Characteristics of Tailpipe and Non-Tailpipe Particulate Matter in Toronto

Cheol H. Jeong[1], Nathan Hilker[1], Jon M. Wang[1,2], Alison Traub[1], Rob Healy[2], Jerzy Debosz[2], Uwayemi Sofowote[2], Yushan Su[2], Michael Noble[2], Tony Munoz[2], Ewa Dabek-Zlotorzynska[3], Valbona Celo[3], Luc White[3], Dennis Herod[3], Greg Evans[1]

1.Southern Ontario Centre for Atmospheric Aerosol Research (SOCAAR), University of Toronto, Toronto, Ontario
2.Ontario Ministry of the Environment, Conservation, and Parks, Toronto, Ontario
3.Environment and Climate Change Canada, Ottawa, Ontario

UNIVERSITY OF TORONTO
FACULTY OF APPLIED SCIENCE & ENGINEERING

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BACKGROUND

- Twenty-four-hour integrated filter-based chemical speciation data of PM2.5 collected over the last 14 years in Toronto were utilized to
  - Identify the long-term trends of PM2.5 sources in the metropolitan area
  - Investigate factors driving change in the trends
  - Assess the source-specific health effects of PM2.5

- Hourly PM2.5 chemical speciation data simultaneously measured at multiple near-road locations were examined to
  - Estimate the contribution of local traffic-related sources on PM2.5
  - Examine spatial and temporal variations of local PM2.5 sources
  - Characterize decay gradients of traffic-related PM2.5 under cold winter temperatures

METHODOLOGY

Site Description

- Downtown Toronto (NR-TOR-2)
  - 24-hr integrated PM2.5 chemical speciation data: March 1, 2004 - April 4, 2017
  - Hourly PM2.5 chemical speciation data: May 10 - Aug. 31, 2016
  - Traffic density: 15 m from the 4-lane arterial road, ~16,000 vehicles/day

- Highway 401 (NR-TOR-1)
  - Hourly PM2.5 chemical speciation data: May 10 - Aug. 31, 2016
  - Traffic density: 10 m from the edge of highway 401, ~410,000 vehicles/day
  - Wintertime hourly PM2.5 chemical speciation data: Feb 6 - Feb 27, 2017 (10 m vs. 150 m from highway 401)

Instrumentation

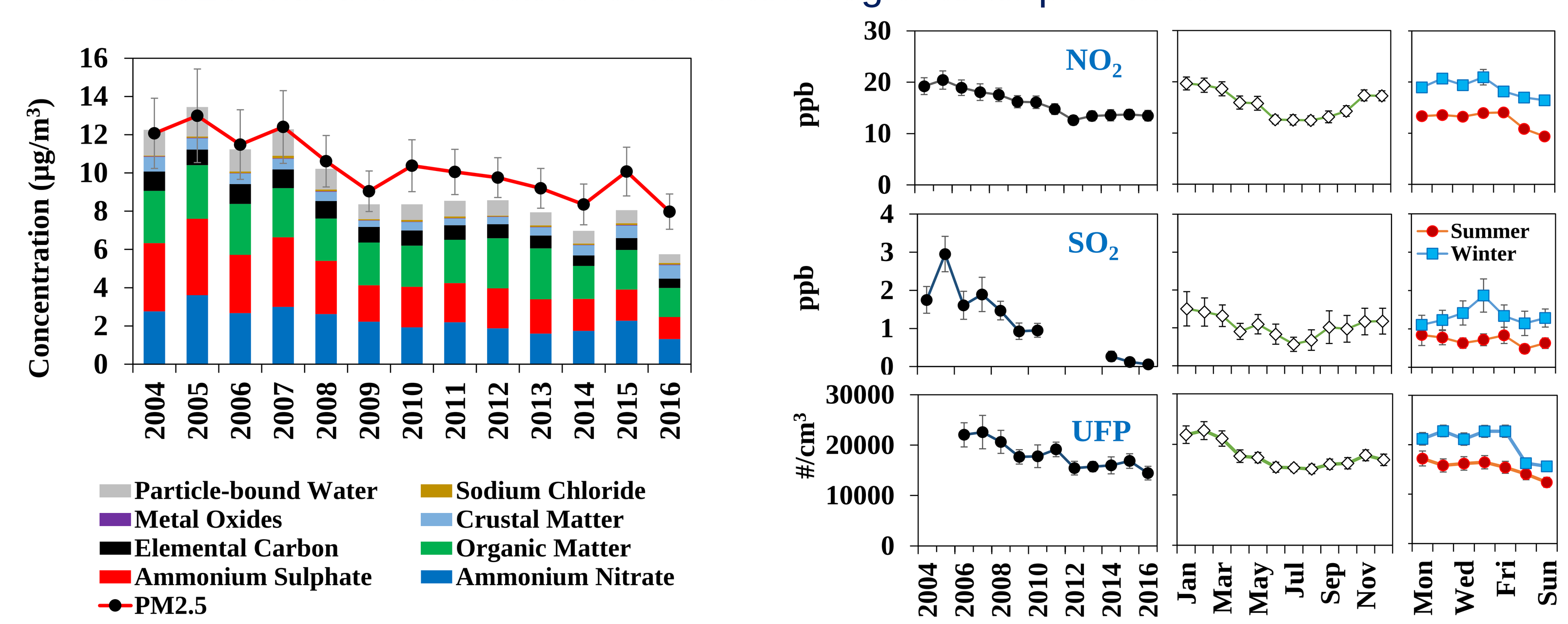
- 24-hr integrated PM2.5 filters collected by two samplers were analyzed by Ion Chromatography (IC), energy dispersive x-ray fluorescence (ED-XRF), acid digestion Inductively-Coupled Plasma Mass Spectrometry (ICPMS), and thermal optical reflectance (TOR)
- Hourly organics, sulphate, nitrate, and ammonium by Aerosol Chemical Speciation Monitor (ACSM, Aerodyne),
- Hourly trace elements by Xact Metals Monitor (Xact 625, Cooper Environ.)
- Real-time gas- and particle-phase air pollutants: NO, NO_2, CO, SO_2, Ultrafine Particles (UFP, FMPS), Black Carbon (BC, AE33), PM2.5 (SHARP)
- Met data: Wind Speed, Wind Direction, Temperature, Relative Humidity

