Evaluation of portable air quality sensors at the Vancouver (Clark Drive) near-road air quality monitoring site

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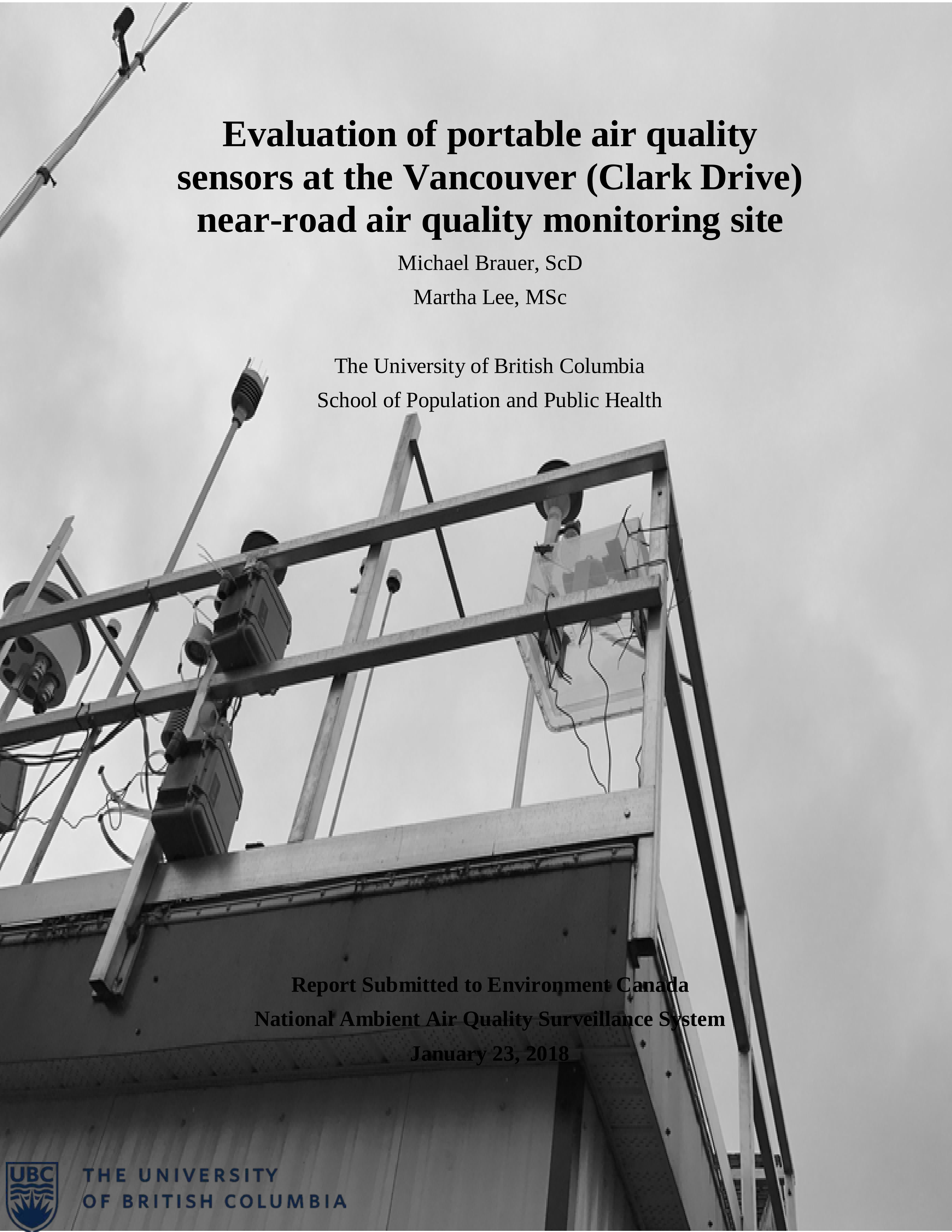

