirmed the commitment of the United States and Canada to consult and develop the means to deal with any existing transboundary air pollution problems.

The increasing evidence on regional transport of ozone outlined above led to a recognition that ground-level ozone would be an appropriate issue to consider for the Canada-U.S. *Air Quality Agreement* as early as 1994 (AQC, 1994). Members from both countries met in 1995 to outline a Canada-U.S. Regional Ozone Study Area (ROSA) project. Under this program, the countries initiated regional modelling to evaluate the relative effectiveness of regional controls for ozone pollution in a broad transboundary area in eastern North America. Both counties are also participating in a coordinated program of scientific research and assessment of ozone and particulate matter under NARSTO. This transboundary work occurred in parallel with the domestic OTAG and NOx/VOC Science Assessment activities. Collectively, these endeavours formed the basis of discussions of policy-makers from both countries.

In April 1997, President Clinton and Prime Minister Chretien's meeting reinforced the importance of Canada-U.S. cooperation to protect North American air quality. As part of the President-Prime Minister meeting agenda, U.S. EPA Administrator Carol Browner and

Canadian Minister of the Environment Sergio Marchi signed a “Commitment to Develop a Joint Plan of Action for Addressing Transboundary Air Pollution on April 7, 1997." The commitment was to address jointly shared air pollution problems with ground-level ozone identified as the next priority. In June 1998, EPA Administrator Browner and Canadian Minister of the Environment Christine Stewart signed a report on progress in developing the *Joint Plan of Action.* The Progress Report set targets and schedules for governments in working toward a negotiated ozone annex to the *Air Quality Agreement*. The report identified a strategy of cooperation and joint work, and called for delivery, by April 1999, of a recommendation on negotiation of an ozone annex to the Canadian Minister of the Environment and the U.S. EPA Administrator.

Joint Workplan

The following technical analyses, described in some detail in this document, enable conclusions regarding the transport of ozone in the border regions of the eastern United States and Canada:

- Air quality data analyses using integrated Canadian and U.S. data for the years 1989-1996 to determine how, when, and where transboundary transport of ozone and precursor emissions occurs within the region and the regional extent of elevated 8-hour ozone levels;

- Analyses of factors affecting ozone formation and transport to identify major source regions within the transboundary region; and

- Joint modelling using Canadian and U.S. data and forecasts of planned reduction programs to demonstrate the likely impact of emission control scenarios within the transboundary region.

This document and its conclusions on ozone transport in the border region fulfils the requirement to account, by April 1999, to the Canada-U.S. Air Quality Committee whose mandate is to implement the *Air Quality Agreement.* Further, the conclusions of this report provide support for drafting of possible elements for an ozone annex pursuant to the *Air Quality Agreement*.

2. AIR QUALITY DATA ANALYSIS

Ozone is a photochemical oxidant formed from reactions involving nitrogen oxides (NOx) and volatile organic compounds (VOC) in the presence of sunlight. In order to understand the nature of ozone levels and transboundary flows of ozone and precursor emissions in the border region, this section presents highlights of several existing analyses, assessments, and publications of air quality and meteorology. This work includes the existing and currently ongoing Canadian Multistakeholder NOx/VOC Science Assessment reports (Multistakeholder, 1997) and the OTAG final report (OTAG, 1997). In addition, new analyses that extend these data and analytical techniques into the Canada-U.S. transboundary region were developed for this report and are summarised below (Dann, 1999, Husar et al., 1999; Schichtel and Husar, 1999).

The sections presented here include: a snapshot of current ozone levels, regional maps showing episodic flows in the border region, emissions information, and an overview and analysis of meteorological factors affecting ozone concentrations and transport.

Air Quality Snapshot

The air quality snapshot depicts the regional extent of elevated ozone concentrations in the Canada-U.S. border area based on analysis and maps in an Environment Canada report (Dann, 1999). Data from 100 Canadian sites and 122 U.S. sites for the ozone season (May to September) for the period 1994 to 1996 were used to demonstrate regional patterns in ozone concentrations. Ozone concentrations were computed for running 8-hour periods and maximum 8-hour concentrations by day were determined. The maximum and the fourth highest daily maximum 8-hour ozone values were then computed by site by year.

Figure 1 shows the distribution of fourth highest daily maximum 8-hour ozone concentrations by monitoring site within each region using data for 1994 to 1996. The boxplot figure provides the median, the 95th, 75th, 25th and 5th percentile site ozone concentrations.[2] Figure 2 maps the 4th highest daily maximum 8-hour ozone concentration for the north-eastern portion of North America averaged over the years 1994-1996. Figure 3 provides similar information but uses the average highest daily maximum 8-hour ozone value.

[2] The 95th percentile value shows, for example, that 5% of the monitoring sites in that monitoring region have ozone concentrations that are equal to or higher than that level.

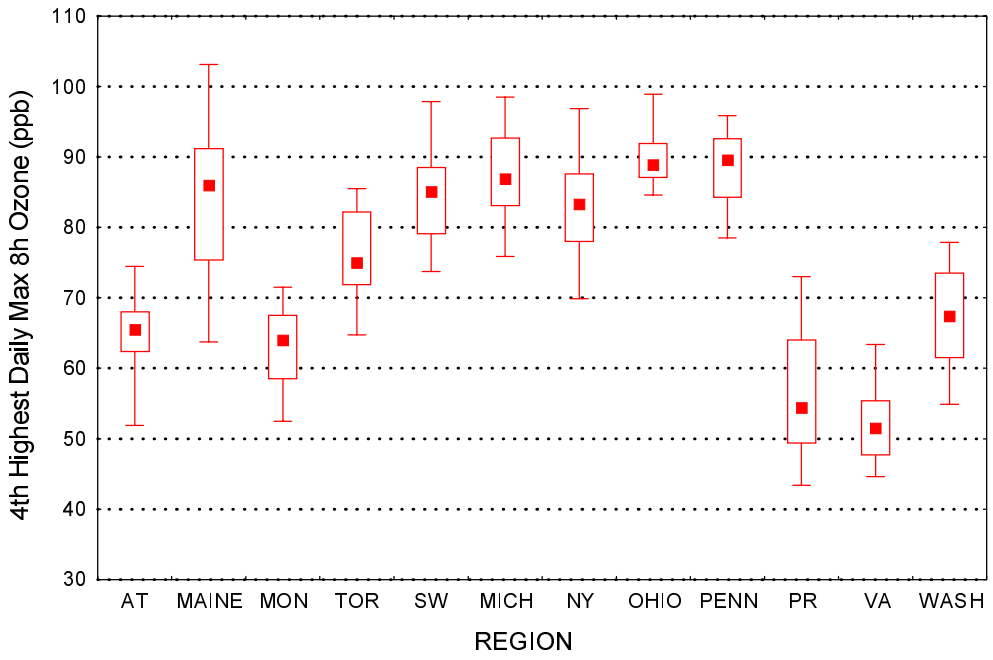


Figure 1. Distribution of 4th Highest Daily 8h Maximum Ozone (ppb) for Regional Sites (1994 to 1996) (Median, 5th, 25th, 75th and 95th Percentiles)[3]. The highest concentrations are recorded at the urban or industrialised sites in the United States (Michigan, New York, Ohio and Pennsylvania) and at the southwestern Ontario (SW) sites. The lowest ozone concentrations are at the Canadian Prairie (Pr) and Vancouver, British Columbia (VA) sites. The state of Maine also records high ozone values that are likely due to transport rather than local generation.

Figures 2 and 3 show large portions of the eastern United States exceeding the 8-hour 85-ppb level with some portions of Ontario also over this threshold. Many regions also exceed the range proposed for the Canada-wide Standard. A significant feature is that ozone concentrations in most of eastern North America, including further east along the coast, into Nova Scotia, and outside the major urban-industrialised areas are well above background concentrations. Maps of ozone episodes are shown in the following section.

[3] Monitoring sites were assigned to the following regions: AT – Canadian Atlantic Provinces, Maine – State of Maine, MON – Montreal Urban Community, TO – Greater Metropolitan Toronto, SW – south-western Ontario, MICH – State of Michigan, NY – State of New York, OHIO – State of Ohio, PENN – State of Pennsylvania, PR – Prairie cities in Manitoba, Saskatchewan, and Alberta, VA – Greater Vancouver Regional District, WASH – State of Washington.

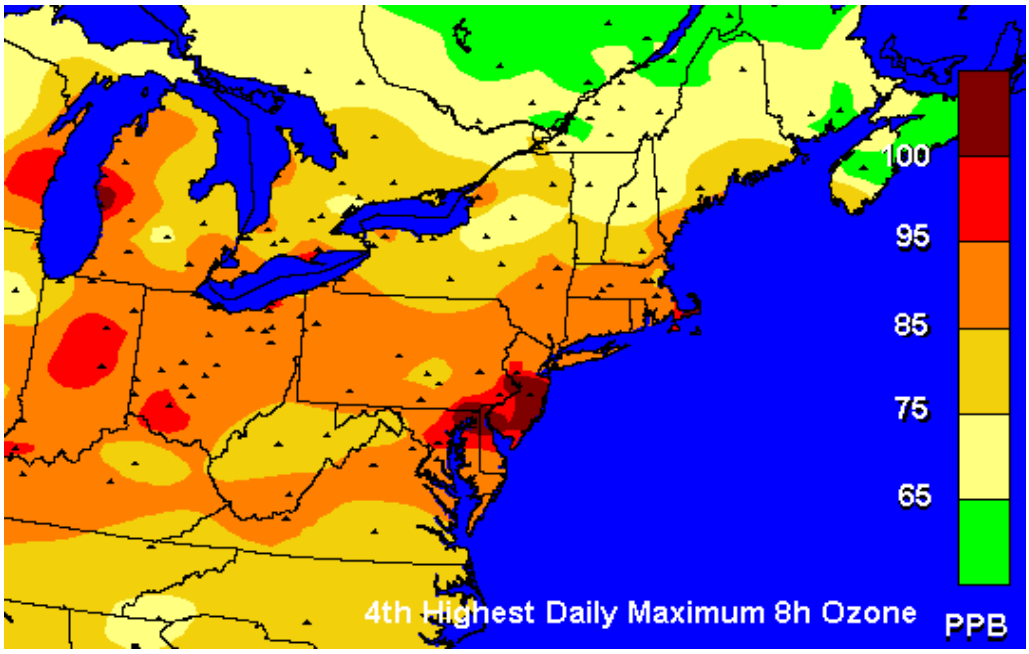


Figure 2. Average of the 4th Highest Daily 8h Maximum Ozone Concentration (ppb) for 1994 to 1996[4].

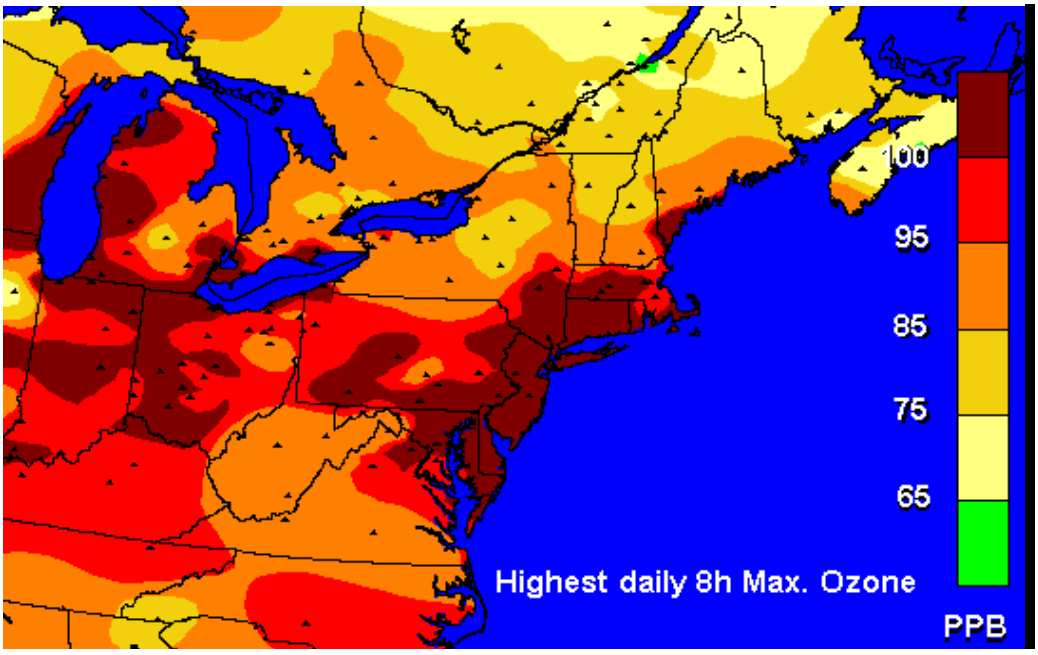


Figure 3. Average of the Highest Daily 8h Maximum Ozone Concentration for 1994 to 1996[4].

[4] Figures 2 and 3 were created using the U.S. EPA sponsored Map Generator program (MCNC-North Carolina Supercomputing Center) and incorporates data from 271 ozone monitoring sites that had at least two years of observations in the 1994-1996 period. The contours were generated using inverse distance weighting interpolation.