Data Analysis

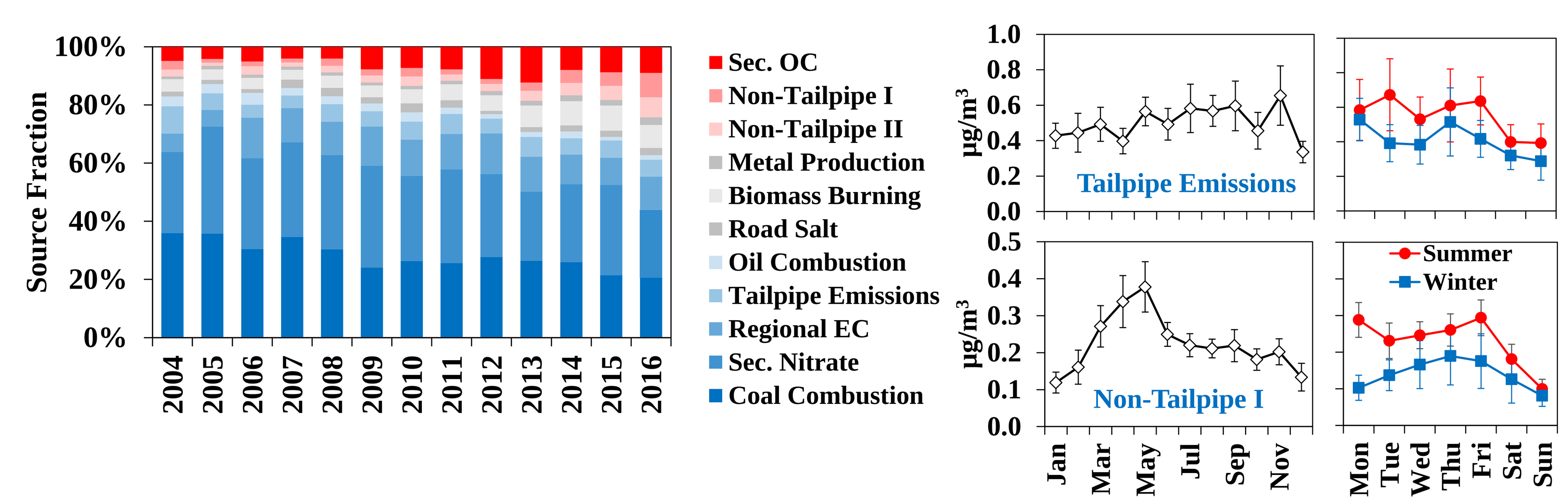
- Receptor modeling: Positive Matrix Factorization (PMF, EPA PMF 5)
- Trend Analysis: Manne-Kendall test and Sen's slope
- Wind sector analysis
- Oxidative Potential (OP): Ascorbate Acid (AA) assay
  - Intrinsic PM redox activity: AA depletion rate normalized by PM mass