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Introduction

This report describes evaluation of six low-cost, low-power air quality sensors and their comparison with co-located reference monitors at the Vancouver (Clark Drive) near-roadway air quality monitoring site operated by Environment Canada and Metro Vancouver. There has been a recent increase in awareness of public health issues associated with air quality combined with the development and availability of numerous low-cost, low-power air quality sensors. These sensors, and the ability of some models to be networked with data streaming to a central server offer the potential for less expensive air quality monitoring and enhanced spatial coverage. Furthermore, the commercial availability of these sensors offers non-regulatory bodies, researchers, and members of the public the possibility of near real-time access to additional air quality data, beyond that already provided by air quality management agencies. However, many of the companies producing these sensors have not compared their devices with regulatory grade monitors; hence, the accuracy, precision and stability of measurements from these sensors is not well understood. Understanding the performance of these devices is important for their use by non-regulatory bodies, researchers, and the general public, and for expanding their potential use for regulatory purposes.

Methods

Site

The low-cost sensors were co-located at the near-roadway monitoring station operated by Metro Vancouver and Environment Canada on Clark Drive at 11th Avenue in Vancouver, British Columbia, Canada (Figure 1). Clark Drive is a north-south thoroughfare traversing Vancouver and conveying both light duty vehicles as well as a high volume of commercial trucking heading to and from the Port of the Vancouver. Due to the proximity of traffic, this site is likely to experience relatively high concentrations of primary pollutants emitted from motor vehicles. Equipment at the site monitor a range of air pollutants including particle number concentrations (ultrafine particulate matter), $PM_{2.5}$ (fine particulate matter), BC (black carbon), NO (nitric oxide), NO_2 (nitrogen dioxide), and O_3 (ozone) (Table 1). The TSI 3031 was later removed from the station due to poor performance.

Table 1: Reference monitor sensors

Instruments	Pollutant	Units
TSI 3031	Particle Number Concentration (~20 nm – 1,000 nm)	particles/cm^3
Teledyne API 651	Particle Number Concentration (7 nm - to ~3,000 nm)	particles/cm^3
SHARP 5030	$PM_{2.5}$	μg/m^3

Magee Scientific AE31	BC	μg/m^3
Thermo Scientific Model 42i NO-NO_2-NO_X Analyzer	NO and NO_2	Ppm
Thermo Scientific Model 49i O_3 Analyzer	O_3	ppm

This site was specifically developed to capture roadside concentrations. A comparable roadside monitoring site in Canada is located in Toronto. Both the Clark Drive site in Vancouver and its counter-part in Toronto are relatively recent additions to the large Canadian monitoring network (National Air Pollution Surveillance Program, 2017) but have only been operational for a few years.

