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Use of a handheld low-cost sensor to explore the effect of urban design features on local-scale spatial and temporal air quality variability

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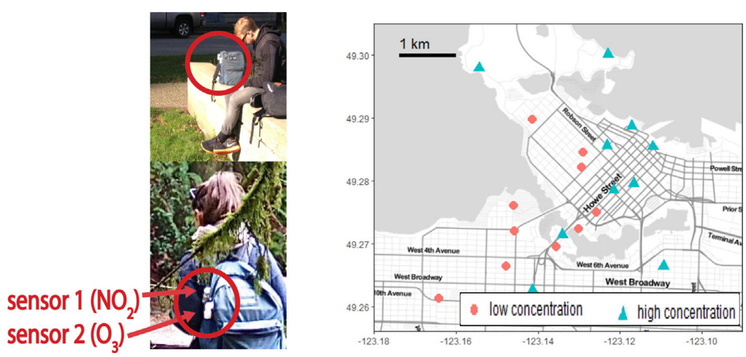
HIGHLIGHTS

- Handheld low-cost instruments successful in measuring high spatio temporal resolution data for exploring urban design effects
- Four land-use regression models made, including three for different times of the day
- Urban design features associated to NO_2 variability were bus proxies and land uses
- NO_2 varied over time, with temperature in morning and downwind ozone in afternoon most significant dynamic variables

GRAPHICAL ABSTRACT



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ABSTRACT

Portable low-cost instruments have been validated and used to measure ambient nitrogen dioxide (NO_2) at multiple sites over a small urban area with 20 min time resolution. We use these results combined with land use regression (LUR) and rank correlation methods to explore the effects of traffic, urban design features, and local meteorology and atmosphere chemistry on small-scale spatio-temporal variations. We measured NO_2 at 45 sites around the downtown area of Vancouver, BC, in spring 2016, and constructed four different models: i) a model based on averaging concentrations observed at each site over the whole measurement period, and separate temporal models for ii) morning, iii) midday, and iv) afternoon. Redesign of the temporal models using the average model predictors as constants gave three 'hybrid' models that used both spatial and temporal variables. These accounted for approximately 50% of the total variation with mean absolute error $\pm$ 5 ppb. Ranking sites by concentration and by change in concentration across the day showed a shift of high NO_2 concentrations across the central city from morning to afternoon. Locations could be identified in which NO_2 concentration was determined by the geography of the site, and others as ones in which the concentration changed markedly from morning to afternoon indicating the importance of temporal controls. Rank correlation results complemented LUR in identifying significant urban design variables that impacted NO_2 concentration. High variability across a relatively small space was partially described by predictor variables related to traffic (bus stop density, speed limits, traffic counts, distance to traffic lights), atmospheric chemistry (ozone, dew point), and environment (land use, trees). A high-density network recording continuously would be needed fully to capture local variations.

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1. Introduction

Changes in urban planning and design of urban form at local to urban scales have the potential to mitigate air pollution problems in cities. However, complex interactions between emission patterns, the built environment, and meteorology mean that urban air quality is highly heterogeneous in time and space which makes it difficult to develop informed decisions as to best practice. Recent developments to develop micro-scale variants of land use regression models (LURs) have shown potential to provide insight into the linkages between air quality and urban design at local scales (Rao et al., 2014; Tunno et al. 2016). However, attempts directly to apply the traditional LUR models developed for larger scales to micro-scale environments have shown poor transferability between and within cities (Mukerjee et al., 2012; Weisset et al., 2018) suggesting that different urban features are important in determining air quality patterns at different spatial scales.

One limitation that neither traditional LUR nor these micro-scale versions have been able to resolve for spatially dense areas, is their reliance on temporally averaged data. This means that links between urban factors and short-term temporal variations in local scale air quality, which may be important in determining links between human exposure and urban design, are not well-represented. Recent studies have shown it is possible to derive LUR models using data with improved temporal resolution using regulatory monitoring networks (Mölter et al., 2010) or handheld sensors (Deville Cavellin et al., 2016). However, this can come at the cost of reduced spatial resolution. This trade-off between temporal and spatial resolution limits the ability effectively to link different land uses or urban features to local-scale air quality.