LONG-TERM TRENDS OF PM2.5 SOURCES

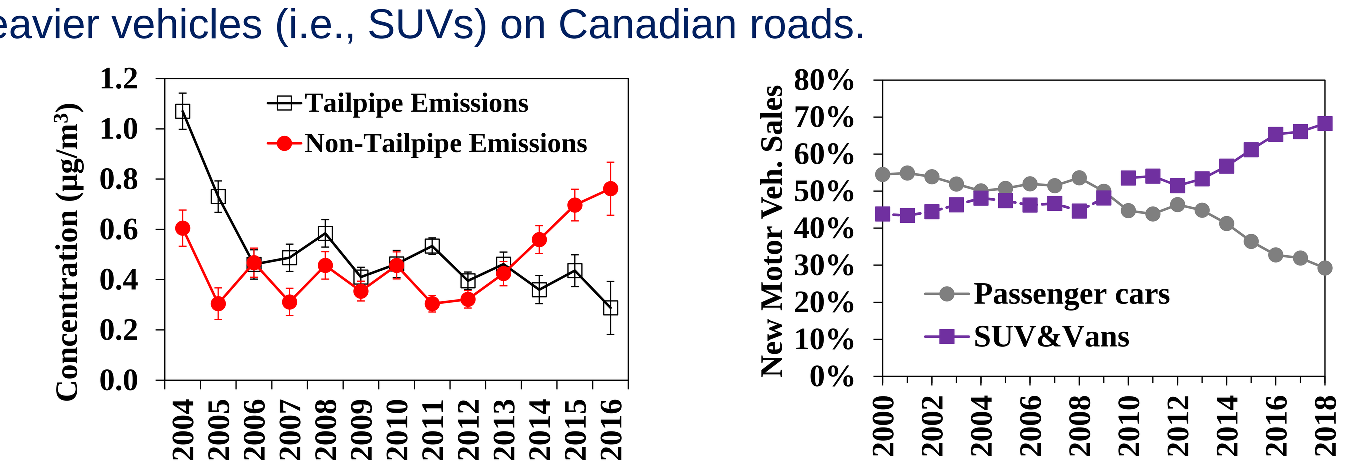
- **Annual concentrations of PM2.5 and reconstructed chemical composition and annual, monthly and day-of-the-week patterns of NO_2, SO_2, and UFP**
  - The annual concentrations of PM2.5 in Toronto decreased by 34% between 2004 and 2016 with the decreases of local and regional air pollutants.



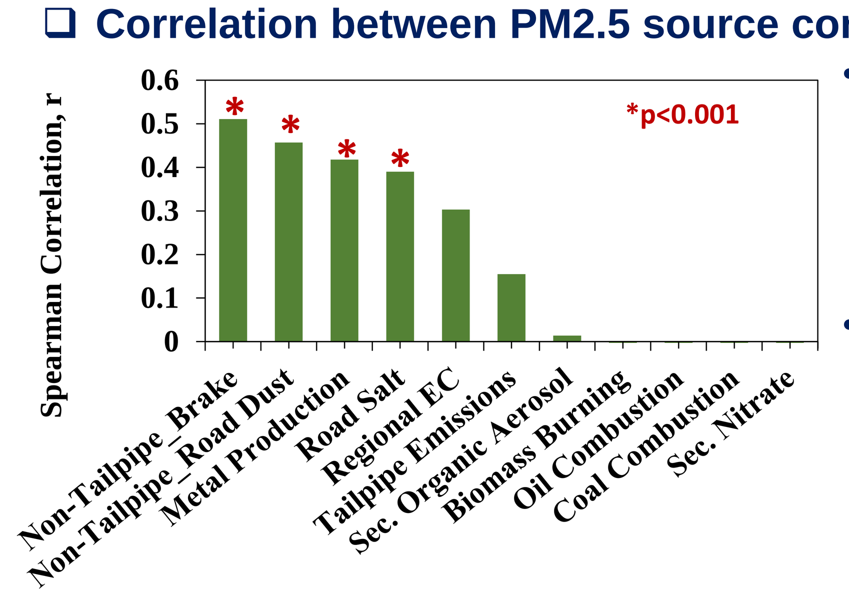
- **Annual contributions of PM2.5 sources in Toronto and monthly and day-of-the-week patterns of Tailpipe and Non-Tailpipe PM2.5 sources**
  - The contributions of emissions from regional sources (e.g., coal-fired power plants, oil combustion) and local tailpipe emissions decreased substantially.



- **Annual concentrations of Tailpipe and Non-Tailpipe PM2.5 and the percentage of sales of passenger cars and light trucks (pick-up trucks, minivans, sport-utility vehicles) in Ontario**
  - Non-tailpipe emissions have been rising since 2012 at a rate of 21%/yr for brake wear particles and 27%/yr for road dust, probably due to the increased number of heavier vehicles (i.e., SUVs) on Canadian roads.



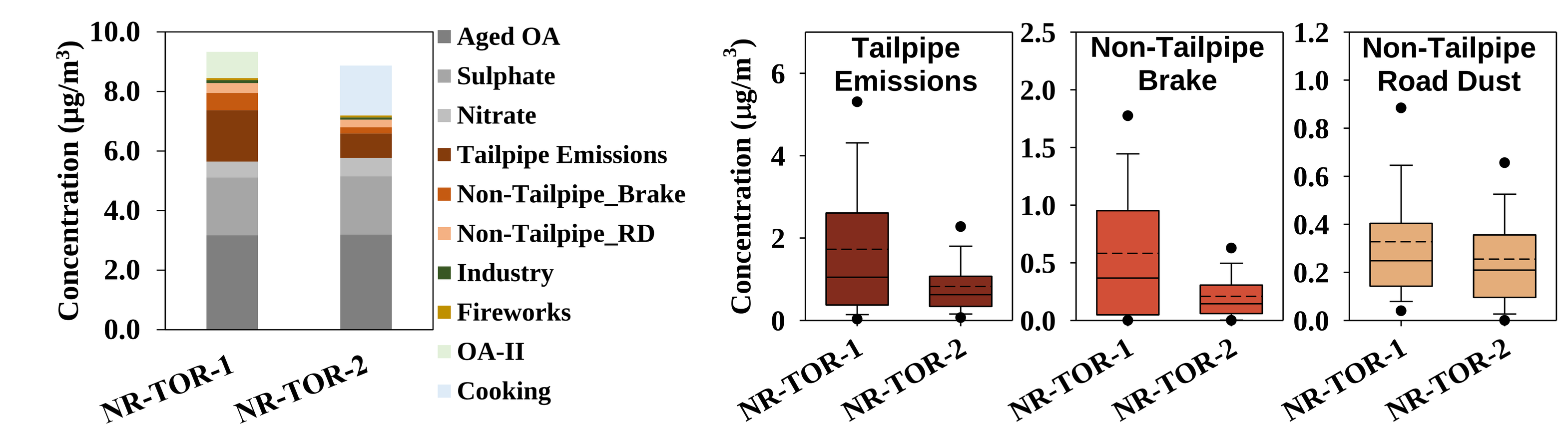
- **Correlation between PM2.5 source contribution and the OP activity**



