J4.18 ATMOSPHERIC EMISSION REDUCTION SCENARIOS SIMULATED BY CANADIAN AURAMS MODEL

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1. INTRODUCTION

The federal and provincial governments of Canada, committed to protecting the environment and public health, consider air pollution to be one of the most important environmental issues for Canadians. The overall objective of this study is to determine the impact of current emission reduction programs (Canada-USA) on air quality in the province of Quebec and provide the public and decision makers with information on their benefits and on future actions needed to improve the regional air quality. Both a current atmospheric emission inventory and estimate for the future are needed to validate current policies aimed at improving air quality. The first complete AURAMS (**A** **U**nified **R**egional **A**ir-quality **M**odelling **S**ystem) version was used for emissions reduction scenario applications. AURAMS is a new, size-resolved, chemically characterized, episodic regional particulate-matter (PM) modelling system being developed by the Meteorological Service of Canada for air quality research and management.

2. EMISSION REDUCTION SCENARIOS

Several emission reduction scenarios were run for selected episodes of the summers of 1999 and 2001 based on the current commitments of the governments of Canada and the United States valid for 2010 and 2020. The simulations consist of reduction of the anthropogenic emissions of smog precursors in the transportation sector, and scenarios included in the Ozone Annex of the Canada-United States Air Quality Accord.

The Control run considers all emissions sources without reduction, based on the 1995-1996 national inventories, and will serve for comparison with the other reduction scenarios for the evaluation of the impact on air quality.

The Base case and Scenario3 include on-road emissions reduction valid for 2020. The Base Case includes light duty vehicle Tier 1 program and National Low Emission Vehicle (NLEV) starting in 2001. The Scenario 3 represents the combined effect from Base Case + light duty Tier 2 program; + 2004 heavy-duty NMHC (Non-Methane hydrocarbon)+ NO_x standards;+ 2007 heavy-duty particulate matter (PM), NO_x and low sulphur on-road diesel. These reductions are applied to some Canadian Provinces and the United States. They were prepared by SENES Consultants Limited (Canada) (SENES, 2001) analyses which estimate on-road particulate matter (PM_{10} and $PM_{2.5}$), VOC, CO, NO_x and SO_2 emissions throughout all Canadian provinces, from 1995 to 2020. The emission forecasts incorporate the effects of all confirmed Canadian regulations to date, including the use of reduced gasoline and diesel sulphur levels and Natural Resources Canada (NRC) latest estimates of the growth in vehicle kilometres travelled by vehicle class for each Province. The equivalent scenarios from US-EPA valid in 2020 also were included (EPA, 2000).

The regulations include the effect from Tier 1 and Tier 2 standards, defined for light-duty vehicles in the Clean Air Act Amendments (CAAA) of 1990. The Tier 2 Vehicle and Gasoline Sulfur Program is a landmark program that affects every new passenger vehicle and every gallon of gasoline sold in the U.S. The Tier 2 standards were phased-in beginning in 2004. The Tier 2 Vehicle and Gasoline Sulfur program is part of a series of major initiatives that will reduce emissions from passenger vehicles, highway trucks and buses, and nonroad diesel equipment. The reduction applied on mobile sources for the Base case and Scenario 3 are presented in Table1.

The BaseCase+O_3 Annex and Scenario 3+O_3 Annex take in consideration the mobile reductions previously discussed plus the current Ozone Annex commitments of the governments of Canada and the United States for 2010.

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Table1. On-road vehicle emission reductions valid for 2020; a) Base case and b) Scenario 3

a) Base case

Pollutant / Canadian Provinces; US	NO_x	VOC	SO_2	$PM_{2.5}$
Northern Quebec	35%	67%	9%	50%
Southern Quebec	46%	73%	38%	51%
Northern Ontario	46%	65%	30%	61%
Southern Ontario	58%	74%	64%	61%
New Brunswick	44%	70%	12%	53%
Nova Scotia	45%	72%	21%	52%
Prince Edward Island	47%	69%	17%	58%
United States	78%	59%	88%	69%

b) Scenario 3

Pollutant / Canadian Provinces; US	NO_x	VOC	SO_2	$PM_{2.5}$
Northern Quebec	86%	73%	93%	85%
Southern Quebec	86%	77%	92%	81%
Northern Ontario	89%	70%	93%	88%
Southern Ontario	90%	78%	92%	82%
New Brunswick	86%	75%	91%	85%
Nova Scotia	86%	77%	90%	83%
Prince Edward Island	81%	73%	91%	83%
United States	78%	59%	88%	69%