Ozone Episodes

Widespread regional episodes are a common feature of eastern North America and have the potential to contribute to exceedences of air quality objectives and standards. To illustrate how a regional episode develops and flows within the region of interest, measured ozone concentration data were compiled from monitoring sites located in eastern United States and eastern Canada for two regional ozone episodes and then mapped. The episode years, 1988 and 1995 were chosen because they show clearly ozone transport within the region of interest over the duration of the episodes. The 1988 episode illustrates ozone transport in both directions across the Canada-U.S. border whereas the 1995 episode illustrates a good example of transport from the United States to Canada. Both episodes were also used in the joint modelling scenarios presented later in this report.

During the summers of 1988 and 1995, ozone-rich plumes were transported across all of eastern North America. Many sites recorded multiple hours and days with ozone concentrations greater than the Canadian and U.S. air quality criteria. The following series of maps (Figures 4, 5 and 6) depict the levels of ozone concentrations in eastern United States and Canada at four progressively later hours in a day during an episode. The maps provide the magnitude and extent of high concentrations while demonstrating movement of ozone over time through the region.

These figures illustrate that essentially all areas of eastern Canada and most areas of the eastern United States experience high concentrations of ozone. Although some areas experience very high 8-hour concentrations, widespread areas experience concentrations ranging from 60-80 ppb and from 80-100 ppb over 8 hours. The following section will discuss what factors contribute to high ozone concentrations locally and regionally.

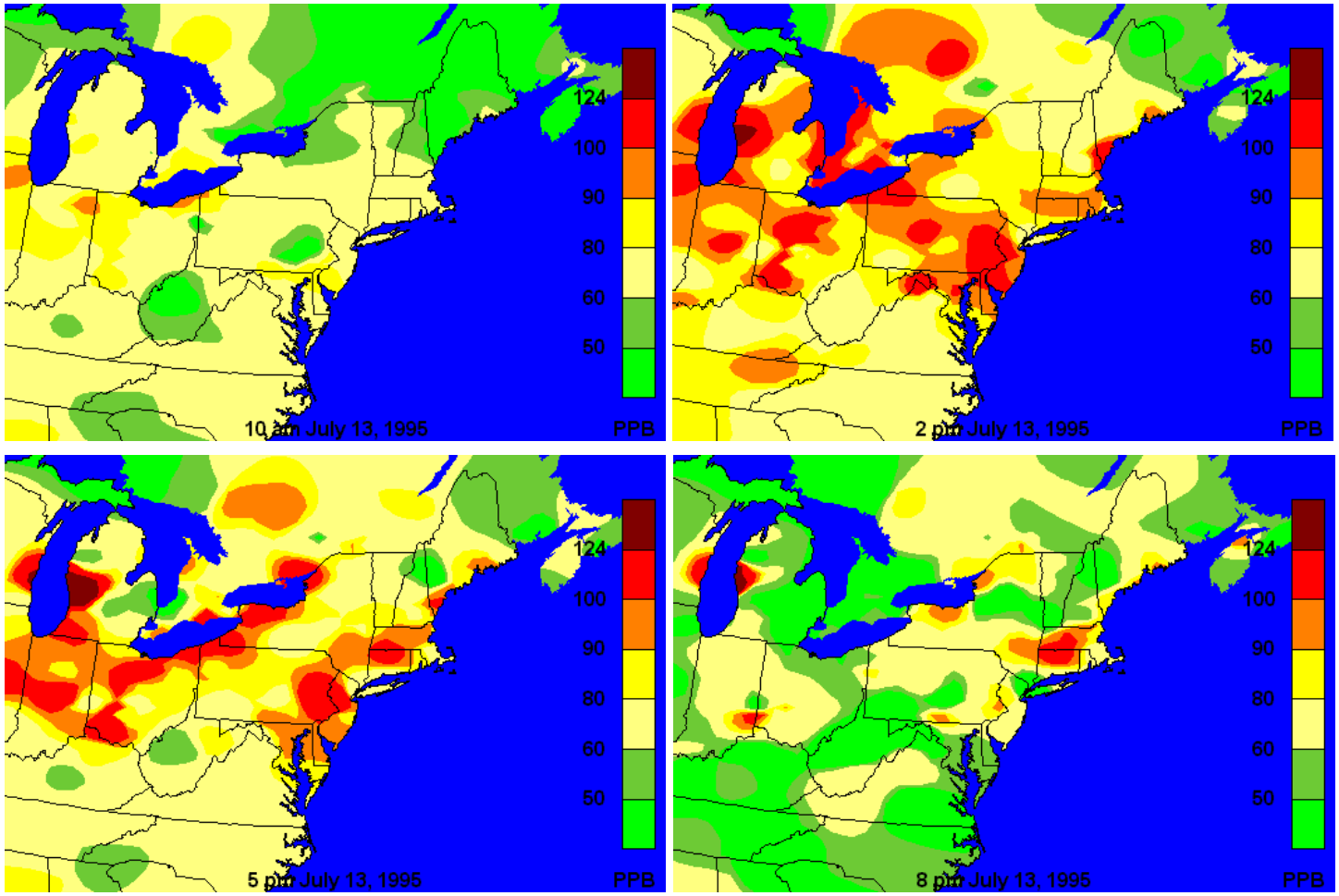


Figure 4. Ozone Transport on July 13, 1995 10AM - 8PM. The first frame shows a regionally uniform pattern of ozone levels. Transport generally followed a north-easterly path, across the heavily industrialised and urbanised area of the U.S. Midwest, then across the Great Lakes (frame 2) into southern Ontario and out to the coast. After picking up local emissions, transport continues west along the St. Lawrence river basin (frame 3) and finally out to the North Atlantic.

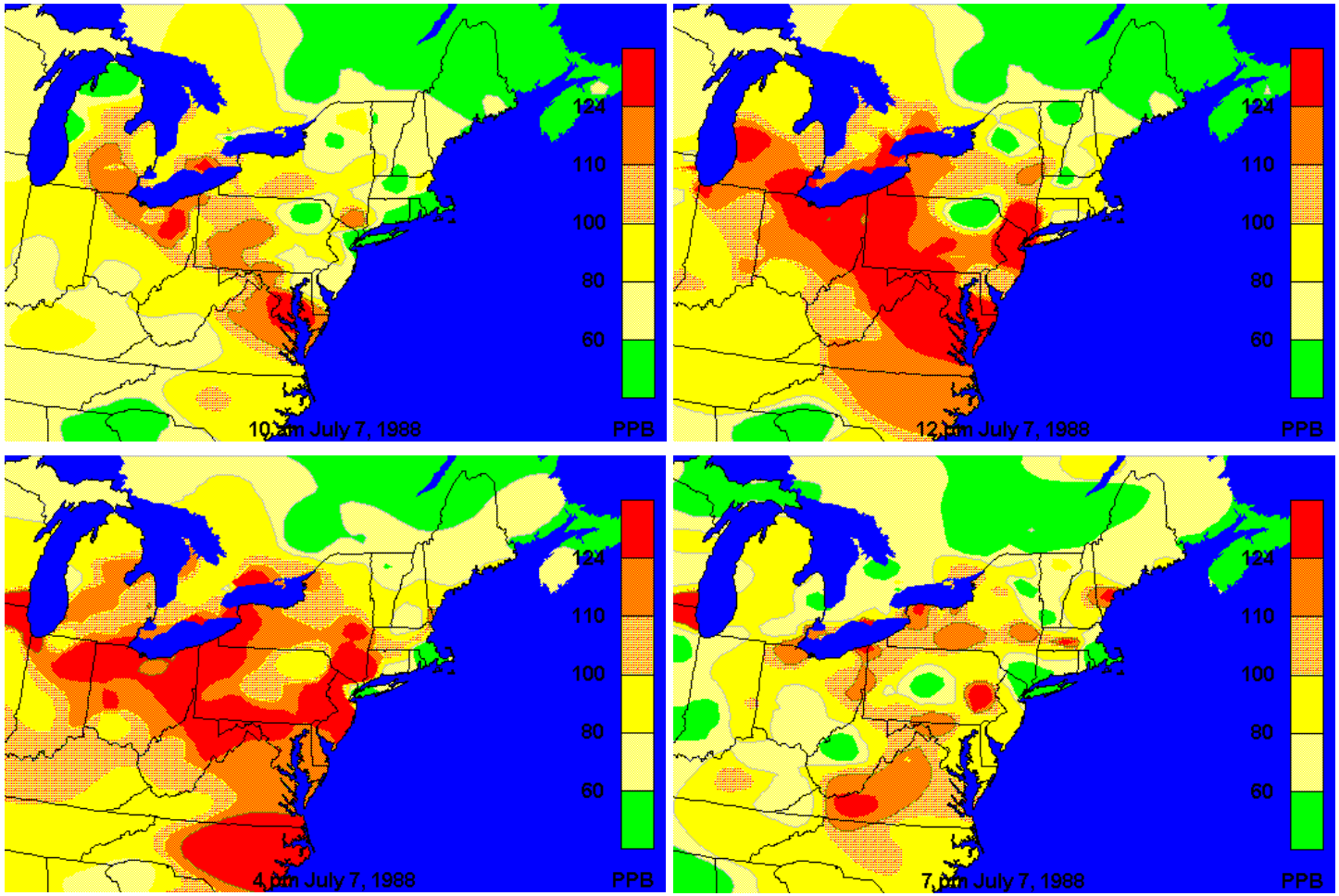


Figure 5. Ozone Transport on July 7 1988, 10AM - 7PM...These frames show fewer urban-industrial peaks and an elevated non-urban pattern extending across most of eastern North America. Both characteristics are evidence of regional scale transport.

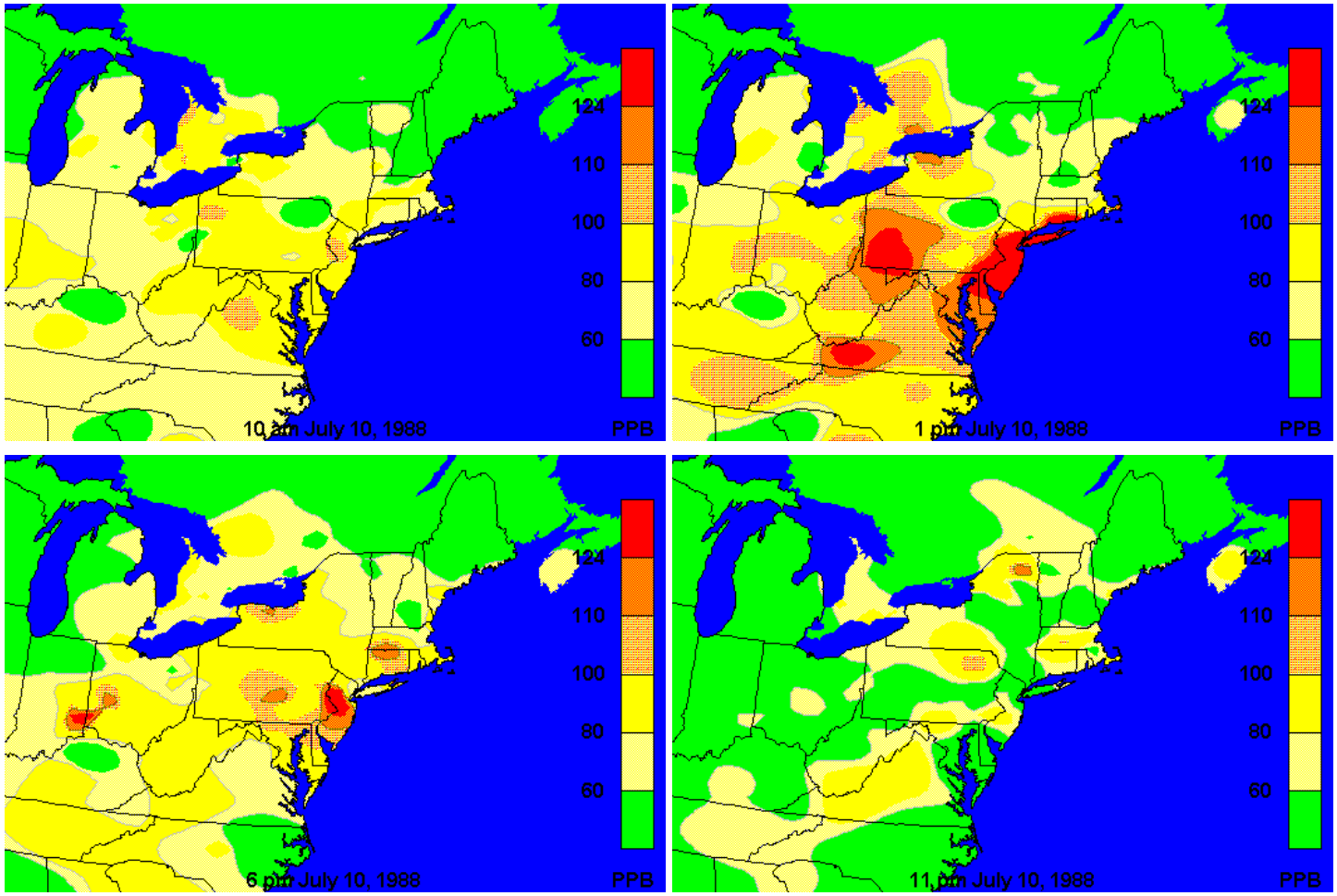


Figure 6. Ozone transport on July 10, 1988, 10AM – 11 PM. Figure 6 shows night time flows into eastern Canada when concentrations greater than 82 ppb occur late in the evening in the southern Atlantic region (frame 4) after high ozone concentrations have moved across the Northeast region (IND, WV, VA, OH, PA, ON) and along the Atlantic seaboard.