- Non-tailpipe PM2.5 related to brake and road dust may disproportionately contribute to PM2.5 toxicity due to the high oxidative potential of some transition metals (e.g., Ba, Cu, Fe).
- Non-tailpipe PM2.5 tends to be more localized near major roads and thus any resulting health impacts can be spatially variable.

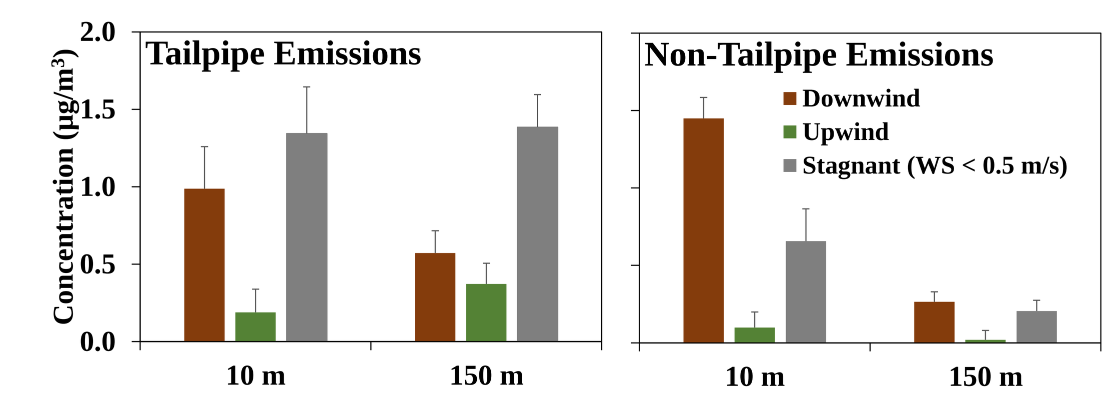
SPATIAL VARIABILITY OF PM2.5 SOURCES

- **Average concentrations of traffic-related PM2.5 sources identified at the highway (NR-TOR-1) and downtown (NR-TOR-2) sites**
  - A strong spatial variability between two sites and distinct diurnal patterns associated with traffic activity imply that exposure to these traffic-related PM2.5 sources varies both temporally and spatially.
  - The influence of the non-exhaust PM2.5 near roadways depends more on the fraction of large trucks present than on total traffic volume.



DECAY GRADIENTS IN WINTER

- **Decay gradients of Tailpipe and Non-Tailpipe PM2.5 during downwind, upwind, and air stagnation conditions at 10 m and 150 m from highway 401**
  - A very sharp decay gradient was observed for non-tailpipe PM2.5.
  - Winter stagnant air conditions further widened this traffic-influenced area to the point where concentrations were similar 10 m and 150 m away from the road, suggesting that the influence of the traffic emissions extended far beyond 150 m.



SUMMARY

- Improvements to vehicle technologies have led to an overall reduction in local tailpipe PM2.5 emissions with the reduction of traffic-related air pollutants.
- Non-tailpipe emissions mainly from brake wear and resuspension of road dust are emerging and contributing more PM2.5 than primary tailpipe emissions.
- Non-tailpipe emissions contributed a substantial fraction of redox-active trace metals.
- Traffic-related PM2.5 showed different degrees of inhomogeneity across the sites in Toronto. Tailpipe and non-tailpipe vehicle emissions are producing, on average, 15% to 28% (29% to 49% during morning rush hour) of the PM2.5 observed near roads.
- Winter stagnant air can widen the near-road influenced area, and thus the extent of human exposure to related pollutants can vary with meteorology.
- Further studies are recommended to understand the implication of heavier vehicles adversely affecting non-tailpipe emissions and the relationship between exposure to non-tailpipe emissions and health outcomes.
- The effectiveness of mitigation strategies, such as road sweeping, trapping brake particles or regulations for the composition of brake pads, needs to be explored.