The Ozone Annex was negotiated to reduce the transboundary movement of smog-causing pollutants to better protect human health and the environment and commits both countries to control and reduce emissions of Nitrogen Oxides (NO_x) and Volatile Organic Compounds (VOC) which are precursors of ground-level ozone, a major component of smog. The Ozone Annex defines an area in each country that is the source of transboundary flow of ozone precursors where the commitments in the Annex will apply. This zone is called Pollution Emission Management Area (PEMA). In Canada, the PEMA includes central and southern Ontario and southern Quebec. In the United States, it includes 18 states of the Northeast and the District of Columbia. These regions represent about 40 percent of the population of the United States and over 50 percent of the population of Canada. The reductions enforced by this agreement are presented in Table2.

Table2. Ozone Annex emission reductions

Pollutant / Canadian Provinces; US	NOx	VOC
Quebec	44%	20%
Ontario	45%	45%
United States	43%	39%

The specific reductions aimed at fossil fuel power plants in the United States were not considered in this study. It shall be noted that the results of the reductions of the mobile on-road sector are included in the ozone Annex. In some states and provinces, it happens that the on-road reductions account for the whole ozone annex reductions so that no further reductions are needed in other sectors such as point sources and area sources. These two scenarios can be summarised as follow: The Base Case+O_3 Annex includes the effects from Base case + supplementary NO_x/VOC reduction from Ozone annex commitment. The Scenario3+O_3 Annex include Scenario3 + supplementary NO_x/VOC reduction from Ozone annex commitment.

3. MODELS DESCRIPTION

In this study, the first complete version of the air quality model AURAMS is used for emission reduction scenario applications. AURAMS requires input variables such as wind, air temperature, humidity and stability to define the overall meteorological conditions and to compute the concentration of ozone and its precursors as well as the fine particles ($PM_{2.5}$) of each of the emission episodes described below (Moran et al., 1998; Makar, 2003; Bouchet et al., 2003).

The meteorological fields are provided by the model GEM (Global Environmental Multi - scale model) which is presently used as a forecasting tool in the Canadian Meteorological Centre (CMC) (Coté and al., 1998).

3.1. The meteorological model GEM (Global Environmental Multi - scale model)

The meteorological model GEM is based on the fully compressible Euler equations, that are solved by implicit and semi-Lagrangian method. The selected domain of integration covers North America so as to include all source regions for modelling air quality over southern Quebec. The horizontal grid contains 270 by 353 points with 28 vertical levels and a horizontal resolution of 24 km. The vertical coordinate is a function of the pressure. The model top is at 10 mb and the first 7 levels are in the boundary layer. The model time step is 450 second. The parameterization of the physical processes used in this study includes Kuo deep convection, ISBA (Interactions, Surface, Biosphere, Atmosphere) surface scheme, and Sundvquist stratiform condensation scheme. The gravity wave drag is not considered. To simulate accurately the meteorological conditions during the chosen episodes the meteorological model was driven by objective analyses all along the integration. Objective analyses are produced by the Canadian Meteorological Centre (CMC) every 6 hours, as part of the process of global and regional data assimilation. The time integration of GEM is done one day at a time. Every day the integration starts 6 hours before the target period of 24 hours, at 1800 GMT, for a total of 30 hours of integration for each day of the episode. Then the first 6 hours are discarded.

3.2. The air-quality model AURAMS (A Unified Regional Air Quality Model)

AURAMS is a new, size-resolved, chemically characterized, episodic regional particulate-matter (PM) modelling system being developed by the Meteorological Service of Canada for air quality research and management (Moran et al., 1998; Makar, 2003; Bouchet et al., 2003). The air quality model AURAMS simulates the life cycle of the atmospheric pollutants including injection in the atmosphere, mixing, transport and vertical diffusion by the wind, chemical and photochemical transformation with other species, and finally the return to the earth surface by deposition processes. It is designed to study interactions between nitrogen oxides (NO_x), volatile organic compounds (VOCs), ammonia (NH_3), ozone (O_3) and, primary and secondary PM through aqueous, gaseous and heterogeneous reactions.

AURAMS is composed of 5 different programs run in sequence (Moran, 1997; Makar et al., 2003). The Canadian Emission Processing System - CEPS- (Scholtz et al., 1999) and the meteorological driver, the Canadian forecast model GEM (Côté et al, 1998), provide the corresponding input fields. The chemical transport model itself uses a non-oscillatory semi-Lagrangian advection scheme (Pudykiewicz et al., 1997) to describe the transport of up to 145 individual chemical tracers.