Factors that Influence Ozone Concentrations

The direction and spatial extent of transport and the relative contribution of transported ozone and precursors to individual ozone exceedences are highly variable. A number of factors influence site-to site differences in ozone concentrations, including sources of precursor emissions and large-scale and local meteorology. The following information comes from several sources, including the Canada-U.S. Air Quality Agreement 1998 Progress Report and analyses conducted for this report as cited above.

Sources of Ozone Precursors and their Influence on Ozone Formation

As discussed previously, ozone is not emitted directly, but formed in the atmosphere by reactions of "precursors" (NOx and VOCs). Both NOx and VOCs are emitted from a variety of sources. Anthropogenic sources of NOx emissions in the United States are 10 times larger and VOC emissions are 7 times larger in magnitude than in Canada, paralleling the relative population ratio between the two countries.

The relative distribution of major sources categories of NOx and VOC emissions in the U.S. and Canada are somewhat different, as shown in Figures 7 and 8. Although transportation is the largest source of both precursor emissions in both countries, there are some significant differences in source apportionment. For instance, electric utilities in the United States generate 27% of total NOx while contributing only 11% in Canada. Although not shown in these figures, natural emissions also play an important role with respect to summertime emissions of VOCs when emissions from vegetation, for example, have been found to equal or exceed manmade VOC emissions over large regions of eastern North America.

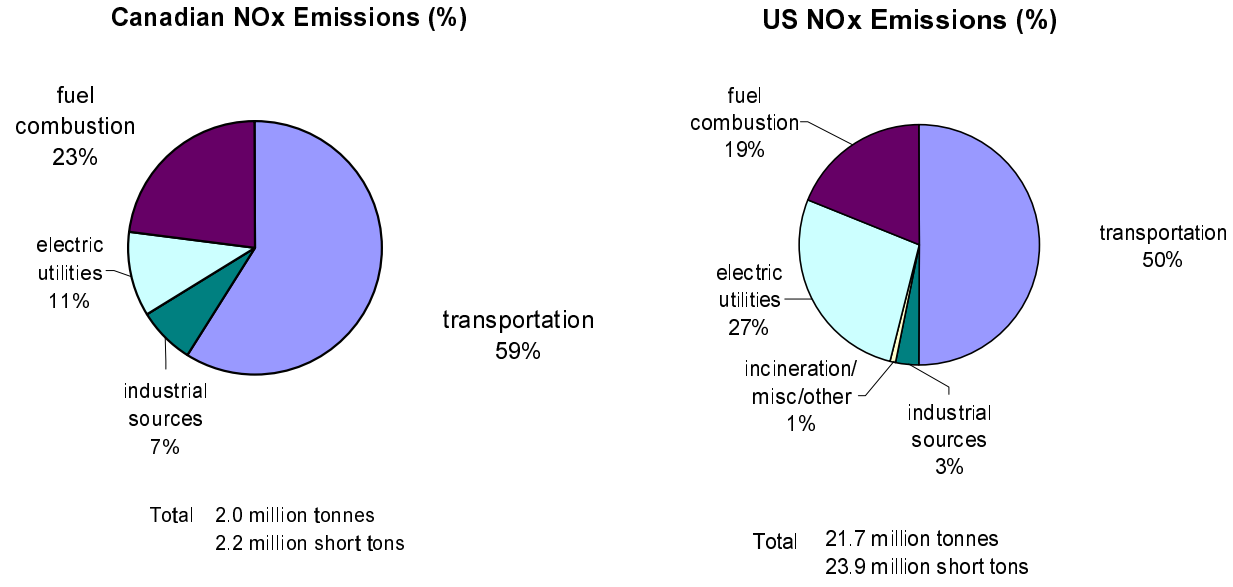


Figure 7. NOx Emissions in Canada and the United States (1995).

Source: Canada-United States Air Quality Agreement 1998 Progress Report, p15.

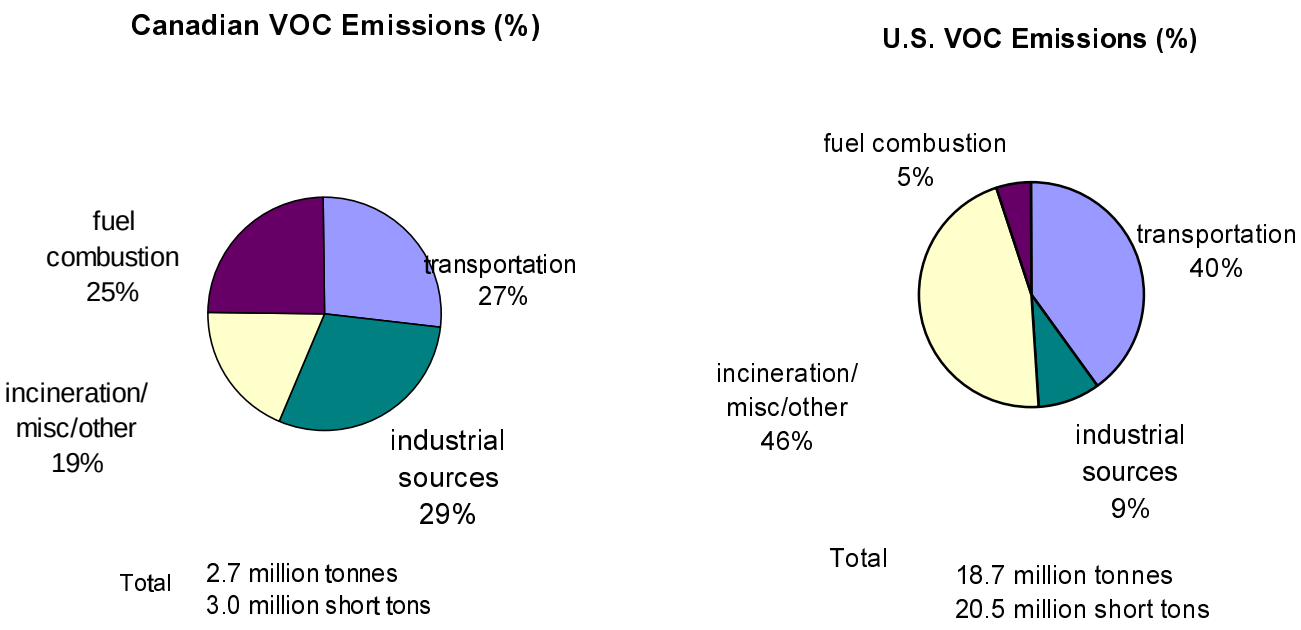


Figure 8. VOC Emissions in Canada and the United States (1995).

Source: Canada-United States Air Quality Agreement 1998 Progress Report, p15.

Although both VOC and NOx emissions contribute to ozone formation, the relative effectiveness of reductions of the two precursors can vary with location and atmospheric conditions. Many publications and reports have examined the impacts of reducing VOCs versus NOx in different urban and regional domains of the United States and Canada (NRC, 1991; OTAG, 1997; Multistakeholder, 1997; CEC, 1997). While the specifics of this situation can be quite complex, the following general conclusions can be reached based on these reports:

1) In urban conditions with relatively low VOC to NOx ratios, anthropogenic VOC reductions can be the most effective strategy for reducing ozone levels; in such conditions, NOx reductions can lead to localised increases in ozone, with decreases in ozone downwind.

2) In conditions with high VOCs relative to NOx, such as downwind of major urban centres, NOx controls may be the most effective strategy for reducing ozone. Due to the day-to-day variability in emission levels, background VOC and NOx concentrations and wind patterns, both NOx and VOC controls may be needed to reduce ozone in particular urban areas.

3) In rural areas of eastern North America, there is an abundance of naturally produced VOCs. In such areas, control of smaller anthropogenic VOC emissions may be ineffective, and NOx controls are an effective control approach.

4) Over a large multi-dimensional region - one that has both urban and rural areas with naturally produced VOCs and anthropogenic NOx emissions transported downwind of urban areas - regional reductions of NOx are the most effective control approach. As shown in this report, the eastern Canada-U.S. border region is such a multi-dimensional region. Therefore, NOx reductions should be the most effective control approach.

The spatial patterns of NOx emission sources in Canada and the United States are shown in Figures 10 and 11. The figures show high NOx emission densities in urban-industrialised areas, although the order of magnitude is different from Canada to the United States.

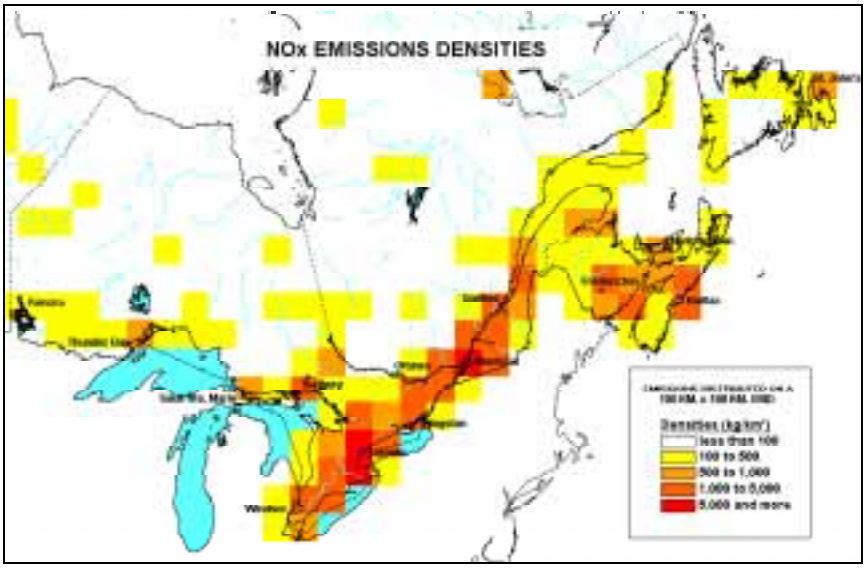


Figure 9. 1995 NOx Emission Densities (in kg/km^2) for Eastern Canada.

Source: Environment Canada Pollution Data Branch.

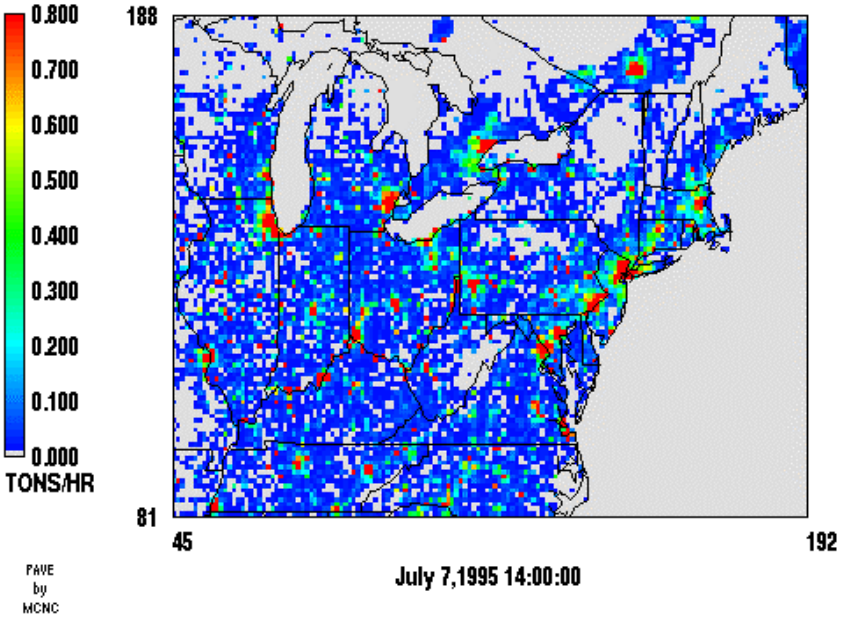


Figure 10. NOx Emission Densities (in tons/hr/grid) in the Eastern United States and Canada. The emissions included on this map for the U.S. reflect the 1995/96 base year emissions that were used in the NOx SIP Call. The emissions for Canada are the 1990 emissions that were used by OTAG.

In the transborder region, the areas of highest emission densities are along the Canada-U.S. border and along the Atlantic coast in the United States. Taken together, these twin corridors of dense population and precursor emissions run from the Southwest to the Northeast, in parallel to weather patterns that frequently occur in the summer. The metropolitan areas along the Canada-U.S. border also have high emission densities of ozone precursors. The following sections present data on transport meteorology, and show the relationship between transport and ozone concentrations within the region.

Ozone as a Function of Wind Speed and Direction

Analysis of ozone a function of wind speed and direction can help provide insight into the relative importance of local and distant sources under varying meteorological conditions. Previous analyses, including those done for OTAG (OTAG, 1997) and for the Canadian Multistakeholder NOx/VOC Science Assessment (Multistakeholder, 1997) indicate that these factors are important influences on the transport of ozone. The series of analyses for the OTAG region has been extended for this report to include Canada to provide more specific insights into transboundary issues (Husar et al., 1999).

In order to analyse the effects of wind speed and direction on ozone concentrations, analysts sorted 11 years of measured ozone concentrations (1989-1996) and averaged for specific wind direction and speed ranges. The average ozone concentration was computed for each wind direction range in 90^{o} increments, starting with 0-90°, i.e. when the wind blew from the North or Northeast. This resulted in four wind directional concentration bins. The average concentrations for each directional bin were further classified by wind speed, ranging between 0-2, 2-4, 4-6, 6-8 metre/second (m/s) increments. Thus, there were four directional and four wind speed bins, yielding a total of 16 concentration bins.