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Contact: ch.jeong@utoronto.ca

Traffic-related air pollution near roadways: Discerning local impacts from background

N. Hilker[1], J. M. Wang[2], C-H. Jeong[1], R. M. Healy[2], U. Sofowote[2], J. Debosz[2], Y. Su[2], M. Noble[2], A. Munoz[2], G. Doerksen[3], L. White[4], C. Audette[4], D. Herod[4], J. R. Brook[1], G. J. Evans[1]
[1] Southern Ontario Centre for Atmospheric Aerosol Research, Department of Chemical Engineering and Applied Chemistry, University of Toronto, Toronto, ON, M5S 3E5, Canada
[2] Environmental Monitoring and Reporting Branch, Ontario Ministry of the Environment Conservation and Parks, Etobicoke, ON, M3P 3V6, Canada
[3] Air Quality Policy and Management Division, Metro Vancouver, Burnaby, BC, V5H 0C6, Canada
[4] Air Quality Research Division, Environment and Climate Change Canada, Ottawa, ON, K1A 0H3, Canada

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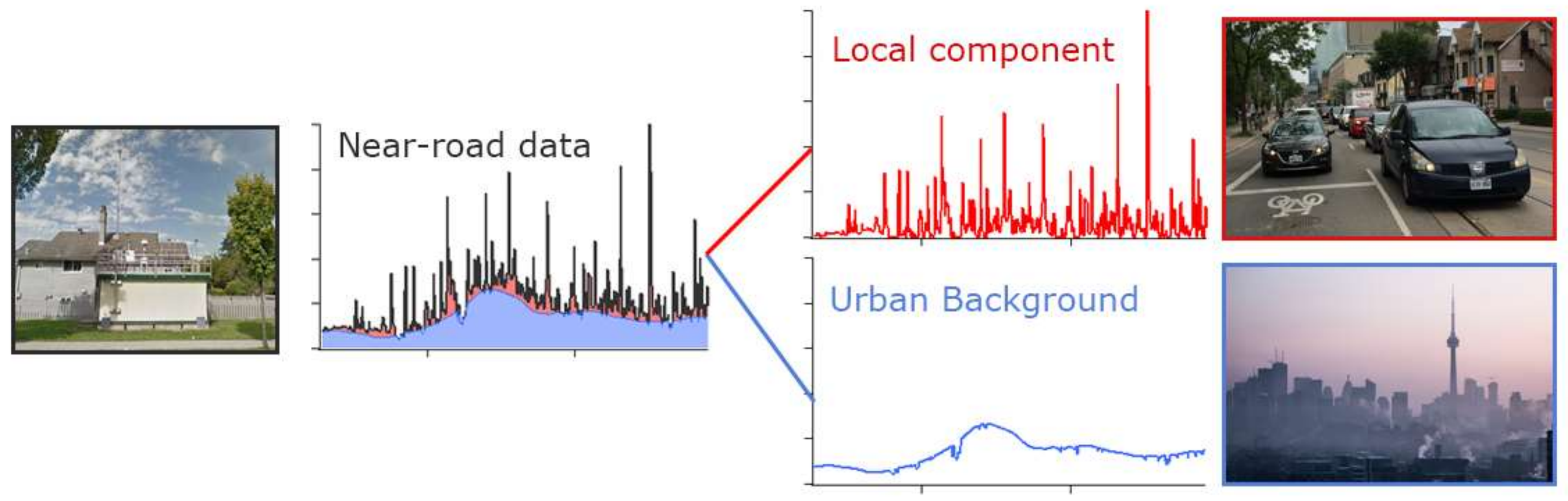
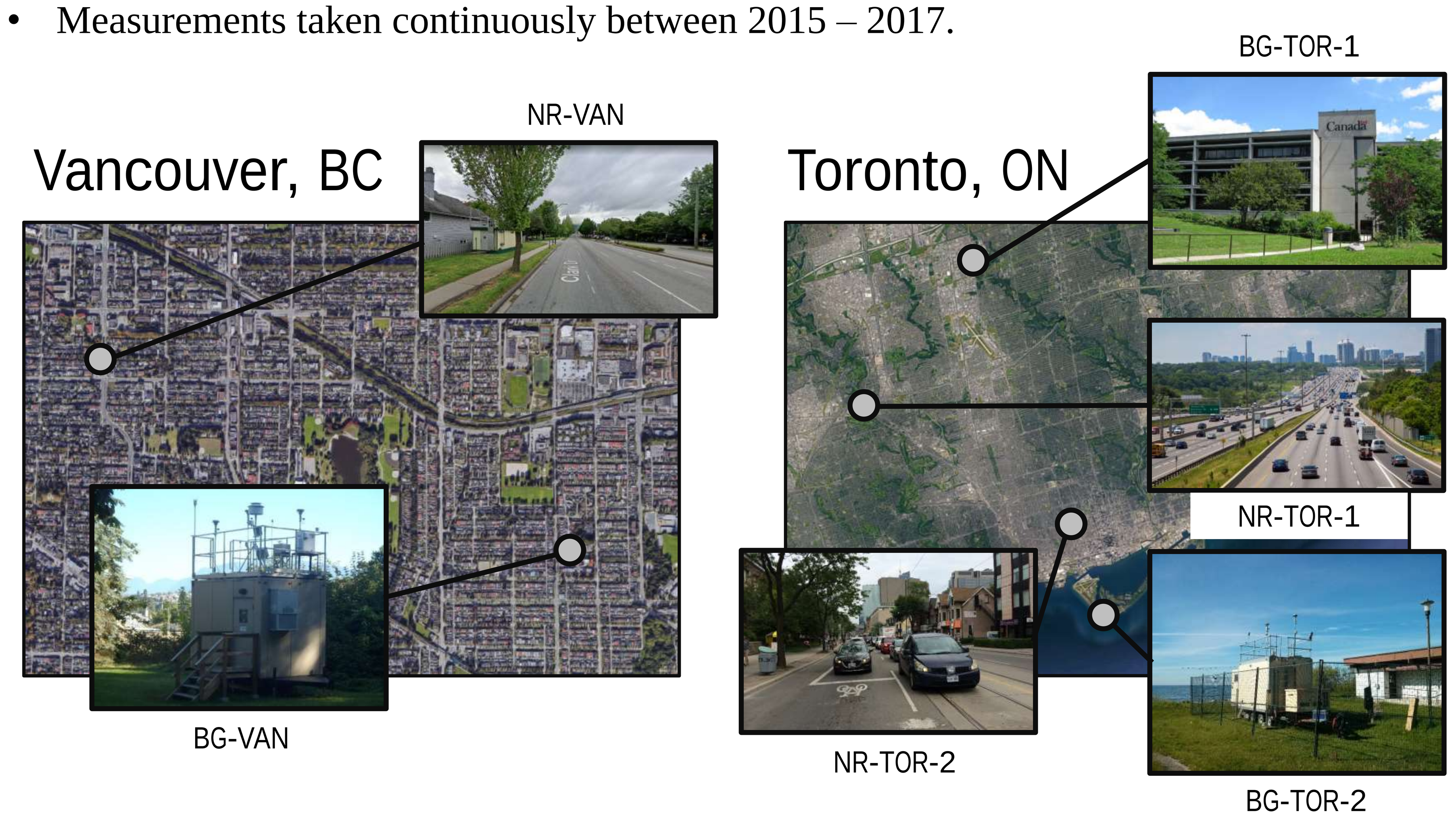
Near-road Measurements