Gas-phase and aqueous chemistry are simulated with the Acid Deposition and Oxidant Model (ADOM) (MacDonald, 1993), with a significant update to allow for secondary organic aerosol (SOA) formation (Odum et al., 1996). The heterogeneous chemistry is based on the module ISORROPIA (Nenes et al., 1998) and desribed in Makar (2003b). The dynamic of internally mixed aerosol is represented by the Canadian Aerosol Module (CAM), (Gong et al., 2003). This aerosol module is size-resolved with 12 bins covering particle sizes from 0.01 to 40.96 microns and includes 8 chemical components: sulphate, nitrate, ammonium, sea salt, black carbon, organic carbon, crustal material and water. Deposition of both gases and particles was updated and is described in Zhang et al. (2001) and Zhang et al. (2002).

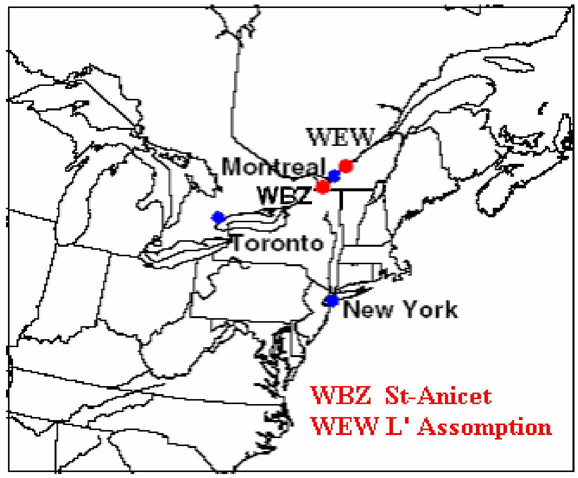

Figure 1: The AURAMS domain

AURAMS was integrated on a polar stereographic projection true at 60°N made of 125 by 110 points on the horizontal plane with 20 vertical levels and a constant horizontal resolution of 21km, covering most of eastern Canada and the United-States (Figure 1). The choice for this particular resolution was dictated by the available gridded emissions for the ADOM chemical mechanism over North America. The input anthropogenic emission rates were based on the 1995-1996 national inventories processed with the Canadian Emission Processing System (CEPS1.0) (Moran, 1997). The Biogenic Emissions Inventory System (BEIS-II) algorithm is used to compute the biogenic emissions. In order to include most of the source regions, the domain spreads to the west as far as Chicago and to the south includes a part of the states of Alabama and Georgia. The model time step is 15 minutes (900 seconds) and the model is integrated for 24 hours at a time. As the grid of GEM is different from the one of AURAMS, the GEM meteorological fields were interpolated into the AURAMS grid.

4. DESCRIPTION OF SIMULATED EPISODES

We choose to study events from 1999 to 2001 where the ground level ozone concentrations and fine particles reached values above the Canada Wide Standards, that is 65 parts per billion (ppbv) for the 8-hour average for ozone and 30μg/m^3 for the 24-hour average for $PM_{2.5}$. Unfortunately, we did not simulate the complete three years due to limited computational resources. Only a subset of all exceedances were simulated. So the periods of simulation were restricted to: July 11 to July 18, 1999, July 29 to August 4, 2001 and from June 12 to June 21, 2001. The simulated periods include exceedances due to local sources as well as long-range transport of pollutants. The typical weather pattern leading to high ozone and $PM_{2.5}$ concentration in Quebec is stagnation under a high pressure system, followed by a south-westerly flow as the high pressure moves eastward over the Atlantic area.

4.1. From July 11 1999 0000 GMT to July 18 1999 2400 GMT (8 days)

During this period, between 15 and 17 July, there were elevated values of ozone concentrations measured over all of southern Quebec. The hourly average of $PM_{2.5}$ was above 30μg/m^3 at all stations. The meteorological conditions were favourable, sunny, hot and humid with temperatures exceeding 30°C in the afternoon. The backtrajectory analysis indicates that this event was caused by long range transport of pollutants from the southwest, in particular the Midwest of the United States.

4.2. From July 29 2001 0000 GMT to August 4 2001 2400 GMT (7 days)

From July 31 to August 1 a local ozone episode was observed in the Montreal region. According to the analysis of the back trajectories, no transport of pollutants was observed. This period contains another day, August 2, where high levels of ozone and $PM_{2.5}$ were measured in all Quebec and was mainly due to long-range transport of pollutants. That day was hot and humid with moderate south-westerly winds. The reported temperature at Montreal international airport this day was 32.5°C.