A B

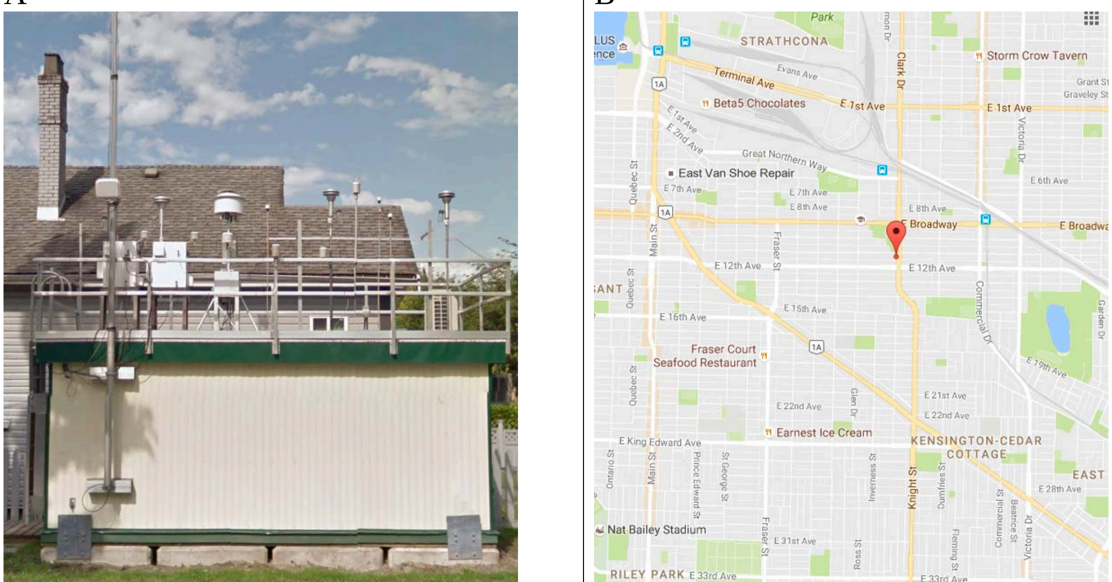

Figure 1: A) the monitoring station and B) the location of the monitoring station on Google Maps (Google Maps, 2017)

Deployment of Low-Cost, Low-Power Sensors

Six low-cost, low-power sensors were selected based on interest from Environment Canada and use by the general public. Sensors were tested from August 30, 2016 to August 17, 2017. (Figure 2). Theses sensors were commercially available and had sampling ranges compatible for environmental use. All sensors were deployed at the Clark Drive monitoring station.

<table>
<tr><td>A TZOA RD02

</td><td>B PurpleAir (PA1003)

</td></tr>
<tr><td>C ES-642
</td><td>D Aeroqual

</td></tr>
<tr><td colspan="2">E microAeth AE51</td></tr>
</table>

Figure 2: The six sensors which were evaluated

a) TZOA RD02

The TZOA (https://www.tzoa.com/) is an optical particle counter and the RD02 is the research model of this sensor (Figure 2). It is manufactured by TZOA Wearables™ (Vancouver, Canada). It also contains temperature and humidity sensors and is powered by an internal 3000mAh battery.

TZOA sensors were deployed in two Pelican™ cases (one per case) to protect them from the weather, particular rain, as these sensors were not built for outdoor deployment (Figure 2). The cases were modified to increase air flow in and out of the case while still prevent rainwater from getting into the boxes. The cases were hung on the railing as close as possible to the ultrafine PM and black carbon reference monitors (Figure 3).


Figure 3: Locations of Pelican™ cases during sensor deployment

Three TZOA sensors (hereafter referred to as TZOA 0010, TZOA 0080, and TZOA 0108) were deployed during the sampling period. At most only two sensors were deployed at one time, mainly TZOA 0010 and TZOA 0080 as TZOA 0108 was being used to test wireless connections and then later became inoperable. Due to sensor failure, towards the end of the campaign only one sensor was deployed. Sensors were also removed during periods of cold weather as the sensor would shut off at temperatures close to 0 °C. The TZOA sensors were first deployed on August 30, 2016 (the first day of sampling) and ran until the end of the sampling period on August 17, 2017. A five-minute sampling interval was used.

b) PurpleAir (PA1003)

The PurpleAir sensors (Figure 2) are optical particle sensors (https://www.purpleair.com/) manufactured by PurpleAir™ (USA). The sensor provides output of $PM_{1.0}$, $PM_{2.5}$, and PM_{10} concentrations based on conversion factors from the manufacturer. The sensor uses a PMS5003 laser particle counter. Readings from this counter are translated into the $PM_{1.0}$, $PM_{2.5}$, and PM_{10} $\mu g/m^3$ by the manufacturer's conversion algorithm. Factory calibration is conducted on both the PMS5003 sensor when manufactured and for the PurpleAir sensors before shipping to users (PurpleAir, 2017). This sensor has no internal data storage and depends on a Wi-Fi connection for data storage. Data from the sensor are transferred to the PurpleAir website and presented on the PurpleAir map where they can then be downloaded. First generation sensors appeared in the fall of 2015 and were used in this study. As there have been promising early results in comparison studies (http://www.aqmd.gov/docs/default-source/aq-spec/laboratory-evaluations/purple-air-pa-ii---lab-evaluation.pdf?sfvrsn=4) by the South Coast Air Quality Management District (2017) there is a growing interest in these sensors especially for $PM_{2.5}$. For example citizen networks have been established on Vancouver Island and in Kamloops BC with additional examples of single monitors deployed elsewhere in BC, Alberta, Ontario and Quebec. Since this sampling program was initiated, a 2nd generation outdoor sensor and an indoor model have also been released.