- Air pollutant measurements near roadways are heavily influenced by traffic.
- Quantifying the amount traffic contributes to these concentrations is challenging.



Canadian Monitoring Initiative

- Six air quality stations were deployed throughout Ontario and Vancouver.
- Measurements taken continuously between 2015 – 2017.



NR-VAN: Located 6 m from Clark Drive, a major roadway experiencing 33,100 vehicles per day across four southbound and three northbound lanes.

BG-VAN: Situated on the property of Sunny Hill Children's Hospital.

NR-TOR-1: Positioned 10 m from Highway 401, with over 400,000 vehicles per day.

NR-TOR-2: Located on the University of Toronto campus in downtown Toronto.

BG-TOR-1: Located on the property of Environment Canada, Downsview.

BG-TOR-2: Located on the southernmost point of Toronto Islands.

Background Subtraction Methods

Method 1: Site Differences

- Near-road pollutant concentrations occurring as a result of traffic were estimated based on differences between near-road and background station pairs (i.e., NR-VAN and BG-VAN, NR-TOR-1 and BG-TOR-1, and NR-TOR-2 and BG-TOR-2).

Method 2: Downwind/Upwind Differences

- For each near-road station, excess pollutant concentrations were determined based on differences between measurements taken downwind and upwind of the road.

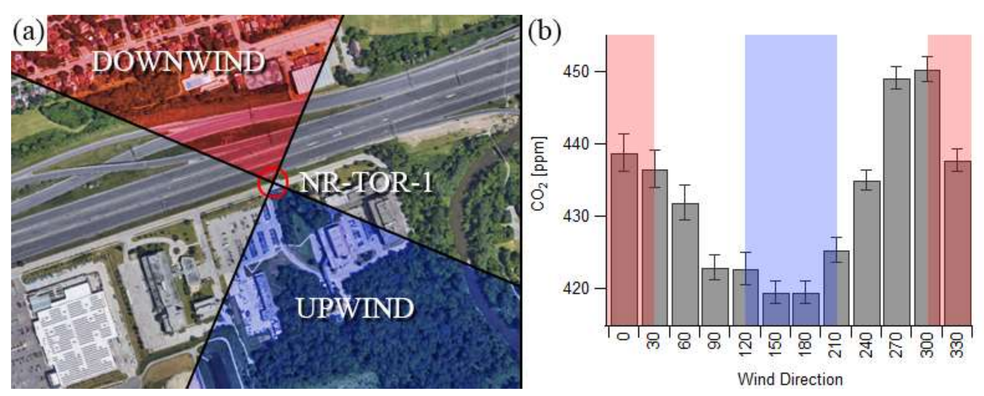
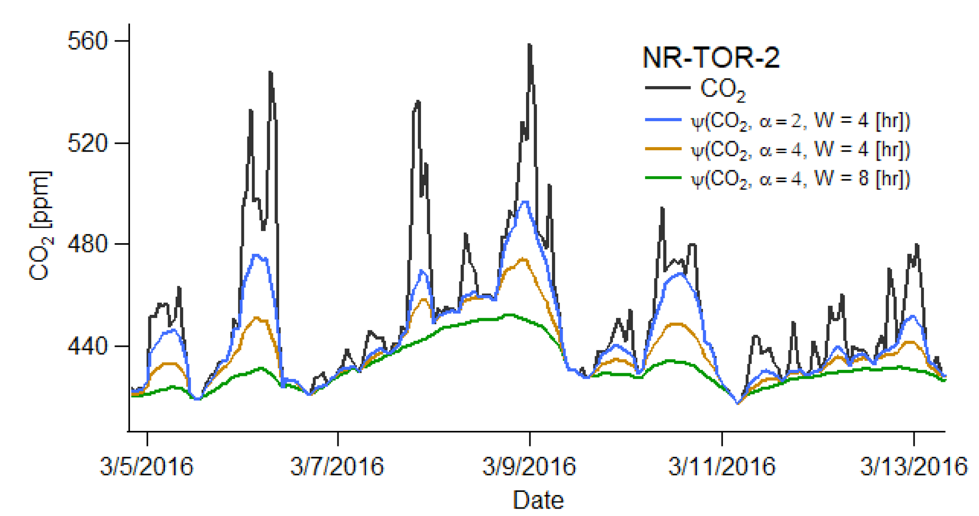