4.3. From June 12 2001 0000 GMT to June 21 2001 2400 GMT (10 days)

On June 15, high concentrations of ozone and $PM_{2.5}$ were observed over all southern Quebec with typical meteorological pattern such as weak south-westerly circulation, sunny with maximal temperatures of 33.6°C in Montreal international airport. Towards the end of this period, another episode of ozone was observed on June 19 for all Quebec. This episode occurring in the evening was due to long-range transport of pollutants in particular those coming from the Midwest of the United States. This day was hot with a maximum temperature of 33.1°C at Montreal international airport and strong south-westerly winds accompanied by thunderstorms in the evening.

5. RESULTS

5.1. Ozone

Evaluation of chemistry/transport models is usually based on the ability of the model to predict O_3 and $PM_{2.5}$ in comparison with ambient measurements. However, success in simulating the observed ozone and $PM_{2.5}$ does not guarantee that models predict the O3-NO_x-VOC and $PM_{2.5}$ response to a change in the emission rates correctly. Observation-based methods can be used to reduce the uncertainty and to provide an evaluation and constraint on chemistry/transport models, in order to reduce the uncertainty in O_3 and $PM_{2.5}$ predictions. In this context the AURAMS model has recently been evaluated with observations of ground level ozone and $PM_{2.5}$ over Southern Quebec (Morneau, 2004). There is a very good agreement between observed and modeled values for almost all validated cases. In this study we will compare the first level of the AURAMS model which is above the ground. The difference between the five simulated scenarios is only the anthropogenic emission input.

The two measurement stations, considered for this study are shown on figure 1. The St-Anicet (WBZ) station is located southwest of Montreal and is an upwind station during typical smog events. L'Assomption (WEW) is situated northeast of Montreal and is a downwind station in that case. During a smog episode in Southern Quebec, the main sources of precursors are the city of Montreal and the long range transport from Southern Ontario and the Midwest of the United States.

The predicted response to reduced emissions is derived by repeating the control run with reduced NO_x and VOC. The model is useful for identifying general futures of ozone-NO_x-VOC chemistry, but predictions for specific events and specific urban areas are uncertain. Generally speaking, the contrast between the NO_x- and VOC-sensitive regimes illustrates the difficulties involved in developing policies to reduce ozone in polluted regions. Ambient O_3 is the result of photochemistry and transport over several hours (and often several days), and ambient VOC and NO_x can vary greatly over time and through the upwind region in which the ozone was produced. As air moves downwind from emission sources and ages photochemically, conditions tend to change from VOC-sensitive (closer to emission sources) to NO_x-sensitive (further from emission sources). This occurs because NO_x is removed more rapidly than VOC as an air mass moves downwind (thus increasing the VOC/NO_x ratio) and because biogenic VOC becomes increasingly important as air moves downwind (Sillman, 1999).

In this context, Figure 2a and 2b shows the ozone daily hourly maximum for the simulated episodes for all emission reduction scenarios for two sites, St-Anicet and l'Assomption. There is evidence that the NO_x and VOC reductions will lead to ozone concentration decrease. As expected from the difference smaller reductions of the ozone concentration are observed between the Base case and the Scenario3; and between the Base case+O_3 Annex and Scenario3+O_3 Annex.

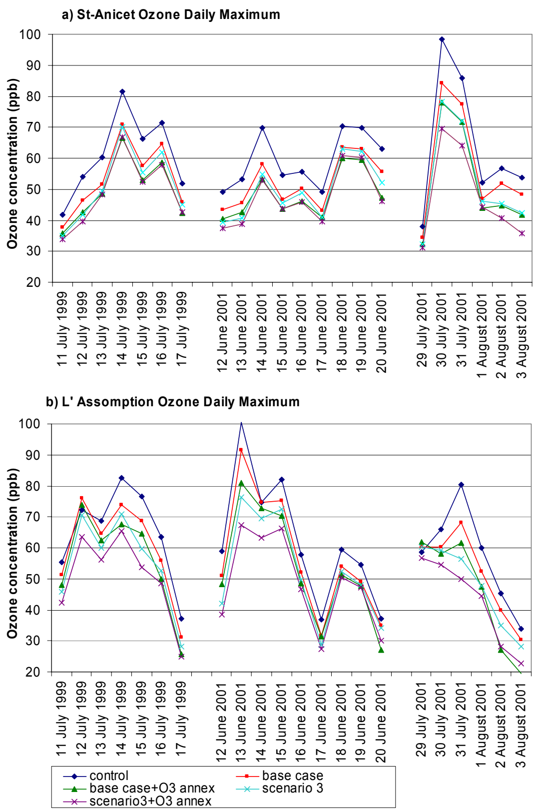

Figure 2: Daily ozone hourly maximum concentration during the three episodes for all simulated emission reduction scenarios. a) St-Anicet and b) L' Assomption.

