1.3 MAPPING SMALL SCALE AIR POLLUTION DISTRIBUTION USING SATELLITE OBSERVATIONS IN A LARGE CANADIAN CITY

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1. INTRODUCTION

The management of air quality in Canada's national capital region requires the identification of small-scale pockets of air pollutants in an area of over 5,000 km^2 and with a population of more than a million inhabitants. To cover this large area, AURA earth satellite observations , supported by local air quality sampling and modelling, were applied to provide comprehensive information about the spatial distribution and dispersion of air pollutants. A combination of information from fixed, mobile and portable air quality monitoring stations at ground level as well as the Aura instruments including the Ozone Monitoring Instrument (OMI) from space was selected as the most effective approach for mapping local air quality. Hourly mapping of six pollutants was complemented by local information on transportation and stationary emission sources, land use, commuting patterns and meteorology. The end result was hourly maps displayed in the Canadian Geospatial Data Infrastructure for the following parameters: NO_2, NO, NOx, $PM_{2.5}$, O_3, and CO. This paper contains an analysis of local geographic conditions, their impact on air quality and selected episodes of NO_2 and $PM_{2.5}$ emissions.

2. METHODOLOGY

The project required detailed ground level air quality sampling (pollutant concentrations); geographical data (position); meteorological data; pre-processed satellite remote sensing data; and road transportation data. All these data were incorporated into a relational database that was later translated into GeoTiff format (maps). The Get Map and Get Feature options of the Web Map Service (WMS) have been applied for the visualization and presentation of the concentration maps. As a final step, the concentration maps were superimposed as layers onto the Atlas Canada mapping service. The application created on the Internet allows the user to download digital maps in Tiff format of any of the pollutants for a specific area and period of time.

The user can request air quality data on the Internet using a Web Map Service enabled client. The default overlays are the road network and the political boundaries. The air quality data, encoded in Geographical Markup Language (GML), was incorporated into a database compatible with an open source WMS server.

The ground base data included the National Air Pollution Surveillance (NAPS) Network measurements as well as measurements provided by mobile labs at 8 sites (see locations in Fig. 1). The satellite digital information used is from the Aura launched in 2004.

The project started in July 2007, with a full year of air quality monitoring through June 2008 followed by three months of data integration, analysis and display. The following parameters were measured and mapped: NO_2, NO, NO_x, $PM_{2.5}$, O_3, and CO.

The ground level data and pre-processed satellite data were integrated into a dispersion model in order to interpolate hourly values. The Aura satellite payload includes a combination of instruments designed to study tropospheric chemistry one of which is the Ozone Monitoring Instrument (OMI). The satellite has a near polar trajectory and a temporal resolution of once a day for a given surface location with 100 minutes orbiting time. It measures radiation, ozone, aerosol optical thickness, aerosol single scattering albedo, NO_2, SO_2, HCHO, BrO, OCIO.

The focus for the project is the National Capital Region (NCR) with a population of 1.45 million (Statistics Canada, 2006 census). The study area, larger than the NCR, covers 5,600 km^2, criss-crossed by the Rideau River in the south and the Gatineau River in the north. The Ottawa River runs from west to east, and constitutes the border between the provinces of Quebec and Ontario. The Gatineau Hills cover the northern part of the study area. The prevailing west to southwest wind brings pollution from the more industrialized southern Ontario. When the wind is from the south-west, the pollution is transported from Ohio and New York in the USA. To the east is Montreal, a large industrialized city that also has an influence on the local air quality. In the absence of polluting industries in the NCR, the greatest source of local emissions comes from vehicles used year round and from the burning of wood as a heating fuel during the winter.

The following data sets were used in developing the air quality maps:

- Data from the Aura satellite which passes over the region daily with a pixel resolution of 13 x 24 km at nadir
- Road transportation and road network data for the City of Ottawa