Figure 1. Satellite image of the NR-TOR-1 site, along with upwind (blue) and downwind (red) quadrant definitions (left). Average CO_2 concentrations as a function of wind direction. Error bars are 95% confidence intervals on the mean (right).

Method 3: Baseline Inference

- Excess concentrations at each near-road station were approximated based on baseline inference using time-series analysis. This inferred baseline is intended to reasonably approximate concentrations measured at nearby background stations.

Figure 2. Method 3 applied to hourly CO_2 concentrations (black) measured at NR-TOR-2. The effect of varying the input parameters α and W on the resulting baseline are shown in blue, orange, and green. See DOI ref. for details.



Method Comparison

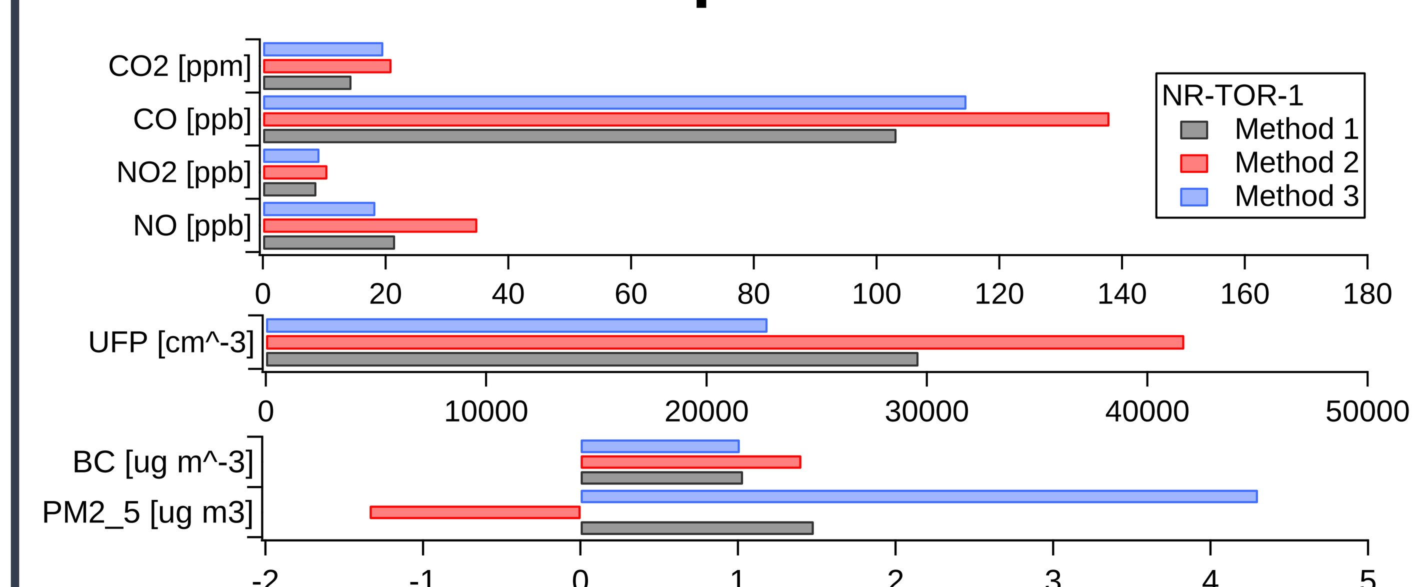


Figure 3. A comparison of local concentrations determined using each method for each pollutant measured in this study at the Highway 401 station, NR-TOR-1.

Effect of Meteorology on Local Concentrations

- Local traffic-related concentrations, as determined using Method 3, were compared with meteorological data from NR-TOR-1 and NR-VAN.
- Concentrations were normalized with respect to mean values for comparability amongst all pollutants.