The most significant reduction is between the control case and all others scenarios. The ozone concentration reduction from the control run is considerable when the Ozone Annex is added to the mobile emission reductions. The significant decrease in ozone concentration of July 31st at both sites indicates that the anticipated reductions will be very effective around Montreal when local sources dominate. In this case, the difference is between 10 and 20 ppb. The peaks correspond to the days when the ozone episode was observed. The daily ozone concentration at l'Assomption is higher that at WBZ due to the strong influence from the city of Montreal, during days of south-westerly flow, and that is valid for all episodes except July 30 and 31.

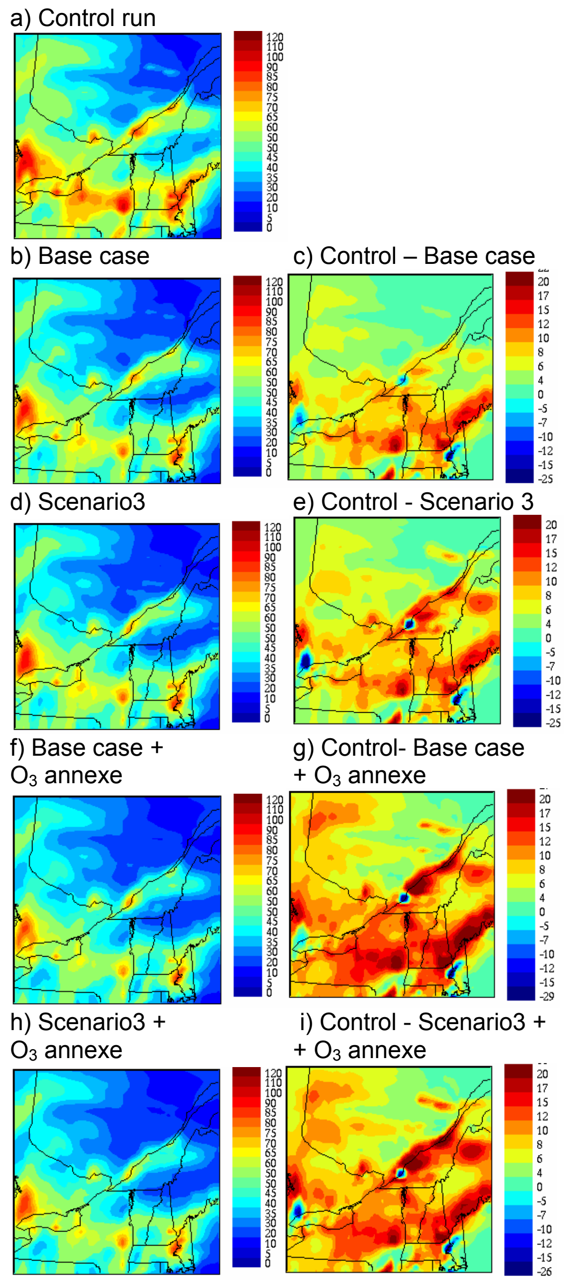

Figure 3 (a-i): Ozone concentration for June 15, 2001 (1800Z) for all simulated emission reduction scenarios.

In order to appreciate the spatial distribution of the change in concentration, hourly ground level ozone concentration predicted by AURAMS for June 15, 2001 at 1800Z for the control run and the others scenarios are presented on the figure 3. The differences between the Control run and the other scenarios are also shown. The figure shows that the difference between the control run and the Base case, Control run and Scenarios 3 are around 17-20 ppb. The differences between the scenarios and Control run go higher than 20ppb when the Ozone Annex is added to the mobile reductions. The decrease of ozone concentration under the elaborated scenarios is significant over Southern Quebec. In major urban areas such as Montreal, as expected, the NO_x reductions lead to an increase of ozone concentrations. As the resolution of the model grid is 21 km, it is not possible to evaluate the boundary between NO_x and VOC sensitive regions around Montreal.

