Air Quality Simulation of Traffic Related Emissions: Application of Fine-Scaled Dispersion Modelling

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Abstract This paper focuses on developing and validating the CALMET-CALPUFF modelling system to be ultimately used as a tool for evaluating the potential air quality impacts of transportation plans. Our study is set in the Montreal Metropolitan Area. For this purpose, emissions of Nitrogen Oxides (NO_x) were modelled using a transportation and emissions model which accounts for individual trips and vehicle types. Hourly Nitrogen dioxide (NO_2) concentrations were simulated and validated against measurements taken for the same time period. Our results show a reasonable performance of the dispersion model with 0.77 correlation between simulated and observed concentrations in January. The simulated concentrations are often lower than the observed concentrations partly due to the fact that the emissions of trucks and point sources (e.g. industrial and residential) are unaccounted for.

Key Words**:** Dispersion modeling, traffic emissions, nitrogen dioxide (NO_2), CALMET, CALPUFF.

1. Introduction

Highways are major sources of Nitrogen Oxide (NOx) emissions and exposure to nitrogen dioxide (NO_2) has been associated with a number of respiratory and cardiovascular effects (Beckerman et al. 2008). Dispersion modelling of traffic sources has been conducted for a variety of road and network configurations (Hatzopoulou et al. 2010) employing a range of dispersion software such as WinOSPM, MM5-ARPS-CMAQ and CALPUFF. CALPUFF is a non-steady state Gaussian puff model which is becoming more commonly applied for the dispersion of traffic emissions because of its capability for handling complex terrain and land use interaction effects (Cohen et al. 2005). This paper describes the development and validation of dispersion modeling for the Montreal Metropolitan Area. The integration between traffic, emission, and dispersion modelling capability will allows us to investigate the effects of transportation plans on air quality and public health.

2. Materials and Methods

Hourly traffic data were obtained for four weeks in January, April, August and October 2008, emissions of NO_x were modelled while accounting for traffic composition, and the CALMET/CALPUFF modeling system was used to simulate hourly NO_2 concentrations which were then validated against measurements taken for the same time period at ten monitoring stations in our study area.

2.1 Emission Modeling

We developed a traffic assignment model for the Montreal region that is linked with an emission model capable of simulating traffic emissions occurring on the road network at the level of each individual driver based on vehicle type, age, speed, and type of road it is circulating on (Sider et al., 2013). Emissions were based on emission factors that we generated using the Mobile Vehicle Emissions Simulator (MOVES) platform developed by the United States Environmental Protection Agency (USEPA) updated with Montreal-specific data. Hourly emissions of NOx were estimated for each road by summing the contributions of all vehicles on every segment.

2.2. Meteorological Modeling

In this study, CALMET (Version 6.334) which is part of CALMET/CALPUFF modeling system (Scire et al. 2000), was used to interpolate winds and temperatures using higher-resolution terrain elevation and land-use data and create detailed hourly meteorological data as well as predict boundary layer parameters such as mixing height. Since the data interpolation process accounts for land slopes, blocking effects of terrain, and preserves the air-mass continuity as a diagnostic model, it must be driven either by observations or by three-dimensional data from prognostic models (MM5, WRF, RAMS, etc.). We generated the input land use data with the resolution of 1 Km x 1 Km. Terrain elevation data were obtained from the Shuttle Radar Topography Mission (SRTM). The data for the modelling domain are in SRTM3 (spacing for individual data points is 3 arcseconds) which corresponds to 90 meters in resolution. Three dimensional hourly meteorological data were obtained from the Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) mesoscale model MM5. Surface meteorological were obtained from the National Oceanic and Atmospheric Administration (NOAA) database for the same period.

2.3. Dispersion Modeling

Following the generation of three-dimensional meteorological data for the modelling domain, the CALMET output file was used to drive the CALPUFF dispersion. CALPUFF as a Lagrangian puff model estimates the growth/diffusion and transport of released puffs, based on the generated wind fields calculated by CALMET. The CALMET meteorological data and link-based emissions were used as inputs into CALPUFF in order to simulate hourly NO_2 concentrations. All the road segments were treated as line sources and a value of 3.5 meters was considered for the initial vertical dispersion coefficient (sigma z), therefore representing traffic-induced mixing near the roadway. Background NO_2 concentrations were also included. The simulation starts at 4:00 LST on the 7^{th} and ends at 4:00 LST on the 14^{th} of the following 4 months: January, April, August and October 2008. CALMET and CALPUFF share the same modeling domain. The domain extends 200 km×140 km centered around the Montreal Island. In the vertical dimension a stretched grid is used, with the layer thicknesses increasing with height. Ten layers extend from the surface to 3000 m above ground level (AGL).

The resulting concentrations were validated against observed data via time-series plots, spearman correlation, and the normalised absolute difference (NAD) indicator (Chang et al. 2004). The NAD performance index is presented in Equation 1.

$$NAD = \frac{|\overline{C_0 - C_P}|}{\overline{C_0} + \overline{C_P}} \qquad (1)$$

Where C_o and C_p represent the observed and predicted concentrations, respectively. The overbar represents the average over the hourly values in the week.

3. Results

In order to validate the meteorological output from CALMET, simulated wind fields were compared with observed data at an airport station (Figure 1). In general, CALMET captures reasonably well the most frequent winds observed at the station (spearman correlation: 0.64 and 0.82 for wind speed and wind direction respectively for April). Moreover, CALMET predicted lower wind speeds and under-represented winds higher than 10 m/s. Similar results were reported in other studies whereby overall wind directions and speeds are well captured by the model but the frequency of high wind speeds is higher among measured data.