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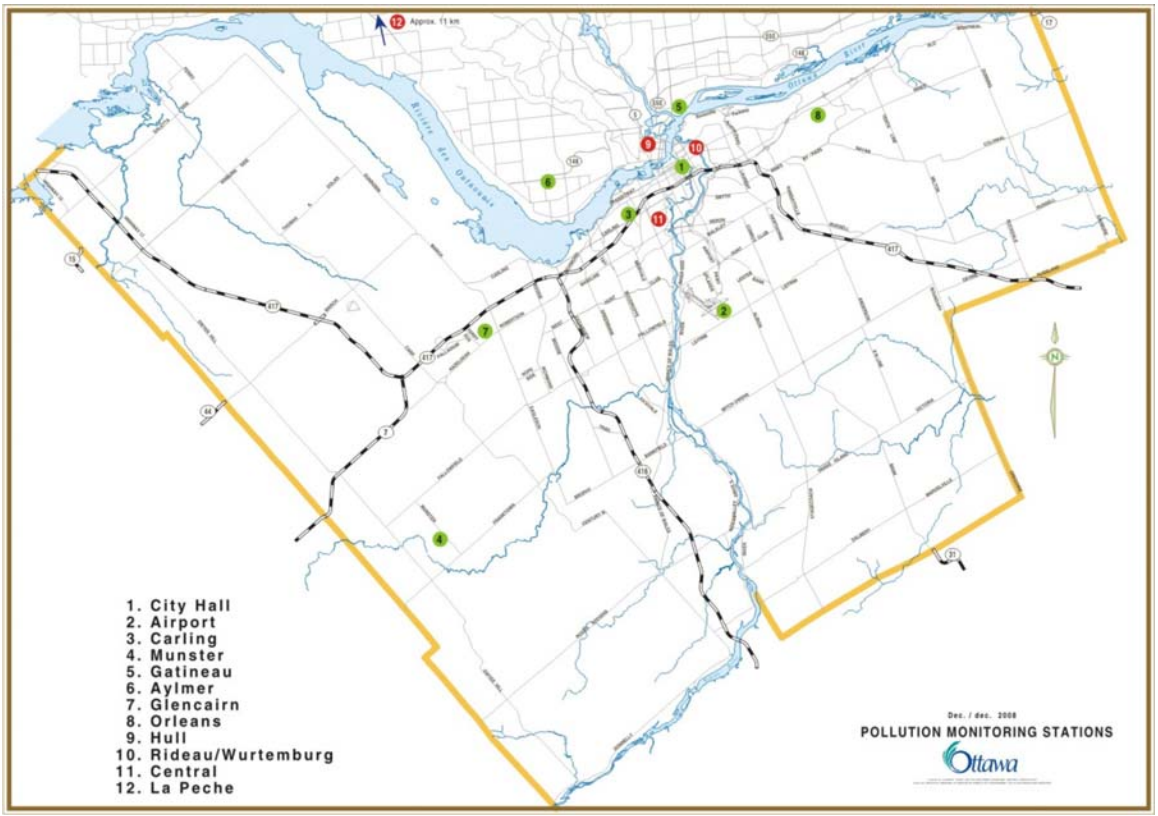

Figure 1. Monitoring locations: red dots are permanent locations, while green dots are mobiles labs

- Meteorological data from the Ottawa International Airport provided by Environment Canada
- Hourly air quality data from 4 permanent stations, 3 NAPS[1] stations, two in Ottawa and one in Gatineau. The fourth station belongs to the Ministère du Développement durable, de l'Environnement et des Parcs of the Quebec provincial network - La Pêche, located north of the City of Gatineau. The latter only provided $PM_{2.5}$ and O_3.
- The mobile laboratories were rotated among 8 sites over the year and contributed hourly measurements for all 6 pollutants.

2.1 Data integration

Data integration began with grid point values at the centre of each satellite pixel. Kriging was then used to interpolate grid point values with a 1-km^2 resolution. Ground level measurements were smoothed using 3-hour running average. The ratio of the ground level measurement to satellite estimate was calculated for each pixel. A spatial average of this calculated field ratio was then used to calibrate each pixel value. Up to this point, all calculations were done at the time of the satellite overpass (in the early afternoon local time).

Following these initial steps, hourly concentrations were calculated from interpolation in time using the closest ground level station and its 24-hour pattern. The validity of this procedure was justified from high inter-site correlations.

Additional pollutant values were calculated for each pixel, based on traffic emissions, calculated from traffic volume for road length sections per unit time. The Green function, a point source emission function, was used along with advection and diffusion equations. The solution, a Bessel function, was obtained through a Sturm-Liouville transformation (Zwillinger, 1997). The final equation to estimate 1-km values was calibrated, in terms of pollutant concentrations, from the measured concentration data at the nearest site to a major traffic emission source (for example, the Carling Avenue site is near the multi lane Highway 417 that transects the city of Ottawa from west to east).