The results of this analysis are presented in maps of average ozone concentration for the four wind directions and three wind speeds - low, medium and high (Figures 11, 12, 13). The detailed results are discussed in a supporting technical paper (Husar et al., 1999).

In summary, average ozone concentration maps at low wind speeds (<3 m/s, Figure 11) show elevated levels of ozone throughout the eastern North American domain. Ozone concentration hot-spots appear over the major metropolitan areas in the United States and the Ohio River Valley but the concentrations are virtually the same regardless of the wind direction. Ozone concentrations in metropolitan areas of Canada are similar to surrounding sites. At intermediate wind speeds (3-6 m/s, Figure 12) the overall concentrations are lower, and the higher ozone concentrations appear to be displaced up to 500 km downwind of the major source areas. At high wind speeds (>6 m/s, Figure 13) most metropolitan source areas do not cause elevated ozone in their own vicinity. Rather, higher concentrations appear in the downwind corners of the eastern North American domain, up to 1000 km from the domain centre.

The ozone concentration pattern at different wind directions and speeds are consistent with an atmospheric ozone lifetime of about one day and a corresponding transport distance of 200, 500 and 800 km at 2, 5, and 8 m/s respectively. Therefore, at low wind speeds, ozone accumulates near precursor emission source areas. Higher wind speeds cause increased dilution of local concentrations and increased transport from one source region to another.

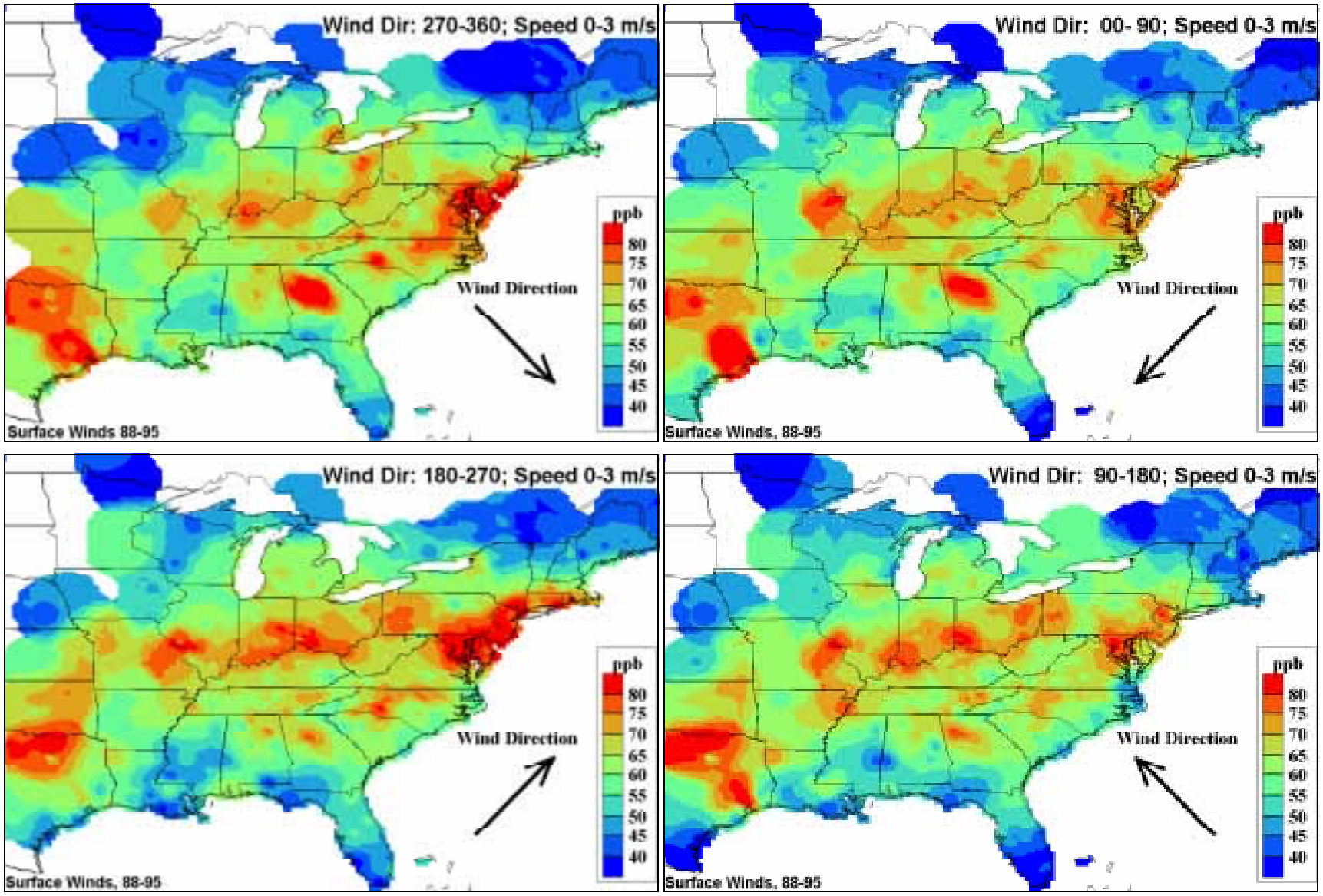


Figure 11. Maps of average ozone concentration at low (<3 m/s) wind speed. a) 270-360 degrees, b) 0-90 degrees, c) 90-180 degrees, d) 180-270 degrees. At low wind speeds, ozone concentrations tend to be somewhat higher just downwind of urban areas. Concentrations tend to be fairly similar, regardless of wind direction. In such cases, local sources likely dominate ozone formation.

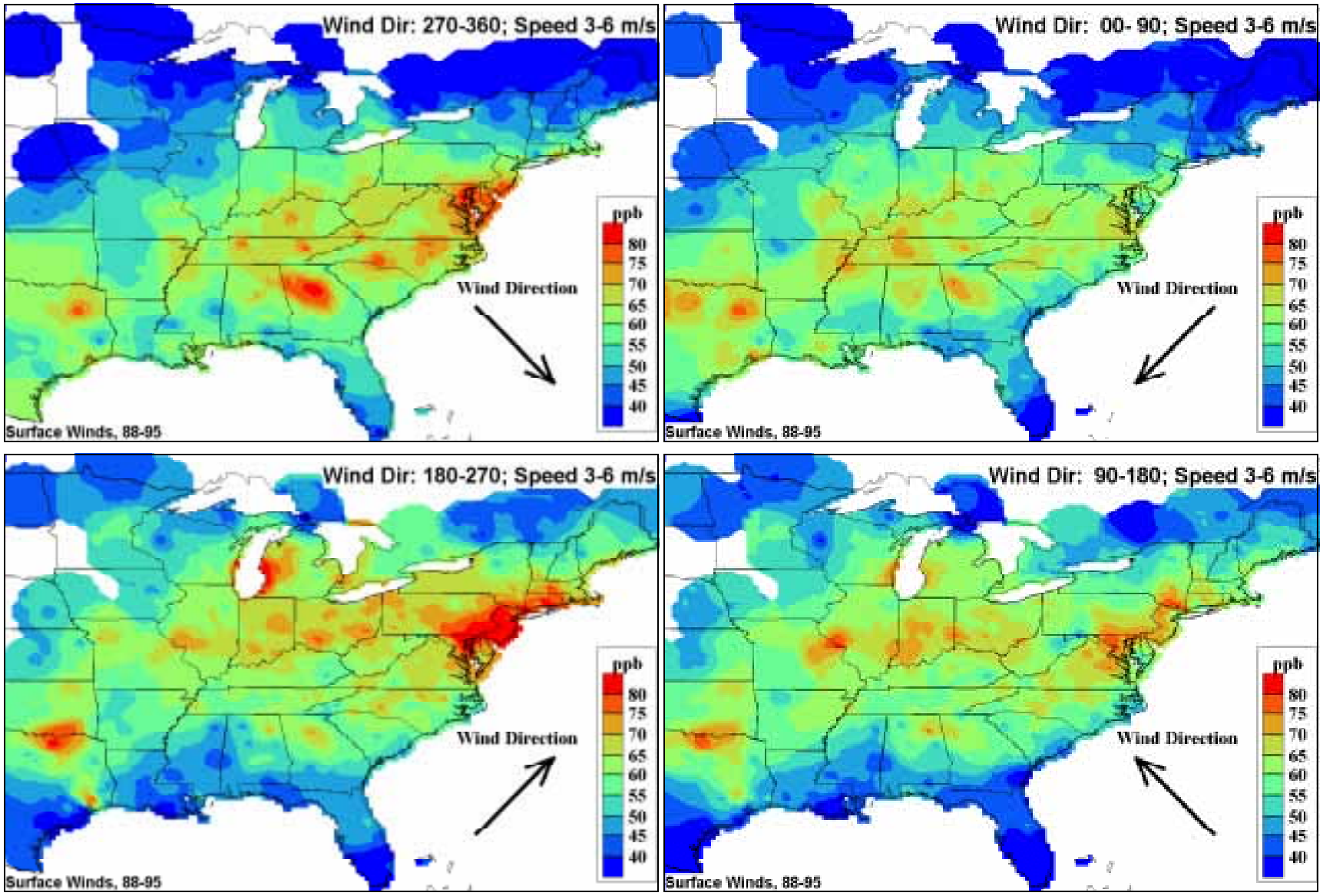


Figure 12. Maps of average ozone concentration at intermediate (3-6 m/s) wind speed. a) 270-360 degrees, b) 0-90 degrees, c) 90-180 degrees, d) 180-270 degrees...At intermediate wind speeds, there are substantial differences between the maps depending on the wind direction. Northerly flows (frames a and b) show low concentrations throughout Canada and the northern United States. Southerly flows result in higher concentrations in the north, especially in the Michigan/Ontario/New York region.

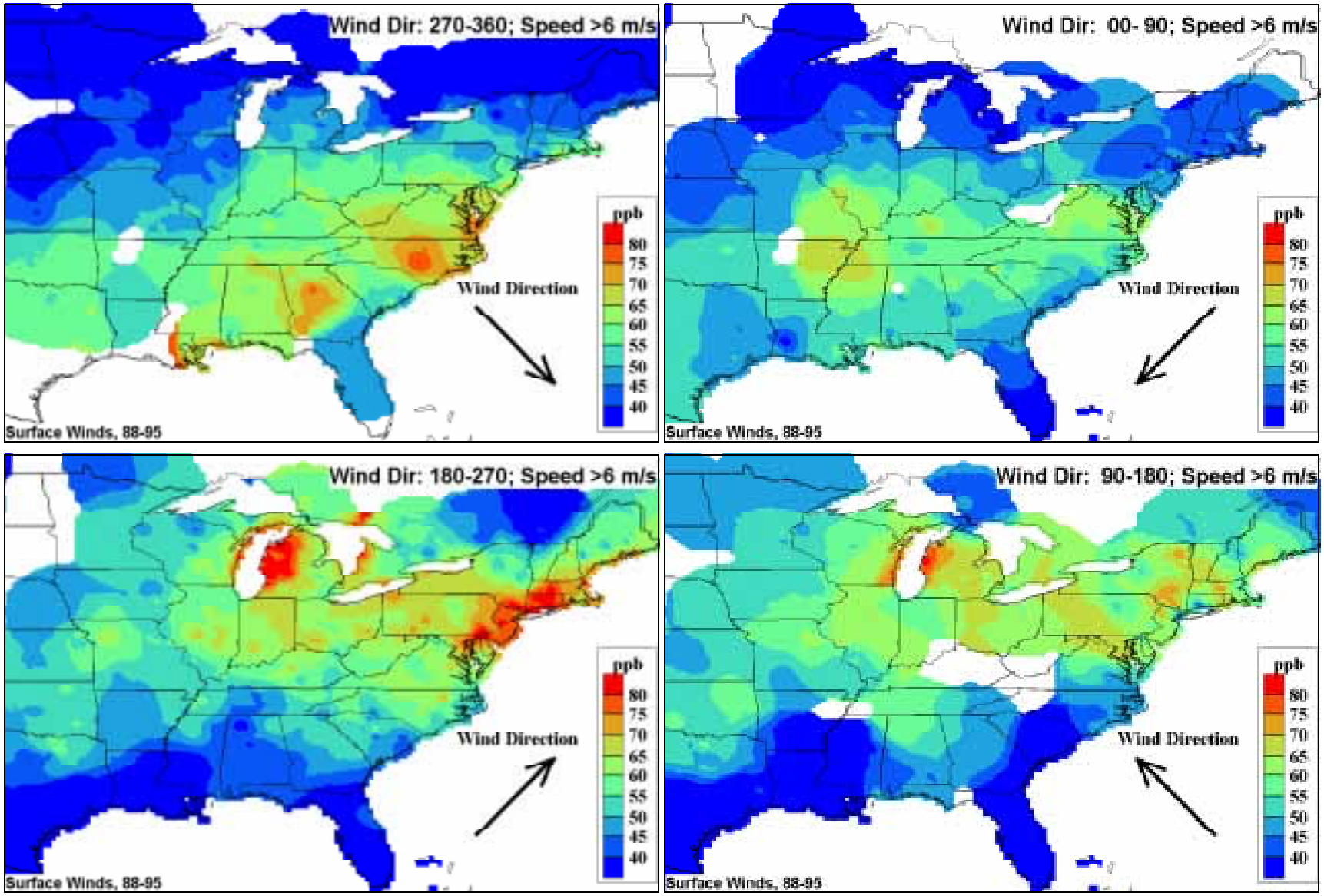
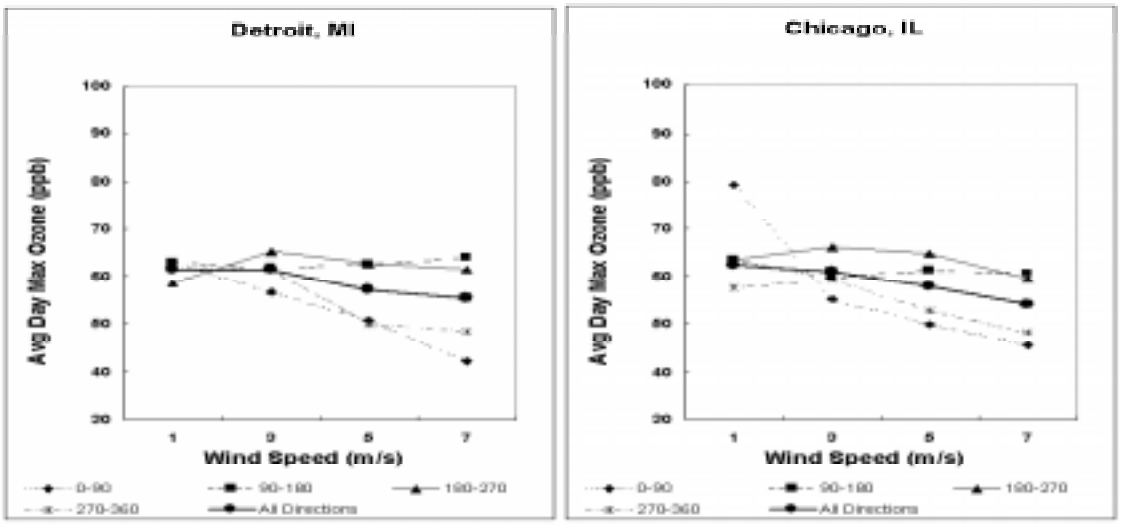