The PurpleAir sensors were built for outdoor deployment and are weatherproof and can be deployed directly outside. In this study, they were hung on the same railing as the Pelican™ cases containing the TZOA sensors placing them as close as possible to the inlets for the PM regulatory monitors. A Wi-Fi hotspot was placed in one of the Pelican™ cases in order to connect the PurpleAir sensors to the company's data storage cloud.

Three PurpleAir sensors (hereafter referred to as PA1, PA2, PA3) were deployed during the sampling period but at different points during the campaign. PA1 was deployed October 11, 2016. PA2 was deployed January 19, 2017 and PA3 was deployed February 16, 2017. Once deployed, all PurpleAir sensors were used until the end of the study. Data were sampled at five minute intervals.

c) Met One ES-642

The ES-642 (Figure 2) is dust monitor measuring total suspended particles (http://metone.com/air-quality-particulate-monitors/fence-line-near-roadside/es-642/) manufactured by Met One Instruments™ (Oregon, USA). For the Clark Drive deployment, a $PM_{2.5}$ cyclone was used. The sensor is a nephelometer using forward laser light scatter to measure airborne particulates in real-time. Air is drawn into the instrument where a laser (Diode Laser, < 5 mW, 670 nm wavelength) interacts with the sampling stream. The reflected and refracted light from the laser is collected by a photodiode detector. This is translated into a particulate mass concentrations (Met One Instruments, 2011). As reported by the manufacturer, the measurement sensitivity is 0.001 mg/m^3 and the nephelometer accuracy is ± 5% based on a traceable standard with 0.6µm PSL. The ES-642 sensor was modified by Akrulogic and outfitted with a weather-proof case, modified for network connection, and a stand.

Only one ES-642 sensor was deployed. To prevent interference with the reference monitors at the Clark Drive stations, the sensor was placed on the opposite side of the monitoring station roof on a tripod stand. The sensor was deployed on March 30, 2017 and operated until the end of the study. One minute sampling averages were used.

d) NO_2 and O_3 Aeroqual series 500

Both the NO_2 and O_3 series 500 (https://www.aeroqual.com/product/series-500-portable-air-pollution-monitor) sensors (Figure 2) are manufactured by Aeroqual™ (New Zealand). The base allows for interchangeable sensor heads with difference sensors for the different pollutants. For this study, the environmental semiconductor oxide O_3 sensor (OZU 0 – 0.15 ppm) and electrochemical NO_2 sensors were tested. Unlike the 200 series, the 500 series sensors log data. A lithium battery is used with a run time of ~8 hours on a full charge. Comparisons of these sensors have been conducted by the South Coast Air Quality Management District (2017), http://www.aqmd.gov/docs/default-source/aq-spec/laboratory-evaluations/aeroqual-s500-o3---lab-evaluation.pdf?sfvrsn=4, and Lin et al. (2015).

NO_2 Aeroquals were deployed in the two Pelican™ cases, one per case, alongside the TZOA sensors. O_3 Aeroqual sensors were deployed under a plastic cover that was hung from the railing. As the O_3 sensor was used to modify the measurements from the NO_2 sensor, Aero 3 was moved under the plastic cover.

