A Mobile Sensor Network to Map CO_2 in Urban Environments

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Introduction

There are a variety of models and methods that can characterize and quantify the global increase in carbon dioxide (CO_2) mixing ratios in the atmosphere and their links to anthropogenic emissions and terrestrial and oceanic sinks (Marland *et al.,* 2009). However, quantifying, mapping, visualizing and monitoring CO_2 emissions and sequestration at policy relevant scales - the local to urban scale - remains a challenge (Christen, 2014). Emerging modular open source technologies are allowing for the miniaturization, mobilization and increasing accessibility of sensor systems that may be a promising way to observe and map CO_2 mixing ratios across heterogenous and complex landscapes, including urban environments (Snik et al., 2014). These measurements can serve as input for inverse modelling of emissions and as input data for the visualization of urban emissions in the context of science-communication to public. We present a system for monitoring CO_2 mixing ratios in cities using a network of mobile CO_2 sensors deployable on vehicles and bikes combined with geo-spatial analysis and visualization tools.

Methods & Results

Design & Testing

Components from the Arduino platform (Arduino CC, Ivrea, Italy), an opensource programmable microcontroller, were coupled with Li-Cor's Li-820 infrared gas analyzer (IRGA) (Licor Inc., Lincoln, NB, USA) to prototype a portable CO_2 analyzer for possible future CO_2 monitoring, and pollution mapping in general. With low cost compact components, open code base, and flexible hardware interfacing, the Arduino platform provided a lightweight and modular prototyping environment capable of communicating digitally with the Li-820 IRGA, a GPS (Adafruit Ultimate GPS Logger Shield with GPS Module, Manhattan, New York, USA) unit, and digital temperature thermometers (Maxim Integrated One Wire Digital Temperature Sensor - DS18B20, San Jose, CA, USA). The system requires 12 volts of power which can be supplied by battery or via car cigarette lighter socket and measures CO_2 mixing ratios, geoposition (latitude/longitude, speed, altitude, and satellite strength), and internal and external air temperature which are logged onto a micro SD card at 1-second intervals. Air is drawn into the system through a 3m long inlet tube (6.35mm diameter, Dekron Bendable Tubing, Mt. Pleasant, Texas, USA) using a small KNF gas pump (KNF Neuberger, Inc., Trenton, NJ, USA) at 700 cc/min as recommended by Licor. The system is 35.8cm x 27.8cm x 11.8cm, weighs 2.6 kg and is contained in a weather-proof case.

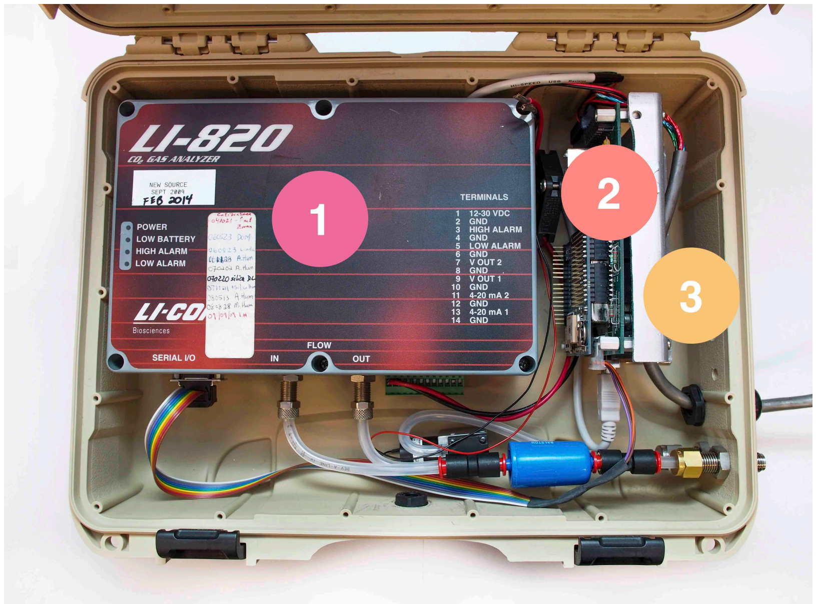

Figure 1: Mobile CO_2 System including (1) Licor Li-820 Infrared gas analyzer, (2) Adafruit GPS, OneWire digital, (3) Arduino Mega Microcontroller, temperature thermometer (not shown).