Here we propose to use the recent improvements in sensor technology which enable dense networks of reliable low-cost instruments that can measure at high temporal resolution (Wang et al., 2016) to explore further developments into local-scale LURs. These sensors enable us to include shorter-term, temporally dynamic controls such as meteorology or local traffic behavior as predictor variables, enabling the identification and modeling of pollutant hotspots which are associated with a particular event such as the morning rush hour (Michanowicz et al., 2016). The study develops multiple LUR models that cover different time periods (morning, midday, afternoon) and uses both static (set in space over time) and dynamic (change in space over time) predictor variables. We used portable sensors around the downtown area of Vancouver, BC, to measure nitrogen dioxide (NO_2). LURs were constructed for the static variables using site-averaged data and typical LUR methodology (ESCAPE, 2010; Henderson et al., 2007) and for the dynamic variables using specific data from each time period. Further, we investigated the importance of different variables and site locations throughout the day based on concentrations rankings (for both high and low values and for temporally consistent and inconsistent), which can collectively help in understanding which urban elements best explain variability at different times over a small area. This has important implications for the evaluation of human exposure, air quality management initiatives and urban design decisions.

2. Methods and materials

2.1. Background and context

Measurements were made around the downtown area of Vancouver, BC (49°15′N 123.6°6′W) during spring 2016 (in local areas Downtown, Fairview, Kitsilano, and West End). This area is 14.63 km^2 with population of 172,050 (Statistics Canada, 2011). Ambient NO_2 is a well-studied atmospheric pollutant, with high concentrations commonly measured within urban areas due to traffic emissions as the principal source (Kim Oanh et al., 2013). A seasonal cycle is present, with concentrations often higher during winter from reduced engine efficiency and less atmospheric mixing including increased observation of temperature inversions. There are also typically two daily peaks that correspond to commuting periods (Mayer, 1999). Two regulatory air quality stations are within the study area (Robson Square and Kitsilano), with only the Robson Square station operational during the measurement campaign. Vancouver has a good record of air pollution research, including a number of LUR studies (Henderson et al., 2007; Abernethy et al., 2013; Su et al., 2008; Wang et al., 2013). Typical predictor variables for NO_2 within these models have been traffic densities (both light and heavy vehicles), land uses, road lengths, building heights, and population densities, with Pearson correlation (R^2) values between 0.52 and 0.67.

2.2. Measurement campaign

Monitoring was carried out over 24 March–21 April 2016, excluding weekends and public holidays. The time of the year was selected because historically concentrations over this period at Robson Square have been similar to annual averages. Instruments were handheld Aeroqual S500 to measure ambient NO_2 and ozone, (O_3 measured due to cross-interferences with NO_2 sensor), a BT-Q1000X GPS to measure latitude and longitude, and a Kestrel 4500 Pocket Weather Tracker to measure air temperature, relative humidity, wind speed, and dew point with instrument specifications in the S.I. We used one NO_2 and one O_3 instrument throughout the entire campaign. They were mounted together and measuring simultaneously. Both devices were set to record a concentration measurement every 1 min. They sampled the air through similar Teflon inlets that were approximately 5 cm apart. The instruments were placed within a backpack with Teflon inlets to ensure consistency in measurement height. Ideally, sites would be monitored continuously in order to capture all spatio-temporal variation evenly, however logistical and resource constraints meant that this was not possible. The compromise was to sample locations during similar times across different days, and was similar to previous handheld LUR sensor work (Deville Cavellin et al., 2016). Each site was visited for 20 min at a time and visited during each of the three times: morning (between 08:00 and 11:00), midday (11:00–15:00) and afternoon (15:00–18:00). Sites were selected using results from previous Vancouver LUR work (Henderson et al., 2007), high-temporal LUR resolution work (Dons et al., 2014), and high-spatial resolution LUR work (Miskell et al., 2015). Areas with high variability in predictor variables were targeted and other sites added to achieve reasonably even spatial coverage. This resulted in 45 sites, with locations in spaces such as large parks, residential, high-rise commercial, or mixed-use shopping settings. Sites were divided into five areal sub-clusters to ensure that each site could be monitored within the required time frame (in S.I.). Traffic variables collected were counts of heavy (truck and buses) and light vehicles along the nearest road. All passing buses or trucks during sampling were counted, along with any passing car within an area where traffic loads were low (e.g. in quiet residential streets). We counted number of cars in busy areas by four one-minute periods throughout sampling. This was due both to the difficulty in counting over the entire sampling time with high traffic loads and that nearby traffic lights (phases around one-minute) caused regular patterns in passing traffic. These four counts were then added and multiplied by five to give a 20-minute estimate on number of passing cars. Notes were also made regarding the immediate surroundings and any events, such as presence of awnings or trees and any nearby construction work. Data from 19 weather underground (WU) stations (five with wind data) were linked to the five areal sub-clusters and medians derived for times when monitoring was completed to give an approximate state of the atmosphere at a wider spatial scale. Summaries on each WU cluster are provided in the S.I.

2.3. Sensor calibration

Field and laboratory calibration against the regulatory monitor and careful assessment of errors from sensors are critical to evaluate the