Concentration contours for NO_2 are presented in Figure 2 for August 13, 2008 at 6 pm. The highest concentrations are close to the highways. The direction of the plume follows the hourly wind. Validation of NO_2 concentrations was conducted for each of the 4 weeks whereby data from 9 monitoring stations in Montreal were used in this exercise. We observe that the spearman correlation coefficient between observed and simulated NO_2 ranges between 0.05 and 0.78 in January, 0.21 and 0.75 in April, 0.17 and 0.67 in August, 0.04 and 0.68 in October (Figure 3)

Finally, the NAD indicator was calculated at each of the 9 stations using the data for the four weeks at each station. It ranges between 0.58 and 0.88 (NAD=0 indicates a perfect model).

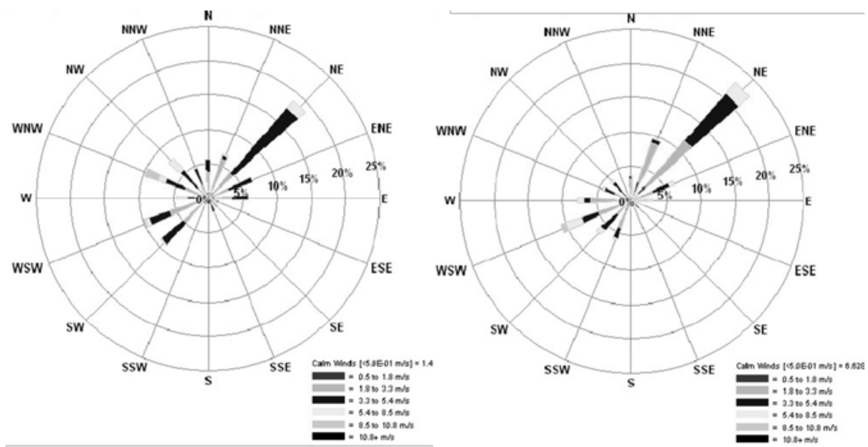

Figure 1 Simulated winds CALMET (left) and observed at Mirabel airport (right) for April 7-14, 2008

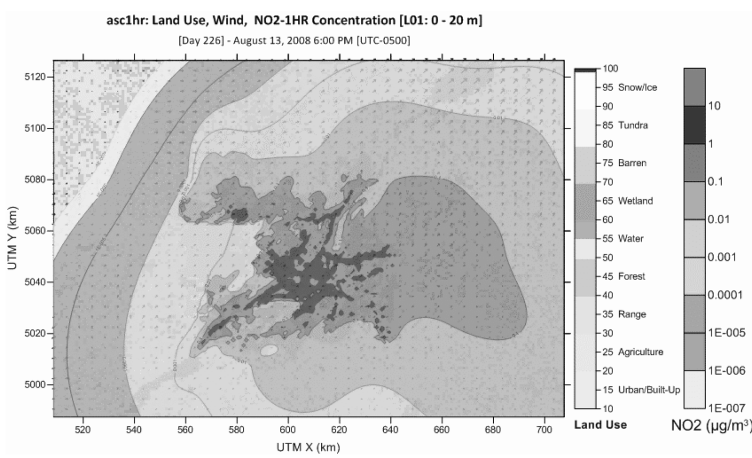

Figure 2 Hourly gridded contours (arrows represent wind directions and speeds)

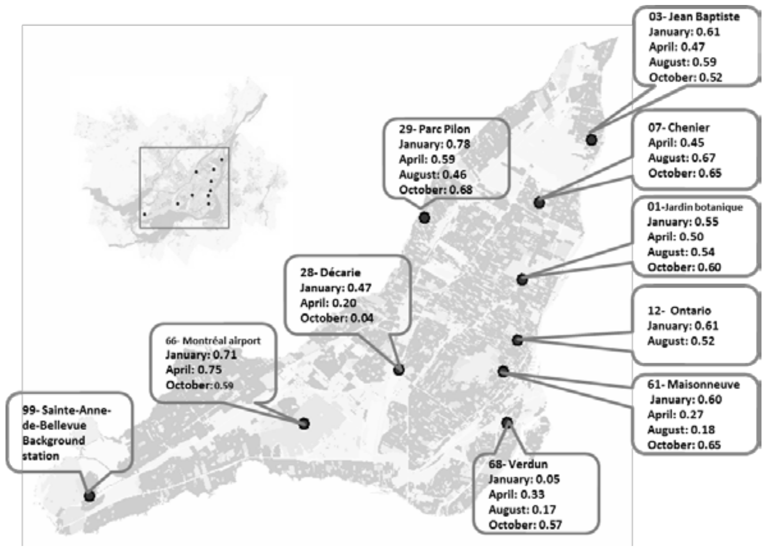

Figure 3 Monitoring stations in Montreal (spearman correlations are presented inside of boxes)

4. Conclusion

This paper describes the development and validation of an emission-dispersion model for the Montreal Metropolitan Area. We treated around 192000 road segments in Montreal as individual line sources in CALPUFF model. The simulated values of meteorological parameters and NO_2 concentrations are compared with different stations within the study area. In general, CALMET captures reasonably well the most frequent winds observed at the meteorological stations. This study also shows that simulated concentrations are correlated to the observed data when detailed meteorological and dispersion characteristics are accounted for. However, the model underestimates observed concentrations partly due to the fact that the emissions of trucks and point sources (e.g. industrial and residential) were not included in the current simulation.

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