Several key system specifications were evaluated, namely: precision, accuracy, drift, and total delayed response time. To test for system precision, a 6-point calibration was performed using six tanks of known mixing ratios of CO_2 calibrated against CDML / NOAA standard tanks. This test showed a strong linearity and a root mean square error (RMSE) of 1.1 ppm for the six different CO_2 mixing ratios at a R^2 of 0.99.

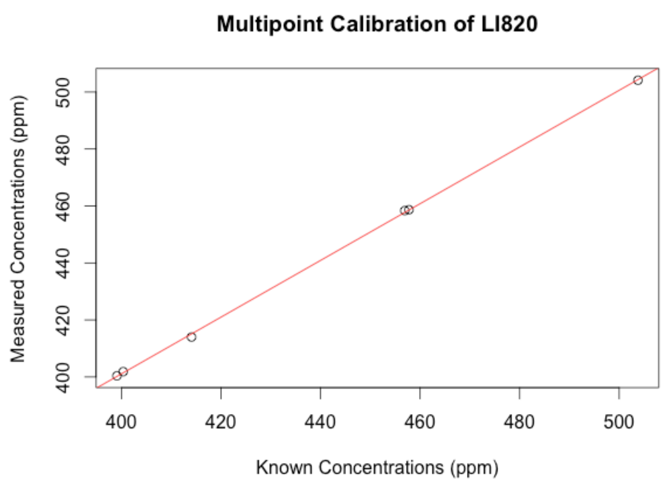

Figure 2: Multipoint Calibration of Sensor System showing observed values versus known concentrations.

Sensor accuracy and drift were tested over the course of 7 days in the lab, each sensor drawing in air from the same point outdoors. The accuracy between the sensors, determined by the RMSE, was +/- 3ppm, while the drift was up to +/- 4 ppm over the seven days from the average of the 5 measurements.

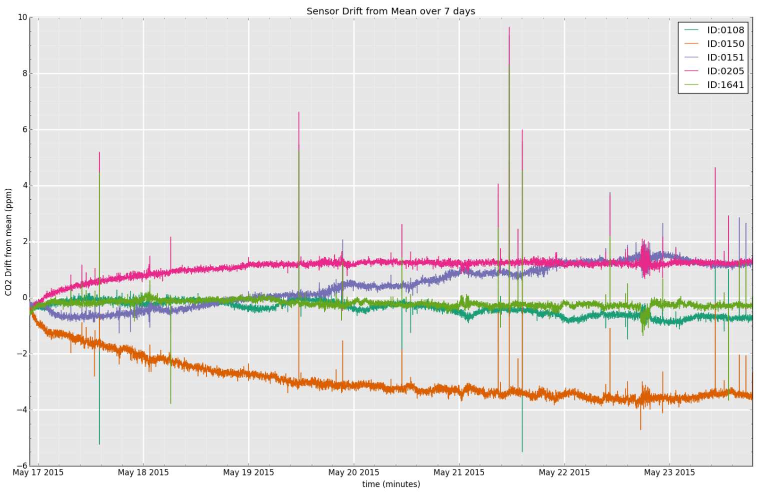

Figure 3: Testing for sensor drift of the five mobile sensors over a seven-day measurement period. Each line corresponds to one of the five mobile CO_2 sensors.

In order to properly geotag the measured CO_2 mixing ratios when traveling on a vehicle, the total delayed response time was calculated based on the cumulative elapsed time between when a sample of air enters the system's 3 m long inlet tube until 50% of the time it takes for the instrument's cell to be filled with the gas and measured by the system itself at a flow rate of 700cc/min. To test this, a solenoid switch was used to pass nitrogen gas ("zero gas") into the sample tube inlet while simultaneously logging the exact second in which the solenoid was triggered. The total delayed response time of the system using a 3 m inlet tube was determined to be 13 seconds; this value is used to offset the measured CO_2 mixing ratios.