3. RESULTS

The hourly 1-km^2 resolution maps of pollutant concentration can be used to identify the location and likely source of higher concentrations of air pollutants. The mapping format helps to visually

[1] National Air Pollution Surveillance Network

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identify areas that require greater scrutiny when planning communities with vulnerable population groups, such as the locations of schools, sports facilities and old age homes. Along with the visual maps, one can also obtain tabular data for each 1-km^2 grid square to identify how often a given location exceeds given air quality standards and thresholds.

The maps provide a picture of pollution distribution across the region. Although 95% of the time pollutants are below the thresholds indicated by the Canada Wide Standards (CWS), there is a west to east pollution gradient, with the eastern part of the region showing a slightly higher level of air pollution. Pollution episodes tend to last longer in the east than in the west. Ozone and nitrogen oxides show a definite west-east pattern (Fig. 2).

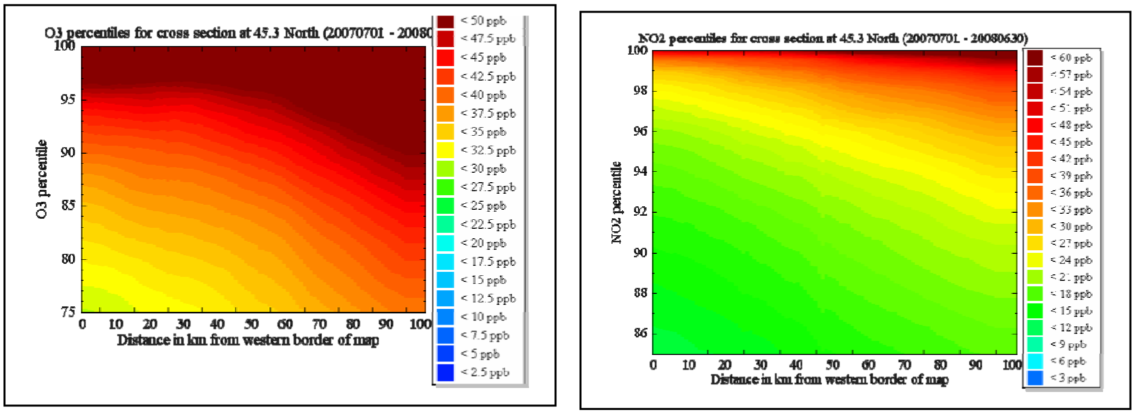

Figure 2. Cross Section of pollution gradient from west to east for ozone (left hand diagram) and nitrogen dioxide (right hand diagram)

This gradient can be explained by the prevailing westerly wind, which pushes the nitrogen oxides and ozone precursors generated from transportation emissions from the west and downtown core towards the east. These pollutants also contribute to higher ozone formation in that area.

The areas affected by nitrogen oxides are, not surprisingly, related to transportation particularly along Highway 417 approaching the downtown core of Ottawa. Higher concentrations are particularly observed at the split of Highways 417 & 174 and at the Nicholas Street exit from the 417. An event of in December shows clearly higher concentrations near the transportation corridors (Fig. 3). January had the highest average NOx with the southeast being the most prominent site (Fig. 4). Observed NO_2 levels seldom reach the hourly standard of 200 ppb.