Figure 13. Maps of average ozone concentration at high (>6 m/s) wind speed. a) 270-360 degrees, b) 0-90 degrees, c) 90-180 degrees, d) 180-270 degrees. At high wind speeds, the eastern North American domain appears as a regional domain, although there are still some near-urban areas of elevated ozone.

Graphs of individual urban areas (Detroit, Chicago and Toronto) in the north-central domain show the average ozone concentrations at four characteristic speeds (1,3,5,7 m/s) from wind speed ranges of 0-2, 2-4, 4-6, 6-8 m/s respectively. The data are further stratified by four wind directional quadrants from 0-90 degrees through 270-360 degrees. A fifth line represents wind speed dependence of ozone, regardless of direction.



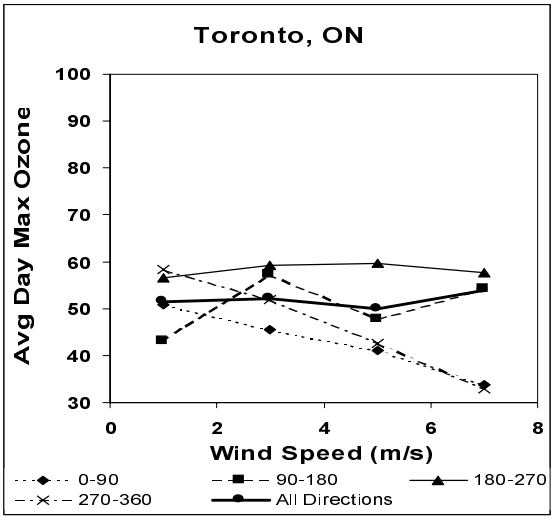


Figure 14. Dependence of ozone concentration on wind speed and direction at different metropolitan areas. The metropolitan areas of Chicago, Detroit and Toronto show a remarkable directionality of the ozone-wind speed dependence. Northerly winds (270-90 degrees) are associated with declining ozone with wind speed. This is interpreted as evidence of substantial local contributions. On the other hand, the wind directions from the centre of the eastern United States are associated with speed-independent ozone levels, implying transported ozone. Taking into account all wind directions, transport is clearly an important component of the ozone problem in each of these areas.

The results for the three urban areas (Figure 14) show remarkable directionality of the ozone-wind speed dependence. For these areas, when the wind blows from the North (270-90 degrees), ozone concentrations decrease with increasing wind speed. This pattern is consistent with locally generated ozone. When the wind blows from the South (90-270 degrees), the graphs show speed-independent ozone concentrations, indicative of levels dominated by transport.

The following section examines the transport of ozone on days of regionally high and low ozone concentrations.

Transport During High and Low Ozone Days

Ozone transport on days of regionally high and low ozone concentrations was also investigated in the analyses conducted for this report. Ozone transport, precursor emissions, and the influence of wind were examined in two ways. First, from the transport climatology, regions were identified where transport conditions are conducive to the accumulation of ozone from local or sub-regional sources, as well as where influence by regional scale transport can be seen. Second, by contrasting the transport conditions during periods of high and low ozone concentrations, unique transport pathways for a given region, as well as common pathways for multiple regions, were identified. The results of this analysis are summarised below and presented fully in a background paper (Schichtel and Husar, 1999).

Transport conditions were established for regionally high (90^{th} percentile) and low (10^{th} percentile) daily maximum 1-hour ozone concentrations. Figure 15 shows source regions of influence (SRI) overlaid with transport wind vectors. The wind vectors convey the direction and magnitude of the air mass transport while the SRIs represent the area encompassing the source impact and resultant air mass transport direction and speed. The SRIs are for the nearest modelled regions to Atlanta, Houston, Chicago, the Ohio River Valley, and New York City. At each source region, the highest and lowest daily maximum ozone values usually occurred on different days. Therefore, the transport conditions at each source region represent transport over different time periods.

Regionally high ozone days (Figure 15A) were associated with slow meandering or recirculating transport over Kentucky, Tennessee, and West Virginia, with strong clockwise transport around this region. It is clear that transport from sources in the southern Great Lakes border region moves from the United States into Canada, over the most dense emission regions of Southern Ontario, and back into New York and the New England States. This flow pattern is consistent with that of a large high-pressure system over eastern North America. The regionally low ozone days (Figure 15B) had northerly flow into Canada from Wisconsin and Michigan that converged over Kentucky and Tennessee with swift westerly-southwesterly flow in the Southeast. In New England, substantial transport occurred in all directions with resultant mass transport to the East.

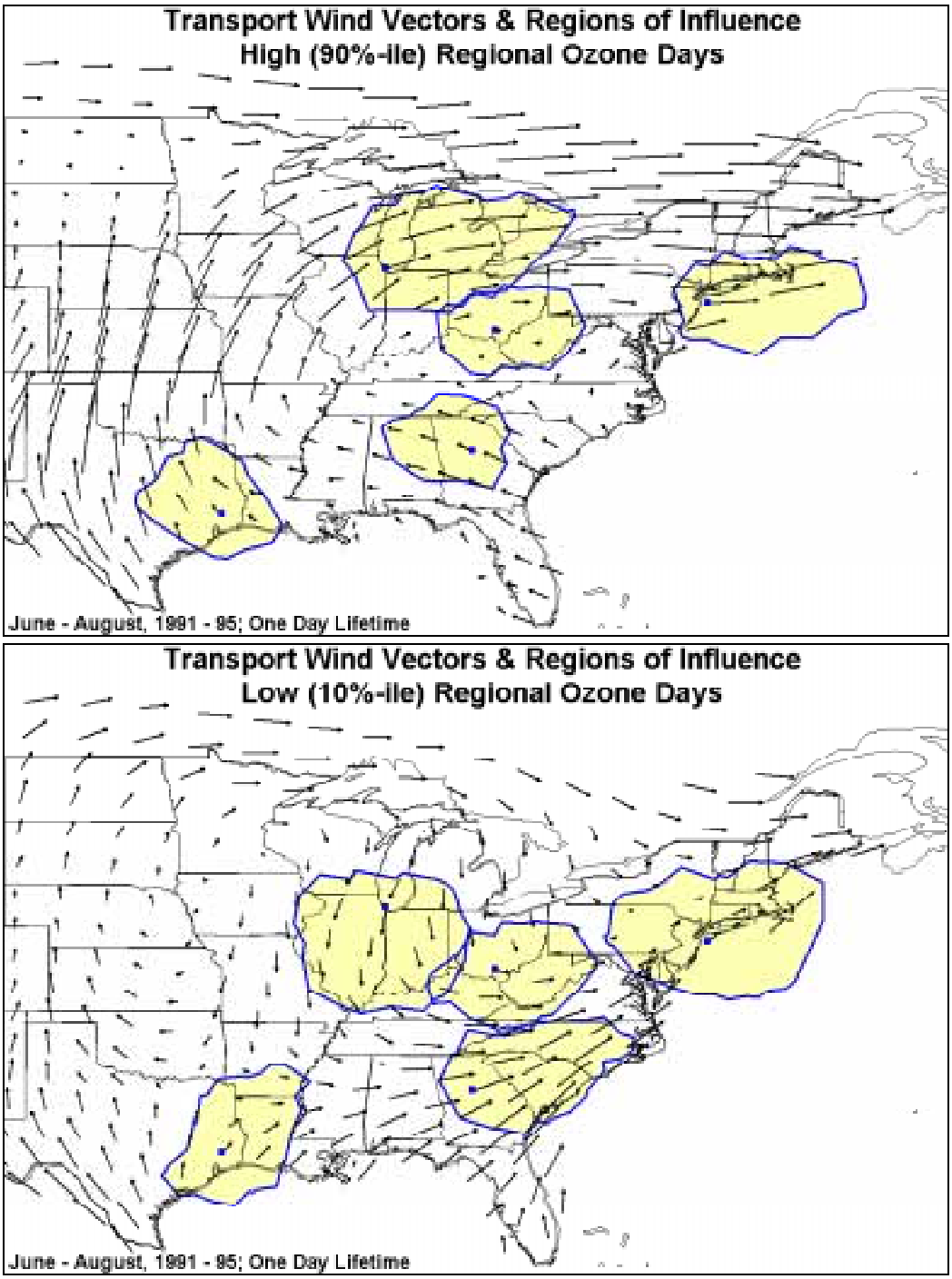


Figure 15. Transport wind vectors and source regions of influence for the highest (A) and lowest (B) 10% of regional ozone days during June – August, 1991 - 1995. Transport vectors in Figure A, regionally high ozone days, show wind speed and directions consistent with regional-scale episode, i.e., strong clockwise transport. There is substantial transport into southern Ontario, particularly from the Chicago source region. Figure B, low regional ozone days, show transport vectors from the Great Plains into the Prairie provinces, east towards southern Ontario and south into the New England states. The New York source region shows substantial transport in all directions, while transport is primarily south in the Chicago source region.

Air Quality Analysis Conclusions

Ozone is not emitted directly, but produced in photochemical reactions involving NOx and VOC emissions. High ozone concentrations occur in and around many of the urban-industrialised areas in the transboundary region in both countries, resulting in frequent exceedences of current and proposed air quality objectives and standards. Elevated concentrations also occur over areas several hundred kilometres downwind of urban areas, causing exceedences of the objectives and standards in relatively less populated non-industrial areas. Some of these exceedences can occur at night as a result of ozone transport.

Transport of ozone and precursors has no boundaries. Polluted air masses can travel across states and provinces and between the United States and Canada. High ozone concentrations are typically located downwind of areas with the highest emissions. In the Canada-U.S. transboundary region, a more uniform pattern of ozone concentrations occurs across the region. The result is a regional "sea" of elevated ozone, extending east from the Mississippi River to the Atlantic coast and north-northeast into the Windsor-Québec City Corridor, New Brunswick, and Nova Scotia, punctuated by "hot-spots" associated with dense emissions areas.

Emissions of NOx in the area were shown to form a boundary around the populated transboundary region, with dense emissions in the Windsor-Quebec corridor, and along the Atlantic coast from New Jersey to Massachusetts. The Ohio River Valley area, dense in precursor emissions, sits at the "entrance" of these twin transboundary emission corridors.

Ozone transboundary flux data, presented in the section on wind speed and direction, illustrate flows in both directions, but are consistent with greater transport of ozone from the United States to Canada than from Canada to the United States. Concentrations along the Detroit-Windsor-Québec City corridor, and eastward, are increased when the wind blows from the "entrance" of the corridor, both towards the northeast, and north-northeast around the Great Lakes and out to the Atlantic.

Increasing wind speeds generally bring about reductions in locally produced ozone concentrations in urban areas. Ozone concentrations in the northeast urban corridor, along the Atlantic coast, are reduced when the ozone and precursor emissions are blown out to sea. For border areas where local concentrations remain constant with wind speed, it appears that the regional transport dominates ozone concentrations. This is observed in several of the urban areas along the border (e.g., Detroit, Windsor, and Toronto) where ozone concentrations were not reduced with increasing wind speeds.

Designing ozone control strategies is complicated because the effectiveness of strategies depends on factors such as meteorological conditions, the absolute and relative amounts of VOCs and NOx, the spatial and temporal distribution of anthropogenic and natural emissions, and background concentrations. The air quality data analysis section discussed the interrelationships between these factors and how each influences ozone concentrations. Some general conclusions can be made, therefore, regarding the effectiveness of strategies in the Canada-U.S. transborder region, based upon the conclusions from earlier reports and the information presented in this report. In the urban areas, a combination of VOC and NOx emission reductions are expected to lead to reductions in high ozone levels locally and downwind. In the areas affected by transport of ozone and precursor emissions, the downwind urban, suburban and rural areas, i.e. the Canada-U.S. transborder region, NOx reductions are expected to be more effective.