Measurement Campaign

A total of 5 mobile prototype sensors were built. This pilot 'fleet' of sensors were tested in a measurement campaign in the city of Vancouver, BC, Canada. In this focused measurement campaign, the goal was to determine the variability of CO_2 in the urban canopy layer, across a range of urban land use types and densities within a short time frame (3.5 hours). The dataset is used to showcase the potential of such measurements to aid in point- and line source mapping. The measurement campaign was designed such that nearly all grid cells sized 100m by 100m within a 12 km^2 transect used in previous research for detailed emissions mapping (Environmental Prediction in Canadian Cities (EPICC) transect from Van der Laan, 2009) would be traversed at least once by one of the sensors during a 3.5 hour measurement period between 10:30 to 14:00. Both cars and bike with sample inlet tubes raised to 2 m height were used to cover the street and lane grid and to traverse paths inaccessible by car.

Figure 4: Environmental Prediction in Canadian Cities (EPiCC) Transect and streets sampled in measurement campaign

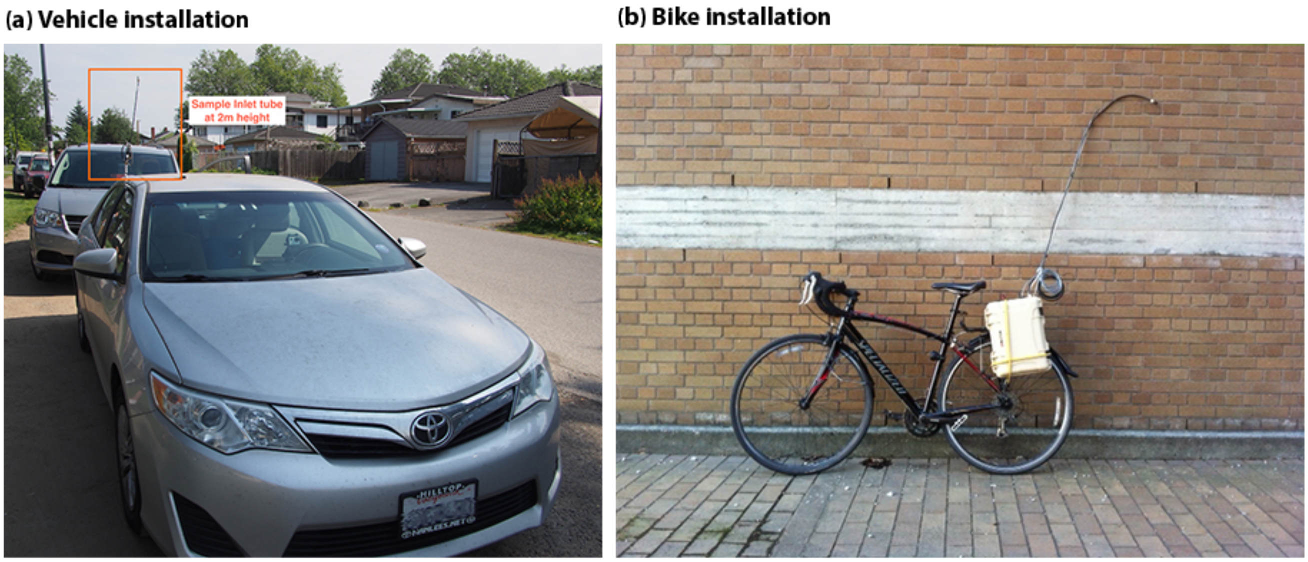

Figure 5: Sensor installation on (a) vehicle and (b) bike. The sample tubes reach approximately 2m height.

The results of the measurement campaign showed CO_2 mixing ratios ranging from 390 ppm, most likely related to areas with high density of photosynthesizing vegetation such as in parks, to 906 ppm in CO_2 plumes from vehicle exhaust. In general, the grid cells covering major arterial roads and downtown core of Vancouver showed the highest maximum, minimum, median and mean of CO_2 mixing ratios (see table 1: “Downtown & Arterial Roads). Conversely, the grid cells covering residential streets and forested trails of Stanley Park in general exhibited the lowest CO_2 mixing ratios for the same summary statistics (see table 1: “Stanley Park (forested) & Residential”). Over 85% of the cells had a positive skewness, implying that, in general, there are intra-grid CO_2 spikes occurring regularly across the city regardless of land use type and density.