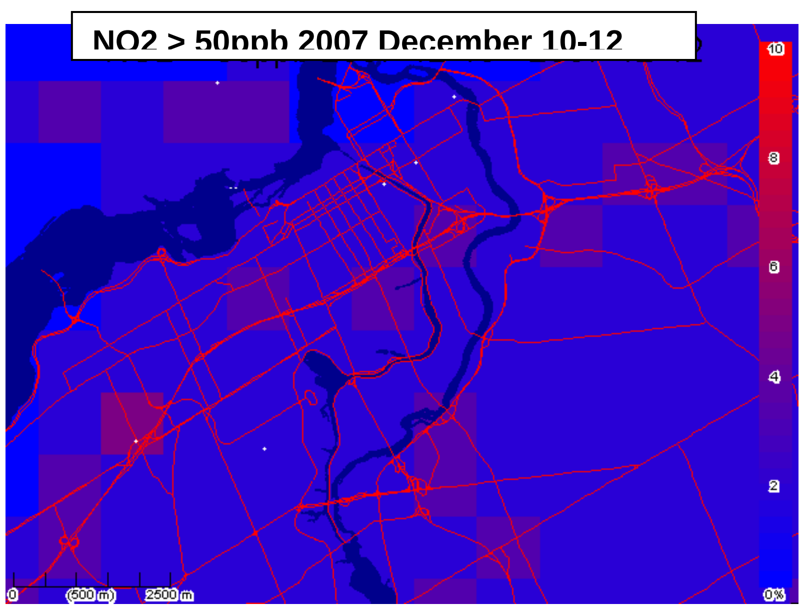

Figure 3. Highest nitrogen concentrations observed during December 10-12, 2007

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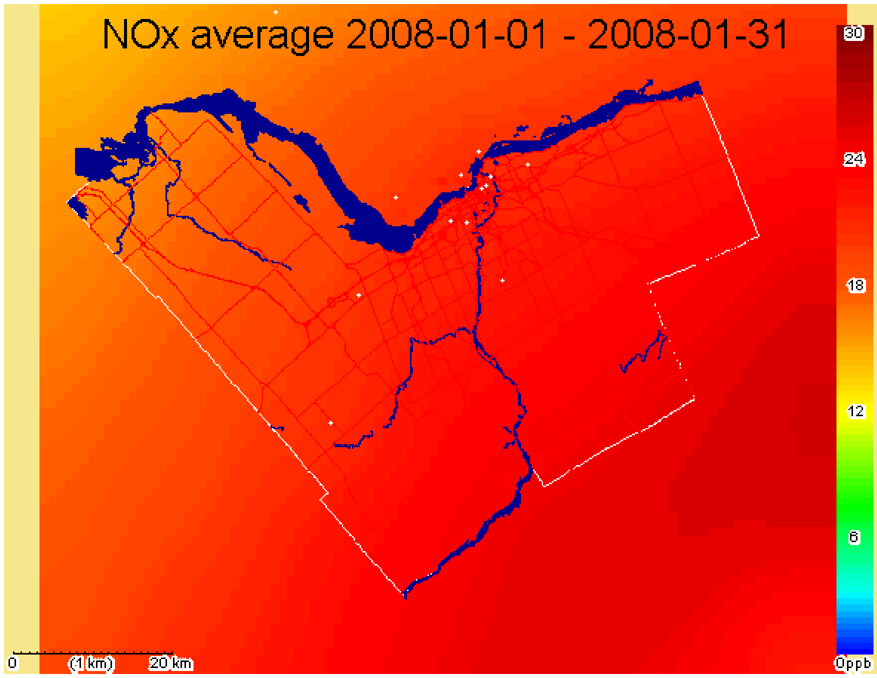

Figure 4. Average NOx concentrations for the month of January

Events of elevated particulate matter are more frequent in the downtown areas of Ottawa and Gatineau where, in one case, the concentration surpassed the CWS standard three times. Some other high pollution incidents were observed in the month of April in Kanata and in June at the Experimental Farm when the PM concentration reached four times the CWS standard. The latter station may have been affected by the agricultural practices in that area. The Kanata case, which occurred at 23:00 hours, is still under investigation.

The worst episodes observed during the year were triggered by $PM_{2.5}$ and had three origins:

- from the east, which seems to have its origins in Montreal, on September 14th 2007 (http://www.amapsenv.com/Movie-Ottawa.html)
- from the south, the Ohio Valley on September 21st and September 25th, 2007
- locally produced and concentrated due to lack of air movement on December 13th 2007(http://www.amapsenv.com/Movie-OttawaCenter.html). During that time, the sky was clear, surface temperature was very cold and wind was light, the perfect condition for an inversion, which caused the concentration of pollution in the downtown core.

4. DISCUSSION

Fine-scale maps of pollution distribution derived from satellite data offer details that otherwise would not be possible from the 4 permanent monitoring stations. The regional scale maps over 5,600 km^2, provide information not only for urban areas, but also for the extensive rural areas of the capital.

Running average over a three hours period was selected in accordance with the common practice regarding assessments of the health impacts of poor air quality. However, for monitoring traffic emissions during morning and late afternoon rush hours, detailed mapping of hourly values or shorter periods are needed for policy development to protect from health impacts. Further refinement of the temporal scales of the mapping is being considered. This is of particular interest since the National Capital Region has a concentration of office workers in the downtown core resulting in a ten-fold population increase during working hours (from 9,750 to 97,770). This increase combines with peak auto-driver rates of 53-57% according to a recent origin-destination survey of the NCR (McCormick Rankin Corporation /Parsons Brinckerhoff, 2006) to make commuting vehicles one of the greatest sources of emissions in the area.