The next section presents the results of air quality modelling using Canadian and U.S. data and forecasts of planned reduction program, focusing on NOx emission reductions to show the likely impact of emission control scenarios in the transboundary region.

3. AIR QUALITY MODELLING

EPA and Environment Canada worked jointly to develop an expanded air quality modelling assessment for this report. The major purpose of this modelling was to evaluate the effectiveness of combined illustrative NOx control strategies in reducing regional ozone concentrations, with an emphasis on the transboundary region of concern. As discussed previously, this modelling focuses on NOx controls because NOx reductions are generally more effective in reducing ozone on a regional basis than VOC reductions. The modelling emphasis on the effectiveness of example NOx control strategies is not intended to constrain the range of control options to be discussed in any future negotiations on an ozone annex.

Model Setup and Episodes

The modelling for the assessment of regional strategies consisted of model runs using the Variable Grid Urban Airshed Model (UAM-V). This model was chosen for several reasons. This model has been widely used and generally accepted for policy applications in the U.S. In addition, it was readily available to be adapted for the analyses done for this report. The inputs needed to run the model (e.g., emissions and meteorological data) have been developed for a domain that covers much of the portion of the Canada-U.S. border that is of primary interest. A wide range of stakeholders reviewed these inputs. The configuration of the model used for this report is the same as that used for OTAG. The OTAG final report (OTAG, 1997) describes this in detail and addresses model performance and other issues related to application of the model for purposes of evaluating regional transport.

Modelling was done using the OTAG modelling domain, which includes portions or all of 37 states and the District of Columbia and parts of three Canadian provinces: Ontario, Quebec, and New Brunswick. The domain, therefore, incorporates some but not all areas of concern in eastern Canada and in particular, leaves out the Southern Atlantic Region. Two episodes were selected for evaluation: July 1-11, 1988 and July 7-18, 1995. These episodes were chosen because they represent conditions that suggest interregional transport over the areas of interest.

Emissions

EPA developed emissions for the United States and Environment Canada provided emissions for the Canadian portion of the modelling domain. The U.S. base year emissions are the same as those used for the development of the final rulemaking for the NOx SIP Call. These emissions are based on continuous emissions monitoring data for utilities and OTAG emissions for other sources and have been revised to reflect comments received during the public comment period for the NOx SIP Call. The base emissions for Canada are taken from the official Canadian 1990 National Emissions Inventory developed and compiled by the federal and provincial/territorial governments.

Scenarios Modelled

Two scenarios were modelled: a projected 2007 base case and one control scenario. The base case scenario is intended to represent conditions in 2007 if no emissions reductions occur in either country beyond what is currently mandated. For the United States, the base

case includes growth to 2007 and the application of Clean Air Act mandated controls as well as certain Federal measures that have been or are expected to be promulgated. This base case is described in detail in the final rulemaking for the NOx SIP Call (EPA, 1998). For Canada, the base case includes growth to 2007 and the implementation of actual programs and measures that are described in detail in the National Air Issues Coordinating Committee (NAICC) Base Case Consensus Forecast (NAICC, 1996).

The control scenario was developed to represent potential additional NOx reductions. For the United States, this includes the effects of the NOx SIP Call as shown in Table 2 and described in detail in the final rulemaking for the NOx SIP Call.

TABLE 2. CONTROLS ASSUMED FOR SOURCES IN THE UNITED STATES.

Sources	Controls
Large Electricity Generating Units	0.15 lb NOx/mmBtu, implemented through a regional trading program
Large Industrial Boilers and Turbines	60% reduction from uncontrolled levels
Large Glass Manufacturing Facilities	30% reduction from uncontrolled levels
Large Internal Combustion Engines	90% reduction from uncontrolled levels

For large electricity generating units, 1995 or 1996 heat input was grown to 2007 and the 0.15 lb NOx/mmBtu limit was applied. For the other categories listed in the table, emissions were projected to 2007, any control efficiency that had been applied was removed, and the control efficiency listed above was applied. For all other sources the control case is the same as the base case.

Because the Canadian NOx reduction program is not yet completely defined, the Canadian control scenario was developed as a "what if" case. The control scenario began from the basis of a “25% across the board” emission reduction for the province of Ontario for all sectors for both NOx and VOC from 1990 by 2007. In terms of the Ontario government Smog Plan commitment to reduce NOx and VOC emissions by 45% from 1990 by 2015, an "across the board" 25% reduction by 2007 was considered an appropriate scenario to model. The application of the “25% across the board” premise resulted in emission reductions as shown in Table 3.

TABLE 3. CONTROLS ASSUMED FOR SOURCES IN ONTARIO.

Category	% NOx Reduction from 1990	% VOC Reduction from 1990
Power Generation	25%	0% (Base Case used)
Industrial Sources	25%	25%
Fuel Combustion	25%	3.5% (Base Case used)
Incineration/other	0% (Base Case used)	25%
Transportation	25%	29% (Base case used)

Wherever a reduction in the Table differs from 25%, the base case scenario reduction was used. The rationale for the use of the base case reduction was:

1) few emissions of that pollutant are produced making a 25% reduction unrealistic (as in the case of VOC emissions from power generation where the provincial total in 1990 was 0.4 kilotonnes);

2) the base case forecast reduction for 2007 is already greater than 25% (as in the case of the VOC emissions from the transportation sector); or

3) an assessment was made that technology to meet a reduction of 25% is not available (as in the case of a 25% reduction of VOC from the fuel combustion sector).

For the provinces of Quebec and New Brunswick, the same approach was used for the transportation sector as for the province of Ontario. With respect to the other sectors, the control case reductions were the same as the base case.

For the purpose of evaluating model results, the 2007 control case is compared to the 2007 base case. It is important to understand the difference in emissions between these two model runs in order to analyse properly the model results. The application of the controls described above translates to a 28% reduction in NOx emissions from the 2007 base case in the United States and a 12% reduction in NOx emissions and a 14% reduction in VOC emissions from the 2007 base case in Canada. These overall percent reductions are influenced by two factors. First, the reductions have been applied to some but not all sectors of the inventory in the United States and Canada. Second, in Canada, the control scenario reductions are applied to the 1990 emissions so that when the 2007 control case scenario emissions are compared with the 2007 base case emissions, the level of the reduction is offset by growth and abatement measures that are already incorporated in the base case scenario.

Analysis of Modelling Results

The impacts of emission controls were evaluated by comparing the results of the base case run with the results of the control case run. Using the results in a comparative sense alleviates some of the concerns with uncertainties in absolute predictions. The 1-hour and 8-hour base case ozone predictions are shown in Figures 16 and 17, respectively. (These Figures and the ones that follow have been cropped so that they do not show the entire OTAG modelling domain but focus on the transboundary area of concern.) The change in the extent of values above the standards or objectives indicates the improvements in air quality due to the reduction in NOx emissions. This can be seen by looking at the difference in concentrations between the base case and control case. Figures 18 and 19 show the composite decrease in ozone concentrations throughout the area of interest. The decreases shown in these figures represent the maximum reduction in each grid over the two episodes modelled. These figures show that the controls assumed in the modelling runs result in a 2-10 ppb reduction in 1-hour and 8-hour ozone concentrations over nearly the entire area. For a large portion of the domain, particularly for the Ohio River Valley and surrounding areas in the United States, southern Ontario, and Sudbury, Canada, the reductions in 1-hour and 8-hour ozone concentrations are predicted to be greater than 14 ppb.

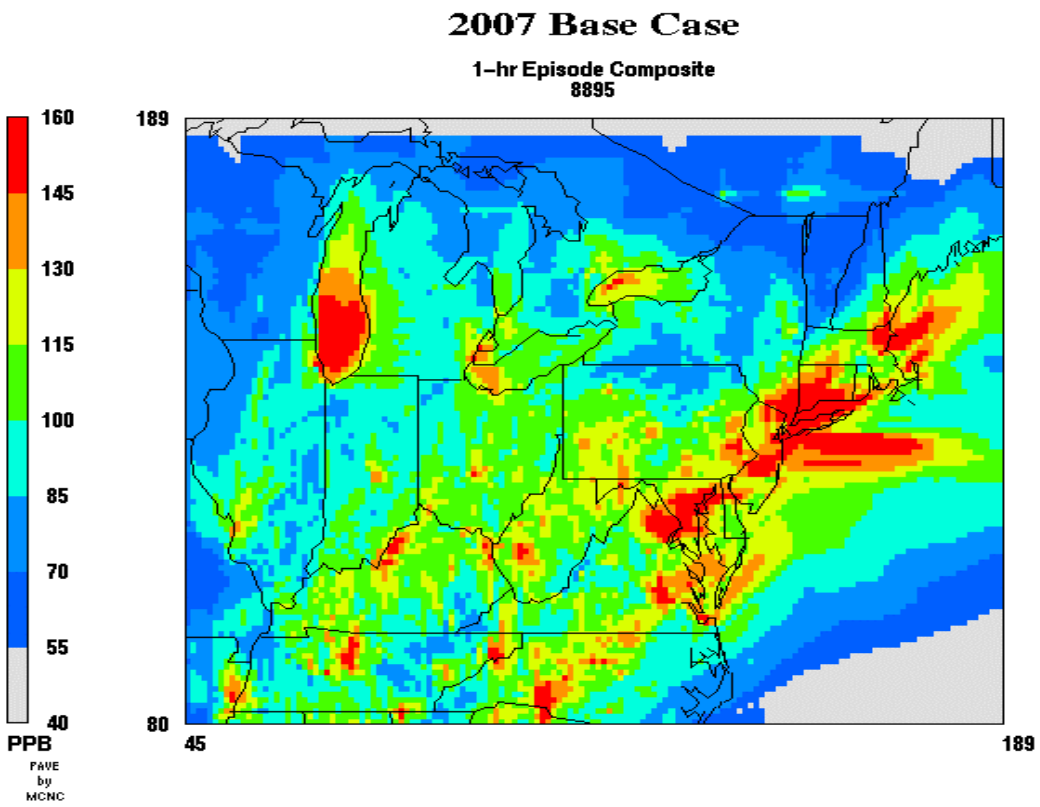


Figure 16. 2007 Base Case Episode Composite 1-hr Ozone Concentrations.

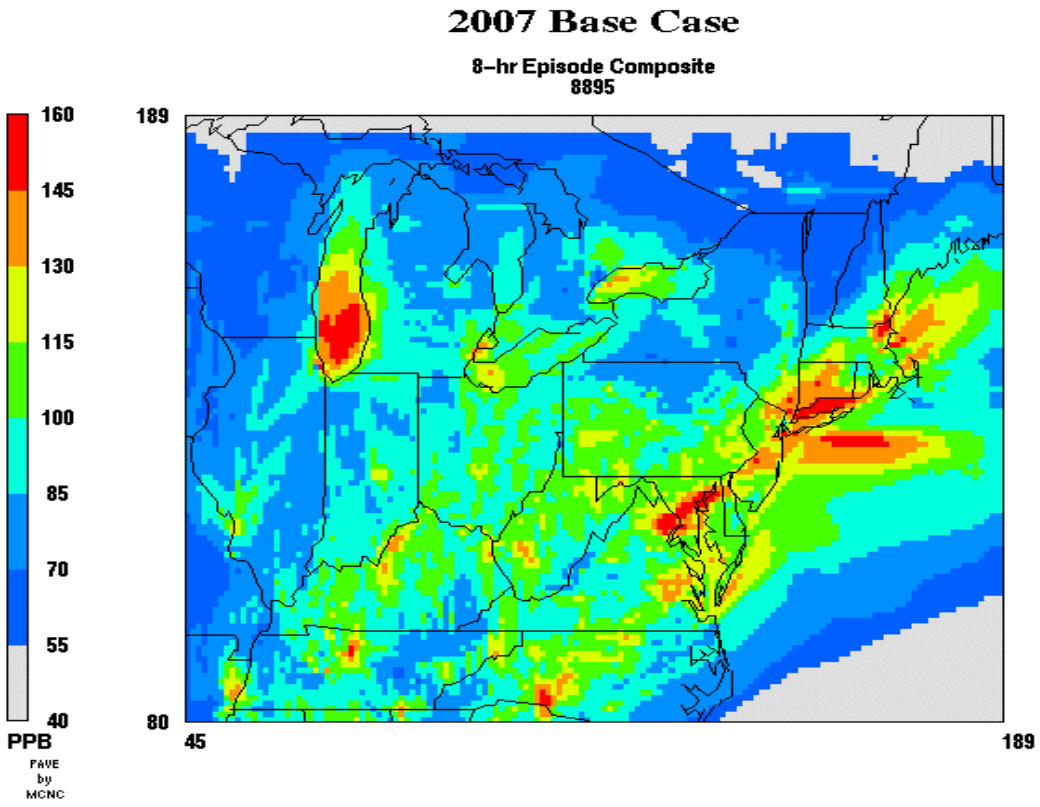


Figure 17. 2007 Base Case Episode Composite 8-hr Ozone Concentrations.