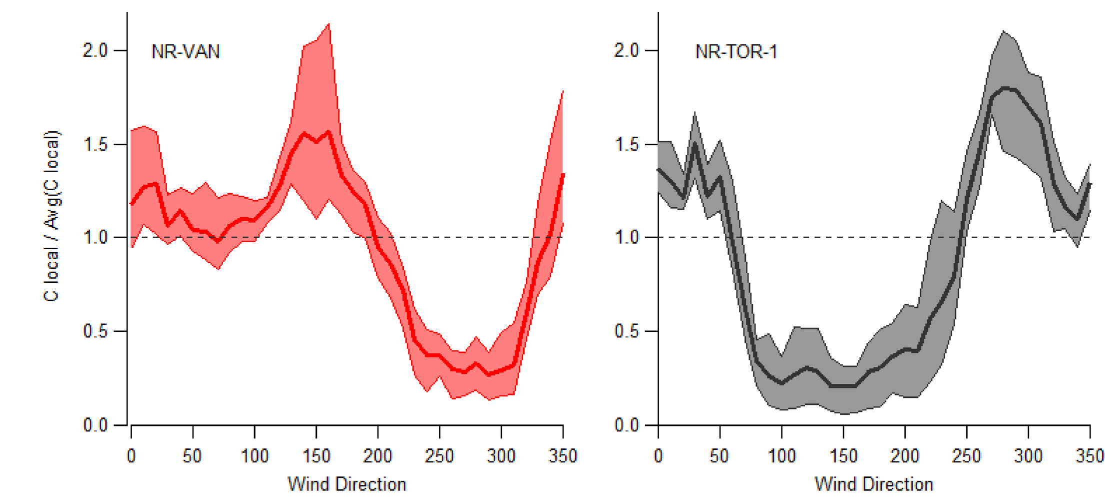


Figure 4. Normalized local pollutant concentrations determined using method 3 as a function of wind direction at NR-VAN (left) and NR-TOR-1 (right). Solid lines are average trends amongst all pollutants, and shaded areas are ranges of variability between the pollutants.

- Wind speed relation regressed against the function: $$\frac{C_{L,3}}{\bar{C}_{L,3}} = \frac{c_1}{WS^{c_2}}$$

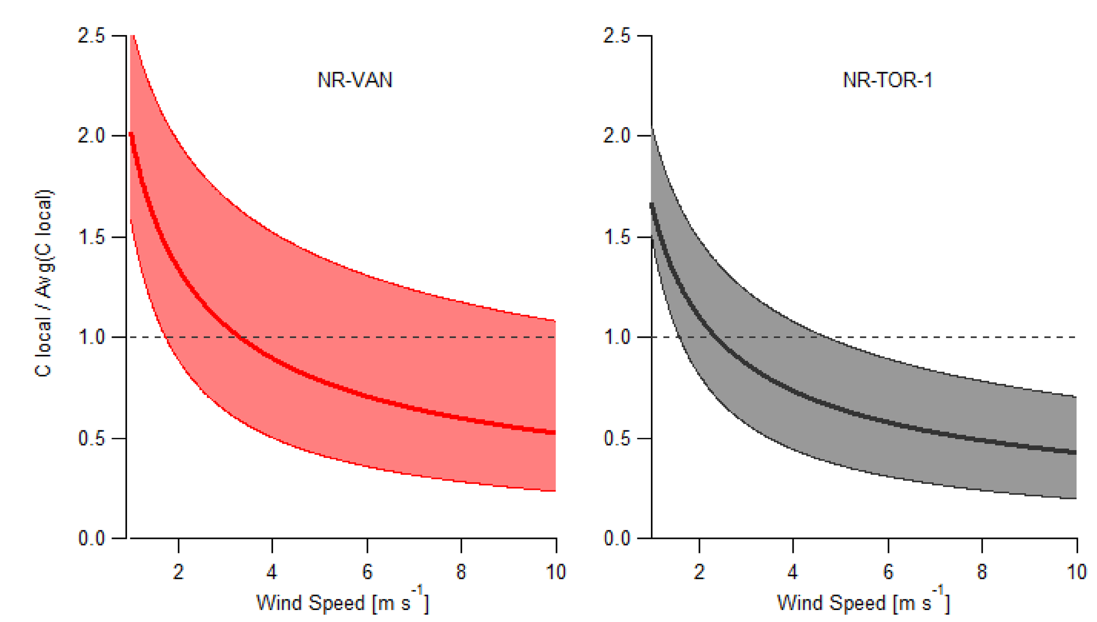
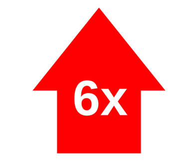


Figure 5. Normalized local pollutant concentrations determined using method 3 as a function of wind speed at NR-VAN (left) and NR-TOR-1 (right). Solid lines are average trends amongst all pollutants, and shaded areas are ranges of variability between the pollutants.

Conclusions



- Local pollutant concentrations were up to six times higher when the monitoring station was directly downwind of the road, compared with the upwind case.

- Pollutant concentrations decreased by a factor of four with increasing wind speeds from 4 to 40 km hr^{-1} (c_2 ~ 0.5-0.6).
- Method 3 (baseline inference) was shown to reliably predict background concentrations (except $PM_{2.5}$), whereas downwind/upwind analysis over-predicted the influence of traffic.

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nathan.hilker@mail.utoronto.ca