The three-hour running average produced the highest correlation with spot measurements of satellite pixel data and is the standard used by the Ontario Ministry of Environment (MOE) for monitoring ambient air quality across the province. A demonstration of an unsmoothed hourly mapping for the region highlights the pollution at peak hour aligned with the main highway that crosses the city of Ottawa and can be found at the following site http://www.amapsenv.com/Movie-NCR-NO2.php. Mapping of hourly data may be more useful for urban planning as well as for public health applications.

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An analysis of the temporal standard deviation (STD) for each pollutant across the region from the mapping exercise corresponds closely with the STD obtained from the two permanent MOE monitoring stations:

Pollutant	STD (map)	STD (MOE)
CO (ppm)	0.1-0.18	0.11 – 0.14
NO (ppb)	5 - 9	8.5 – 8.74
NO_2 (ppb)	5 - 10	10.65 - 11.5
NOx (ppb)	12 - 18	17 –17.5
O_3 (ppb)	11 - 14	13 – 13.78
$PM_{2.5}$ (ug/m^3)	6	5.84 – 6.75

A full validation process across the National Capital Region has not been completed yet, but a single pixel comparison of the Orleans (east) site measurements using mobile lab data show that the cross-validation between the results of the modeling and ground measurements is remarkably good:

Pollutant	STD
CO	0.07(ppm)
NO	2.4(ppb)
NO_2	3.0 (ppb)
NOx	4.4 (ppb)
O_3	3.8 (ppb)
$PM_{2.5}$	3.3 (ug/m^3)

In a cross-validation applied to the data exceeding the instrumental noise threshold for the Orleans area, the calculated mean normalized error was between 25 - 35% (equation 1). MOE is considering a possible cross-validation of this tool for regional air quality monitoring which the City of Ottawa would welcome.

$$E_n = 1/N * \Sigma\{||Pi-Oi||/Oi\} \qquad (1)$$

where Pi, Oi are respectively the i-th predicted and observed value; ||.|| stands for the absolute value.

4.1 Challenges for Public Health

The European Commission requires air quality assessments and corrective action by management if certain pollution levels are exceeded in areas of highest concentrations, such as near busy roads or industrial installations (Entec UK Ltd., 2008). Policies aiming at a reduction of the health burden to the general public by air pollution are encouraged. This is especially true for pollutants that have no safe minimum threshold impacts and for those pollutants where there is a "linear response between exposure and response." The Commission states that public health burden of exposures to hot spots has been shown to be significant. People living close to busy roads (within 500 m) experience greater impacts from air pollution than those living further away. The distribution of health risks due to air pollution has caused increasing concerns for environmental justice and equity.

The recently updated Public Health Standards of Ontario (Ministry of Health and Long Term Care, 2008) place a greater emphasis on the need to develop community-wide policies and increased public awareness of health risks associated with outdoor air quality. For the City of Ottawa, it is estimated that air pollution is responsible for 503 acute premature deaths per year (ICAP CMA, 2008; OMA, 2008). Reducing emissions from transportation by implementing comprehensive, integrated policies and programs are expected to reduce total vehicle travel by 30 to 50% (McKeown, 2007), which in the NCR would have a significant impact. Under the goal of prevention and reduction of the burden of illness from health hazards in the physical environment, requirements around outdoor air quality include efforts to develop local communications strategies and to assist community partners to develop healthy policies related to reducing exposure to outdoor air pollution.

The level of information that the current mapping project offers for the development of air quality management policies requires answers to the following questions:

- what sort of accuracy for mapped or point measurements of air pollution is needed to trigger a response from public health,
- what sort of response or action is needed at various levels - either for individuals, at urban hotspots for short duration high intensity events or across the city for extended events, and
- what threshold for each pollutant should be established as a trigger for corrective action.

5. CONCLUSION

Mapping of air quality from satellite data provides an excellent way of assessing air quality on a regional or sub-regional scale. Given that the National Capital Region is quite large, the information provided by this tool provides valuable information previously unavailable for the rural areas of the region. For the urban centre, mapping hourly values of the air pollutant concentrations will require more attention. From the municipal policy point of view, accuracy of the data and thresholds with respect to the air pollution impacts need to be further addressed.

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