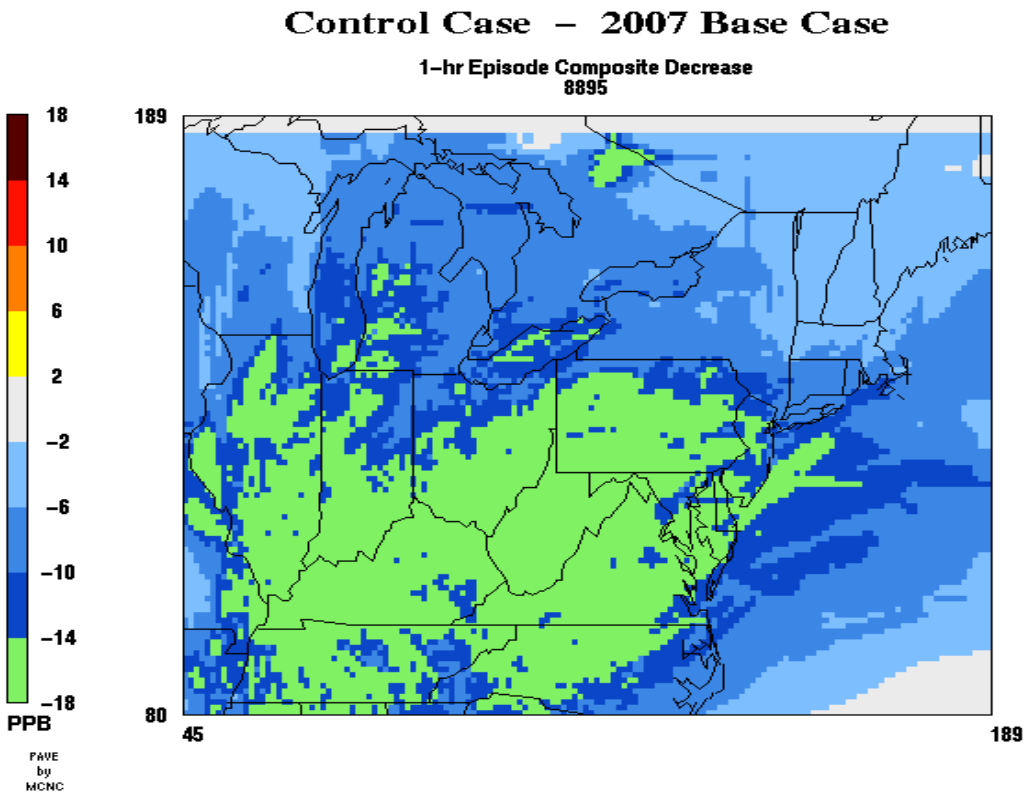


Figure 18. Episode Composite Decrease in 1-hour Ozone Concentrations Between the Base Case and the Control Case.

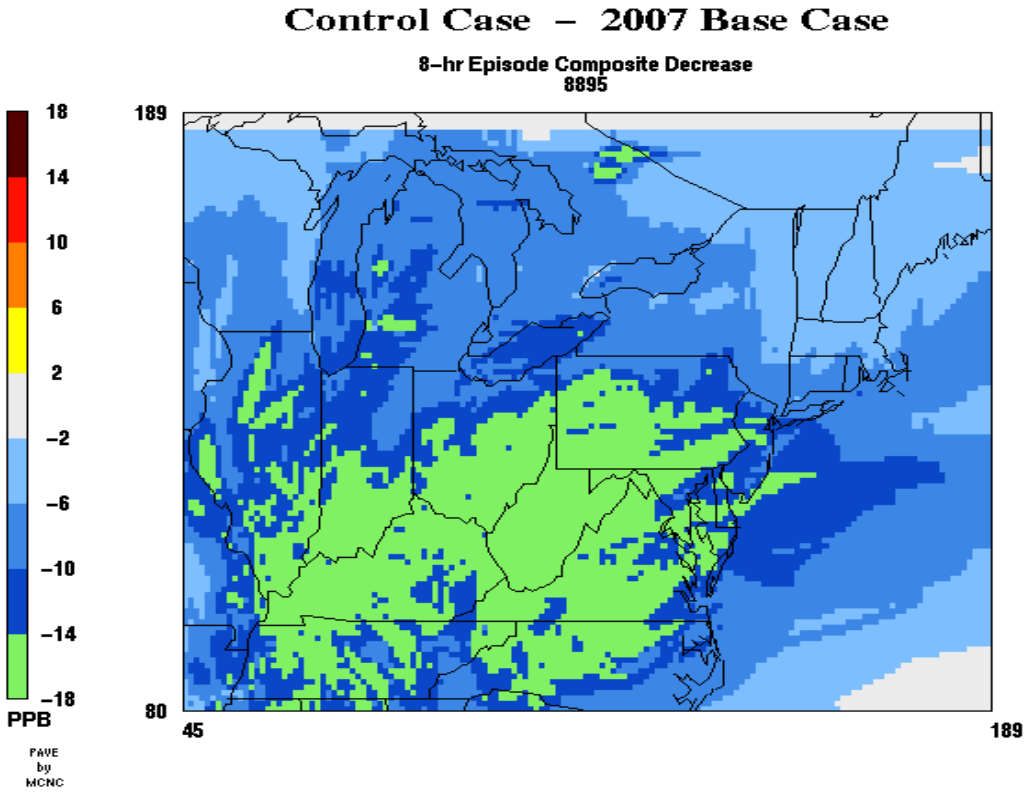


Figure 19. Episode Composite Decreases in 8-hour Ozone Concentrations Between the Base Case and Control Case.

In order to evaluate whether the reductions shown in Figures 18 and 19 are occurring in the areas of concern, the predicted maximum decreases that occur in areas that are above specified threshold levels in the base case were examined, along with predicted maximum increases in these areas. Figures 20 and 21 show these results for the thresholds considered. In these figures, the magnitude of decreases or increases is indicated using the colour scale shown at the left of each figure. The white areas on the maps indicate areas where the base case predicted ozone concentration is below the specified threshold. The grey areas indicate areas where the predicted base case ozone concentration is above the threshold, but there are no decreases or increases above 2 ppb. The thresholds chosen were 82 ppb for 1-hour values, which is the level of the current Canadian objective and 85 ppb for 8-hour values, which is the level of the current US 8-hour standard.

The results for the 1-hour 82 ppb and 8-hour 85 ppb thresholds are similar, although the geographic extent of reductions is somewhat smaller. Decreases are in the range of 10-14 ppb and higher in a broad area in both the United States and Canada. Increases are similar in magnitude and location in both cases.

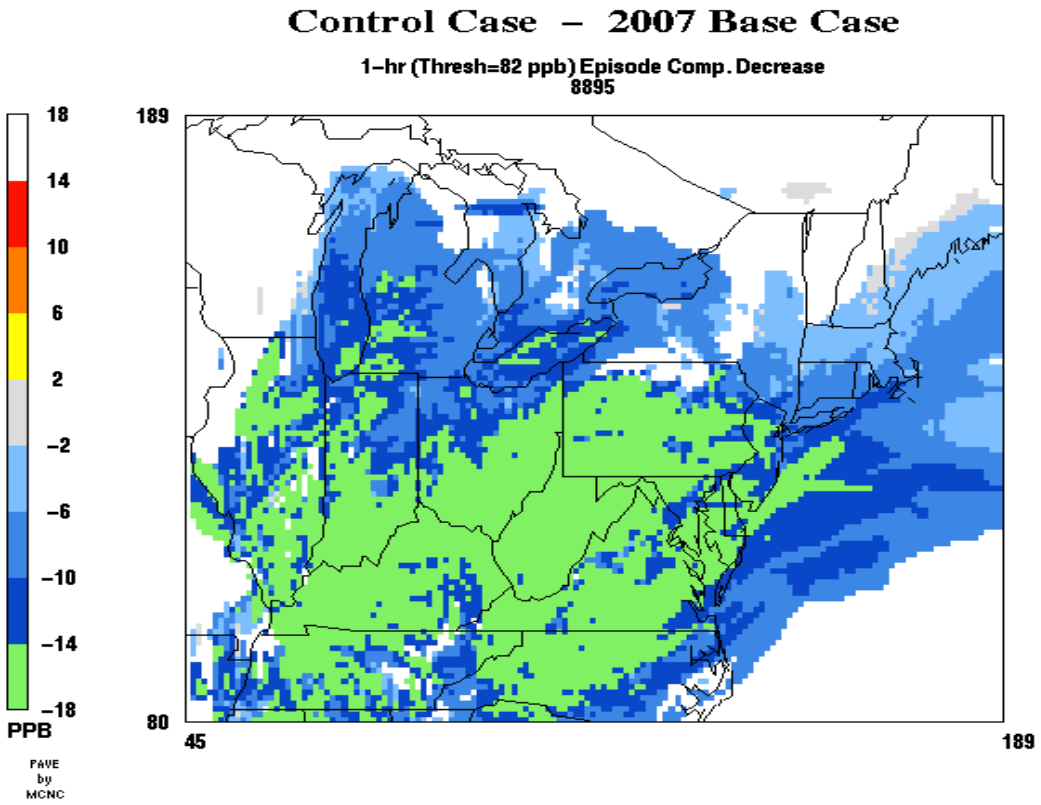
Air Quality Modelling Conclusions

The results of the model runs show that there are substantial benefits to controlling NOx emissions in the United States and Canada. In the 2007 base case, without any additional controls, predicted ozone concentrations exceed the Canadian 1-hour objective and the U.S. 8-hour standard in a large portion of the modelling domain. The assumed reductions forecast for 2007 result in both 1- and 8-hour episode reductions of 6 to over 14 ppb ozone in a corridor from Michigan/western Ohio/southwestern Ontario to New York and eastern Ontario. Reductions of 2 to 6 ppb occur in New England states and Quebec. When the evaluation of the results is restricted to only those areas that are above specific thresholds in the base case, there are still benefits in the 6-14 ppb range and higher in many areas. The geographic extent of the benefits that are seen depends on the threshold that is chosen.

The benefits tend to be larger in the United States. This may be due, in part, to the fact that the emission reductions in the United States are larger both in term of percentage and total mass. The NOx SIP call strategy that was modelled for the United States results in a 28% reduction in NOx and the scenario modelled for Canada results in a 12% reduction in NOx and a 14% reduction in VOC. A control scenario in Canada that resulted in higher percentage reductions would increase the benefits that would be seen in Canada and the border region. Although the results also show predicted increases in some areas, they are more limited in geographic extent and are offset by the larger benefits. In fact, the benefits may be even greater than is indicated because of the limitation of the modelling domain with respect to Canada's Southern Atlantic Region and parts of the Windsor-Québec City Corridor.

In addition, there are other non-ozone benefits that can be expected from widespread NOx reductions. Decreases in NOx emissions will also decrease acid deposition, nitrates in drinking water, excessive nitrogen loadings to aquatic and terrestrial ecosystems, and ambient concentrations of nitrogen dioxide, particulate matter, and toxics.