Land Use	Mean (ppm)	Median (ppm)	Minimum (ppm)	Maximum (ppm)
Stanley Park (forested) & Residential	475 – 513	462– 505	390 - 401	713 – 906
Downtown & Arterial Roads	394 – 412	394– 407	422 - 427	395 - 440

Table 1: Summary statistics for land uses exhibiting similar CO_2 mixing ratios for the observed time period. The table summarizes the mean, median, minimum, and maximum range of values for the forested trails of Stanley Park and the residential roads and laneways and the dense urban downtown core and arterial roads.

(a) Median CO2 per grid cell - 100 m x 100m

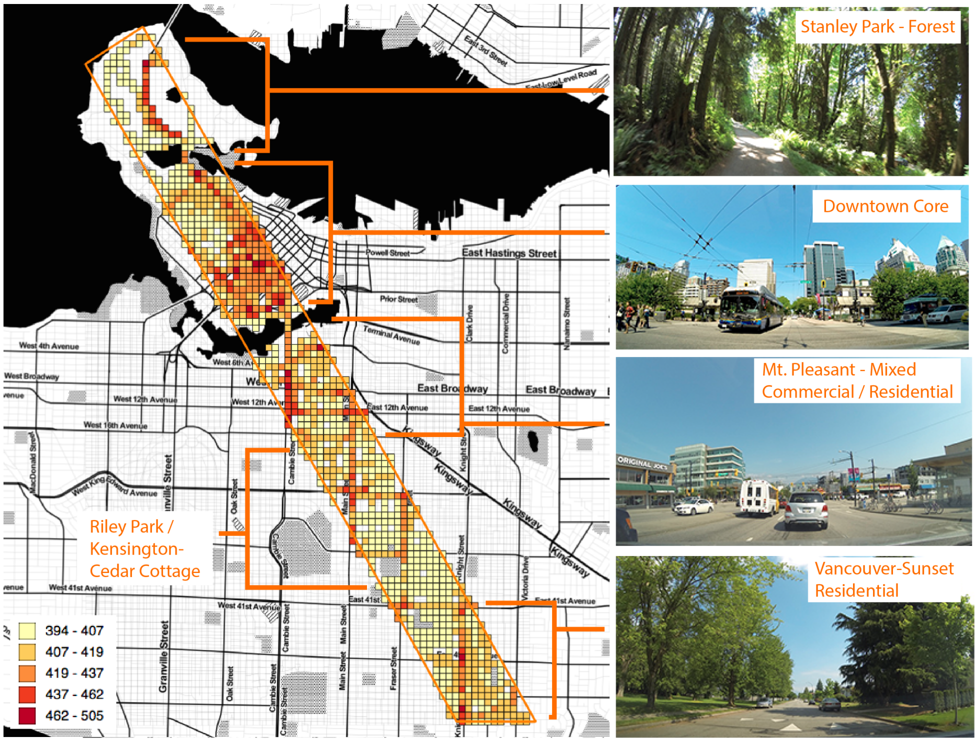

Figure 6: Median CO_2 aggregated to a 100 m x 100 m grid. Images show general land cover for the given areas. Stanley Park is forested, The Downtown core is high density urban, Mt. Pleasant is mixed commercial/residential, and Vancouver-Sunset and Riley Park/Kensington-Cedar Cottage are mostly residential with some commercial areas along the major arterial roads. The images shown were taken by a camera attached to the vehicle dashboard and bike helmet during the sensor deployment.

Vancouver's vehicle count data (Vancouver Open Data Catalogue) for the duration of the measurement period is used to quantify the relationship between the vehicle traffic and measured CO_2 mixing ratios, using known vehicle emission factors as a method of correlating vehicle count to the observed measurements.