In order to evaluate the overall effect of the emission reductions on ozone concentration, an index was defined based on the duration and area of exceedance of the hourly threshold of 82 ppb. This index is defined as the number of hours above the threshold times the area covered by the exceedance expressed as model grid point. The table 3 shows this index computed over Southern Quebec. This index gives a clear indication that each reduction scenarios will provide additional benefit to the air quality as far as ozone is concerned. The decrease in the duration and area of ozone exceedances vary from one episode to the other. In general there will be a steady decrease towards better air quality as the successive reduction program are in effect.

Table 3: Numbers of hours of ozone exeedance (>82 ppb) multiplied by the area

Scenarios / Episode	Control	Base Case	Scenario 3	Base Case + O3 Annex	Scenario 3 + O3 Annex
11-18 July 1999	110	14	7	4	0
12-21 June 2001	163	81	84	84	51
29 July - 4 Aug 2001	174	121	103	104	69

5.1. $PM_{2.5}$

Aerosols are under scrutiny for their impact in human health and visibility. Unlike ozone, $PM_{2.5}$ can occur year round. However, the selected episodes were in the summer, and no cold weather conditions are presented. On-road vehicle emission reductions (Base case and Scenario 3) include primary PM as well as precursors reductions.

The modeled daily average $PM_{2.5}$ concentration is presented on figure 4 (a and b). At the St-Anicet site usually upwind of Montreal, the difference between the scenarios is small, less than 2 µg/m^3. The effects of the reduction programs become significant when local influence of the city of Montreal dominates, such as on July 30 and 31 2001. At the l' Assomption site, usually downwind of Montreal, on the other hand, the reductions scenarios translates to a reduction of $PM_{2.5}$ concentrations. In summary, each reduction programs have a positive effect of decreasing the particles concentrations when the winds come from the city of Montreal. In other cases, the effect of the reduction scenarios remains very small compare to the benefits for the ozone concentrations.

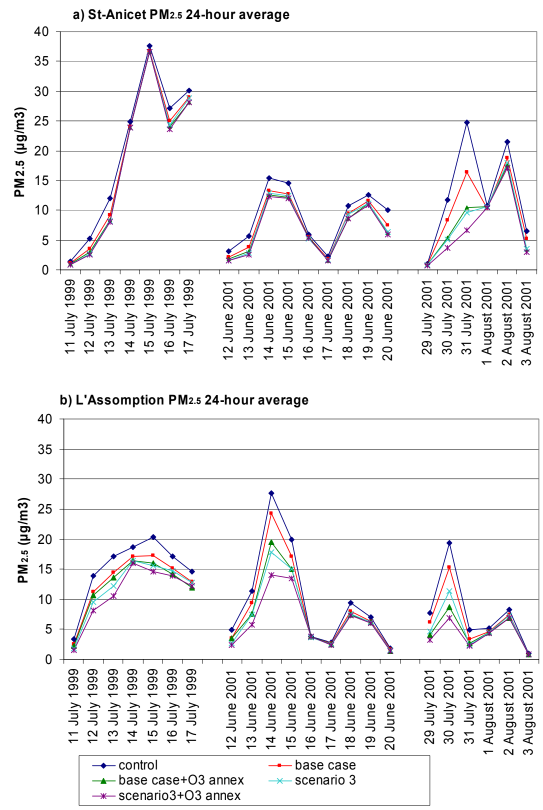

Figure 4: $PM_{2.5}$ 24-hours average concentration during the three episodes for all simulated emission reduction scenarios. a) St-Anicet and b) L' Assomption

6. CONCLUSIONS

The model outputs clearly show that under the prepared scenarios, significant ozone and $PM_{2.5}$ reductions are observed. This study shows that in Quebec the ozone daily maximum is reduced by 60-70% when running the mobile emission reduction scenarios valid for 2020. When the Ozone Annex commitment valid for 2010 is added to the anticipated mobile emission scenario there is a 70-80% maximum daily ozone reduction observed in Quebec. While the ozone is significantly reduced away from major urban areas the model shows an increase in ozone concentrations in urban centres, due to NO_x emissions reductions. The difference between the scenarios for $PM_{2.5}$ is very small when transboundary transport is dominant and larger during local episodes. Some more work has to be done to find the causes of smaller benefit of the scenarios for the $PM_{2.5}$. AURAMS is still under development but it shows very good performance and adequately responds to the reductions of the emissions.

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