A



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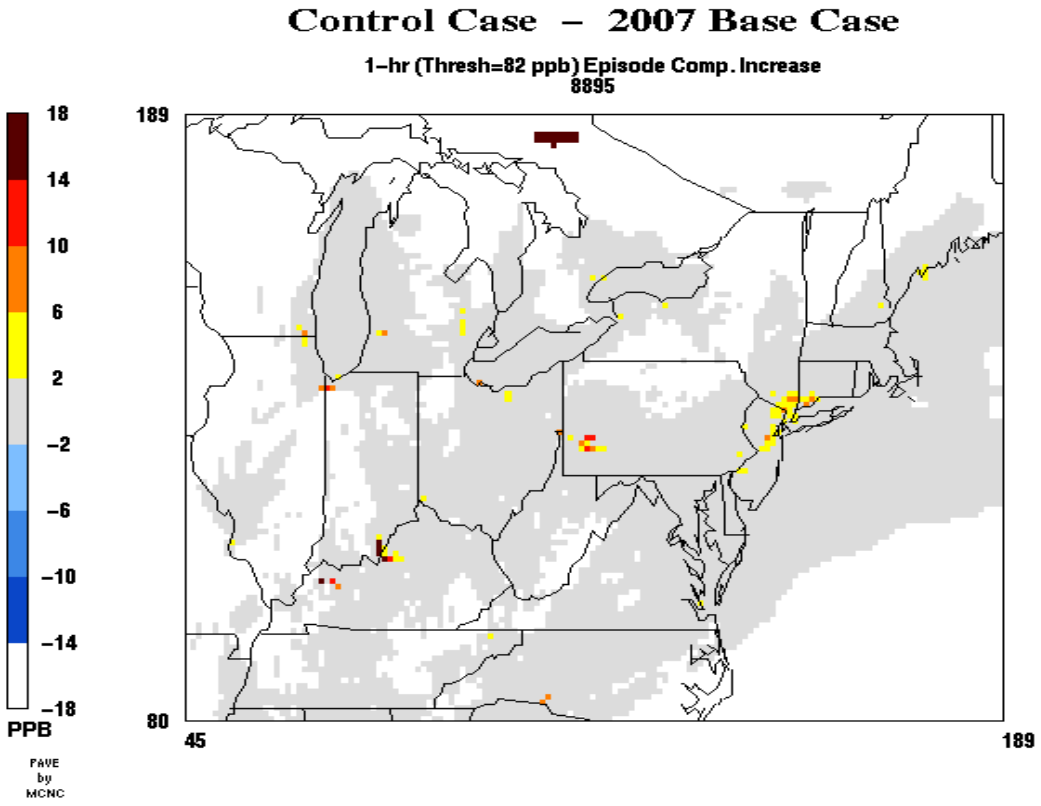
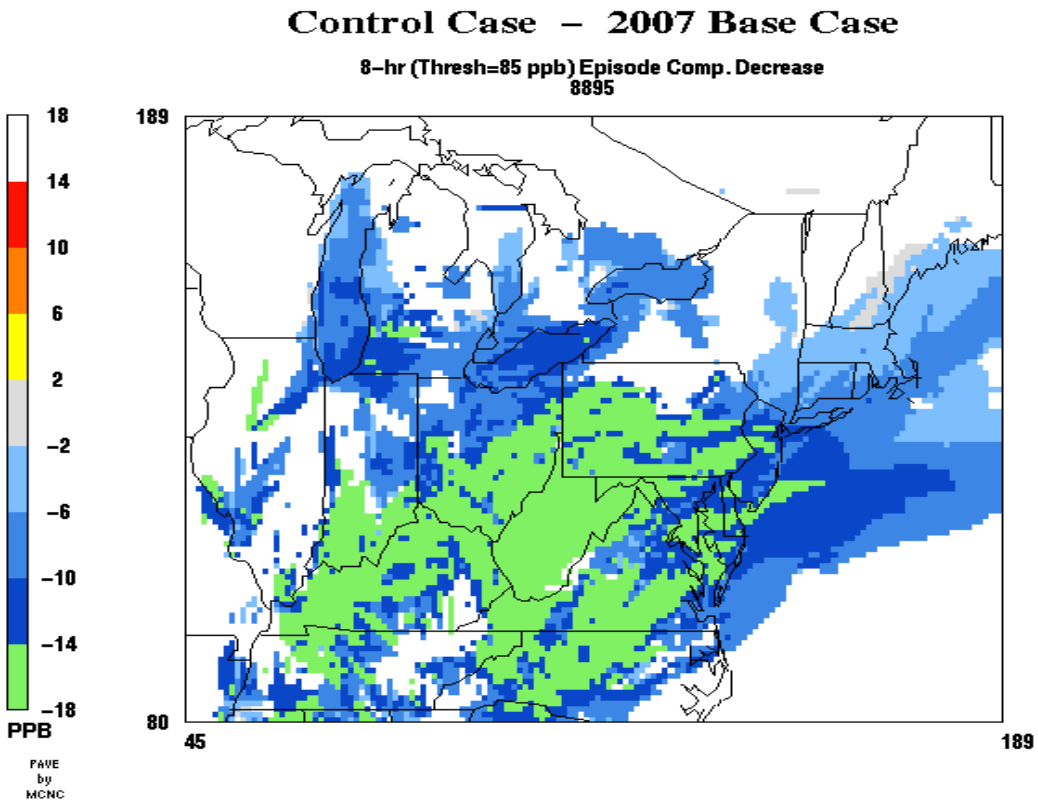


Figure 20. Predicted Maximum A) Decreases and B) Increases in 1-hr Ozone Concentrations in Areas >= 82 ppb in the Base Case.

A



B

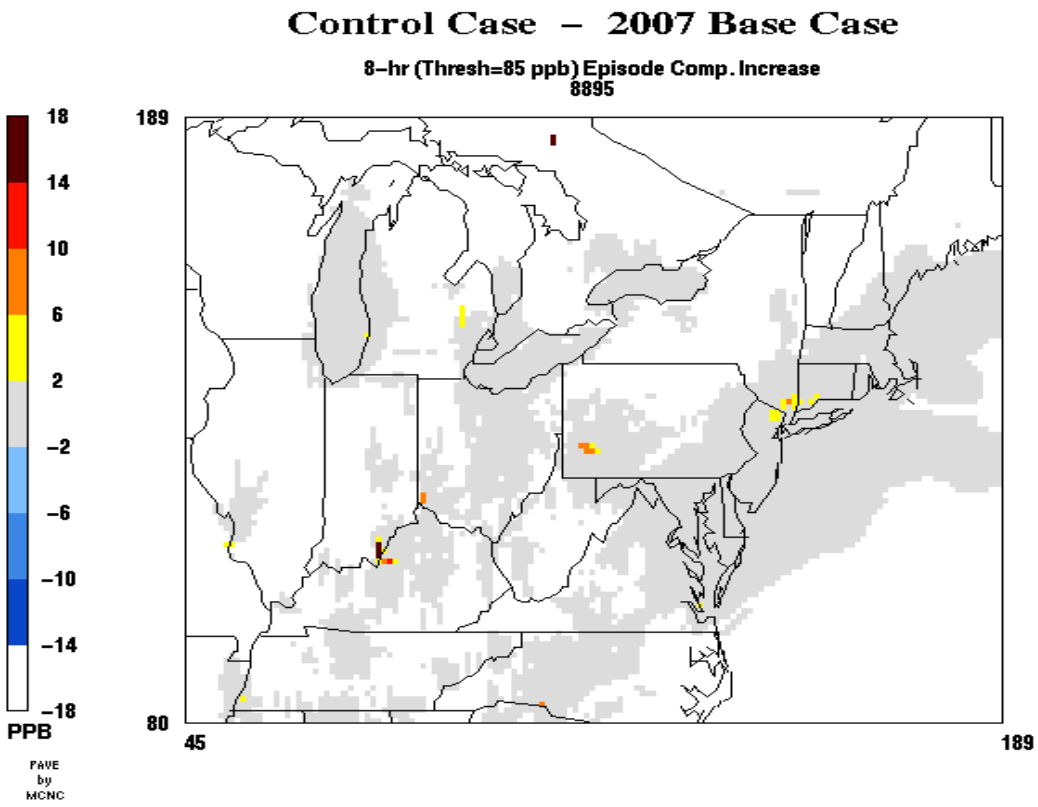


Figure 21. Predicted Maximum A) Decreases and B) Increases in 8-hr Ozone Concentrations in Areas >= 85 ppb in the Base Case.

4. POLICY CONCLUSIONS RELEVANT TO THE CONSIDERATION OF AN OZONE ANNEX BY THE CANADA-U.S. AIR QUALITY COMMITTEE

In eastern North America, ozone levels that exceed established and proposed norms often occur in large-scale regional episodes that do not respect political borders. Ozone is a reactive respiratory irritant and is associated with decreases in lung function, aggravation of respiratory disease, increases in hospital admissions and related health effects. Ozone also causes damage to forested ecosystems and agriculture. Furthermore, precursors that form ozone include substances that cause or contribute to acid rain and eutrophication of sensitive estuaries as well as toxic organic air pollutants.

This document presents results of cooperative efforts to analyse ozone transport in eastern North America. The approaches taken in the analyses represent an extension into the transboundary area of concern of analytical techniques, methodologies, and tools already being used in both countries to address domestic air pollution. They include integrated air quality data analyses of patterns and episodes, consideration of emissions patterns together with analyses of ozone as a function of changing meteorological conditions and transport climatology, and finally, joint modelling of regional scale ozone transport and responses to control scenarios.

These technical analyses clearly demonstrate the connections between emissions, transport, and ozone occurrences on both sides of the border. These results strongly support the common-sense conclusion that coordination of planning and execution of control strategies for ozone precursors (NOx and VOC) for all source categories would be more beneficial than individual initiatives.

The United States has made major steps forward in addressing air quality in general and ozone in particular in recent years. Significant progress has been made in implementing the provisions of the 1990 Clear Air Act Amendments with respect to ozone precursors. The U.S. Air Quality Standards for ozone and particulate matter in air have been revised and tightened. The Ozone Transport Assessment Group (OTAG) successfully completed intergovernmental negotiations on ozone transport among 37 states. Finally, EPA has finalised a rule concerning revisions to State Implementation Plans (SIPs) in 22 States and the District of Columbia to respond to ozone transport through reductions in NOx emissions by 2007. Further actions are planned with respect to fuel sulphur and vehicular emissions.

In Canada, there have been similar efforts on air quality and ozone. The first and second phases of the NOx/VOC management program are complete with substantial programs for major sources of NOx and VOC nationally and in key problem regions aimed at achieving the current Canadian air quality objective of 1-hour 82 ppb. The Phase 3 Federal Smog Plan is underway for both ozone and inhalable particles and the Ontario Smog Plan is being implemented to reduce provincial emissions of NOx and VOC by 45% from 1990 levels by 2015. New sulphur in gasoline regulations are being promulgated and action on vehicular emissions are planned. Finally, Canadian governments are now engaged in developing, for the first time, Canada-Wide Standards and implementation plans for ozone and particulate matter in air.

The air quality data analyses conducted for this report focused on determining the pattern of transport in the transboundary area of concern in the eastern United States and Canada. The results indicate that long-range transport of ozone and its precursors significantly influences the magnitude and persistence of high ozone concentrations in eastern North America. Air masses from the United States contribute to high ozone concentrations in Ontario, Quebec, New Brunswick and Nova Scotia. When winds blow from Canada, the southern shores of Lake Erie and the eastern shores of Lake Ontario experience high ozone levels. Due to the relative amounts of emissions in each country and the prevailing winds during the summer ozone season, more ozone and precursors flow north-northeast from the United States into Canada than south-southeast from Canada into the United States.

The extended regional air quality modelling conducted for this report demonstrates the effectiveness of illustrative joint precursor emission reduction strategies on ozone concentrations in the United States and Canada. The modelling indicates that there are substantial transboundary regional benefits to controlling NOx emissions in the United States and Canada. The assumed reductions forecast for 2007 result in both 1- and 8-hour episode reductions of 6 to over 14 ppb ozone in a corridor from Michigan/western Ohio/southern Ontario to New York and eastern Ontario. Reductions of 2 to 6 ppb occur in New England states and Quebec. Although not part of the modelling domain, it can be expected that there would also be reductions in ozone concentrations in the Southern Atlantic Region of Canada. While these analyses did not attempt to examine reduced acid deposition, nutrient loadings, and particulate matter levels that would accompany such strategies, these corollary improvements would certainly add to the total benefits of these example strategies.

The spatial and temporal patterns exhibited in the analyses of empirical air quality and emissions data are qualitatively consistent with the results of the air quality modelling analyses. Taken together, these results offer clear evidence of the rationale for discussing an effective bi-national approach for management of ozone and its precursors in eastern North America.

5. REFERENCES

AQC, 1994. *United States-Canada Air Quality Agreement: 1994 Progress Report*, Air Quality Committee. (This report is also known as the Canada-United States Air Quality Agreement: 1994 Progress Report.)

AQC, 1996. *Canada-United States Air Quality Agreement: 1996 Progress Report*, Air Quality Committee. (This report is also known as the United States-Canada Air Quality Agreement: 1996 Progress Report.)

AQC, 1998. *Canada-United States Air Quality Agreement: 1998 Progress Report*, Air Quality Committee. (This report is also known as the United States-Canada Air Quality Agreement: 1998 Progress Report.)

CCME, 1990. *Management Plan For Nitrogen Oxides and Volatile Organic Compounds*, Canadian Council of Ministers of the Environment (CCME).

CCME, 1994. *Management Plan: Status Report 1994*,,Canadian Council of Ministers of the Environment (CCME).

CEC, 1997. *Continental Pollutant Pathways: An Agenda for Co-operation to Address Long Range Transport of Air Pollution in North America*,,Commission for Environmental Co-operation.

Dann, T., 1999. *Ozone, NOx and VOC Analysis 1989-1996*,,Environment Canada, Environmental Technology Centre.

EPA, 1998. "*Finding of Significant Contribution and Rulemaking for Certain States in the Ozone Transport Assessment Group Region for Purposes of Reducing Regional Transport of Ozone*," 63 FR 57356.

Husar, et al., 1999. *Ozone as a Function of Local Wind Speed and Direction: Evidence of Local and Regional Transport*,,R.A. Husar, W.P. Renard, B.A. Schichtel, http://capita.wustl.edu/CAPITA/CapitaReports/O3FncOfWind/html/O3asFncWnd.html.

IJC, 1998. *Special Report on Transboundary Air Quality Issues*,,International Joint Commission.

Multistakeholder, 1997. *Canadian 1996 NOx/VOC Science Assessment.* Multistakeholder NOx/VOC Science Program, Environment Canada.

Ground-Level Ozone and Its Precursors,,1980-1993-Report of the Data Analysis Working Group

Modelling Of Ground-Level Ozone in the Windsor-Quebec City Corridor and in the Southern Atlantic Region - Report of the Windsor-Quebec City Corridor and Southern Atlantic Region Modelling and Measurement Working Group

Modelling of Ground-Level Ozone in the Lower Fraser Valley - Report of the Lower Fraser Valley Modelling and Measurement Working Group

Summary for Policy Makers: A Synthesis of the Key Results of the NOx/VOC Science Program

NAICC, 1996. *NAICC National Base Case Consensus Forecast*,,presented to the NAICC in May 1996. http://www2.ec.gc.ca/pdb.eft/eft.html.

NRC, 1991. *Rethinking the Ozone Problem in Urban and Regional Air Pollution*,,National Research Council.

OTAG, 1997. "*OTAG Technical Supporting Document*," http://www.epa.gpv/ttn/otag/finalrpt.

Schichtel and Husar, 1999. *Eastern North America Transport Climatology During Average, High and Low Ozone Days*,,B.A. Schichtel, R.B. Husar, http://capita.wustl.edu/CAPITA/CapitaReports/NAMTrnsClim/html/NamTrnsClim.html.