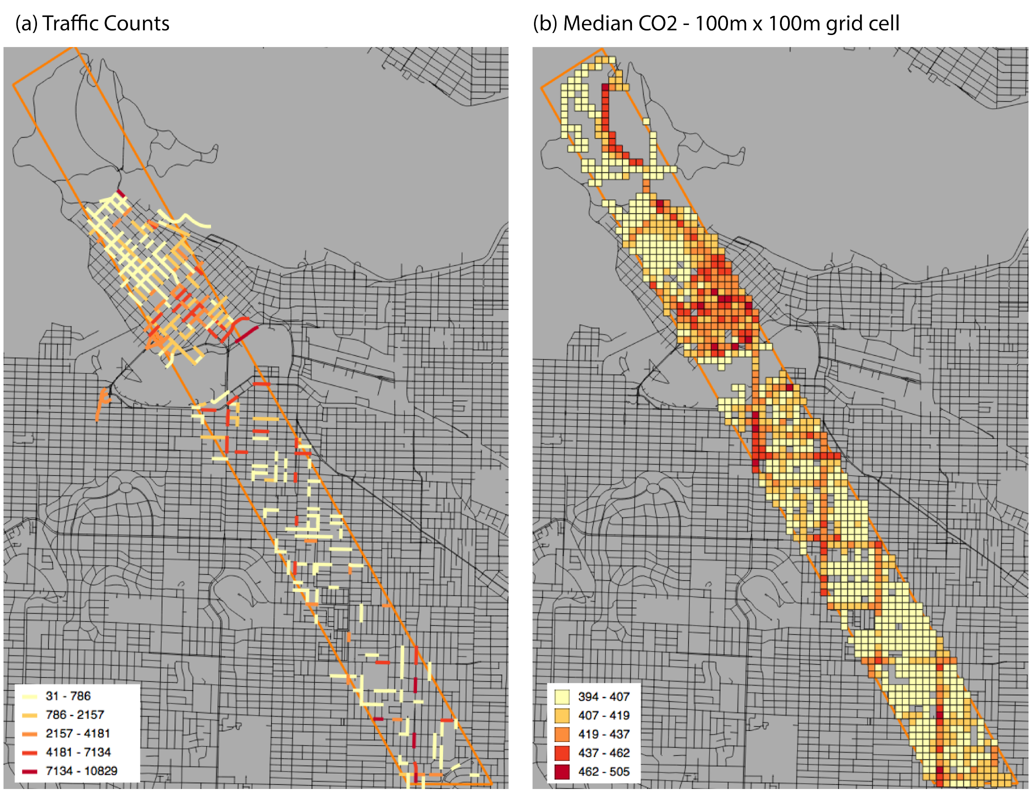

Figure 7: Visual comparison of (a) Vancouver's traffic count data and (b) measured CO_2 mixing ratios aggregated to 100m x 100m grid cells shows generally good agreement.

Visualization Tools

The measured data is processed and then visualized in an interactive web-based mapping application. The tool, built on open source web technologies, allows users to explore various spatio-temporal dimensions of the data in the web browser, including filtering by space and time, calculating basic grid statistics (e.g. minimum, maximum, range, average, etc.) and comparing additional contextual layers such as traffic counts and population density. The web application also allows for further investigation with its open data application programming interface (API) which allows users to download the data or interface with the data in other applications. The tool is aimed to help increase access of urban climate research for research purposes, but also to the informed public, citizen scientists, and urban planners and policy makers. With an open code base and API, the technology stack can be reused and remixed to visualize other types of mobile measurements, such as air pollutants or temperature for urban heat island studies.

Summary & Future Directions

This project goal was to design and test a mobile sensor system to characterize CO_2 mixing ratios across a complex urban environment. The study shows that such a mobile sensing system is capable of measuring at a resolution of +/- 1ppm at an accuracy of up to +/- 7ppm depending on sensor calibration and drift and resolve variations at a scale of < 100 m at 3.5 km^2 per hour. The result of the measurement campaign indicates that a mobile CO_2 system can be a viable method of monitoring canopy layer CO_2 mixing ratios in complex urban environments, but considerations should be made with respect to sampling density, bias towards roadways, and instrument calibration. Additional analysis relating traffic count and building emissions will be conducted to examine possible correlations between inventory data and measured near-field CO_2 enrichment. Furthermore, long-term seasonal and diurnal measurements could be done to examine temporal variability on the observed patterns. By collaborating with existing mobility providers, it may be possible to achieve extensive and intensive measurements across city on pollution and greenhouse gases in real-time.

Acknowledgements

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