In total three NO_2 Aeroquals (Aero1, Aero 2, and Aero 3) were used in this study, however initially only two sensors (Aero1 and Aero 2) were available. Both were deployed on August 30, 2016. Aero 2 was collected October 6, 2016 to test wireless data transfer. Aero 3 was deployed on March 20, 2017. The subsequent sampling used three O_3 Aeroquals (Aero 4, Aero 5, and Aero 6). Aero 4 and Aero 6 were deployed on April 4, 2017, however Aero 6 was replaced by Aero 5 on May 5, 2017. Ten-minute sampling intervals use used due to the limited internal memory of the devices.

e) mircoAeth AE51

The microAeth AE51 (https://aethlabs.com/microaeth) is a portable real-time data logging black carbon (BC) aerosol sensor. It is manufactured by AethLabs (San Francisco, CA) and utilizes Aethalometer technology, which measures the rate of change in absorption of light (880 nm wavelength) transmitted to estimate BC levels. Air is pulled into the unit and through a filter via a pump. Attenuation of light from the replaceable filter strip relative to the clear reference area on the same filter is used to calculate the concentration of BC in the air. These sensors have a measurement range of 0 – 1 mg BC/m^3 with a resolution of 0.001 µg BC/m^3. Flow rate can be set to 50, 100, 150, or 200 ml/min and a time base of 1, 10, 30, 60, and 300 sec. The sensors run on a rechargeable internal lithium-ion battery. This sensor has been used extensively for environmental and personal monitoring within air quality research. The South Coast Air Quality Management District (2017) also have run a comparison study (http://www.aqmd.gov/docs/default-source/aq-spec/field-evaluations/micro-aeth---field-evaluation.pdf?sfvrsn=2) where the sensors performed well.

The mircoAeths were deployed in the Pelican™ cases, one per case. A sampling line was run outside of the case and the lines from both boxes were coiled and attached to the railing with their inlets located side by side. Five microAeths were utilized through the campaign. AE1309 and AE1067 were deployed together on August 30, 2016 and were collected for maintenance on December 22, 2016. During this period AE0910 was deployed. On April 20, 2017 the newly maintained AE959 and AE963 were deployed. A five minute sampling period was used.

Other Monitoring Stations

Data from reference monitors located at the Burnaby South monitoring site and the Sunny Hill monitoring site were used to assess the level of spatial similarity in pollution levels in the area around the Clark Drive station during the sampling period. Burnaby South operated in parallel for the full sampling period while the Sunny Hill site was decommissioned in August 2016. Sunny Hill (located at the Sunny Hill Health Centre for Children) was the closest (2.3 km) full air quality monitoring station to Clark Drive prior to its decommissioning. Burnaby South was the next closest (8.4 km) and is located on the roof of Burnaby South Secondary School.

Data Treatment

The MicroAeth data were post-processed using the Optimized Noise-reduction Averaging (ONA) algorithm as described by Hagler et al. (2011). This is one of the default post-processing methods provided on the Aethlab (the manufacture) website. Aeroqual NO_2 values were adjusted by subtracting the reference NO_2 and then a simple linear regression was used to correct the Aeroqual NO_2 values using O_3 data from Aero4. Unit Aero4 was used for correction as it had the greater amount of overlapping data from the relevant period. Aero2 was not adjusted as there was no overlap in its deployment with any of the O_3 sensors. This method was outlined in Lin et al., (2015). All sensor data was averaged hourly. All time stamps were converted Pacific Standard Time (PST).

The data from the regulatory monitors provided by Metro Vancouver were unverified hourly data as verified data were not yet fully available at the time of data analysis. Limited automated QA/AC (quality assurance/quality control) procedures were applied to this dataset, however, manual QA/AC were conducted on this dataset.

Results and Discussion

Sensor comparison

<u>TZOA R2D2</u>

In general, the Pearson's correlations amongst the TZOAs monitors were high but correlation with the SHARP reference monitor was low during the 50.3 week deployment (Table 2, Figures 4-5). TZOA_10 had a number of outliers, defined as measurements with > 25,000 counts. These values tended to be clustered together and were more frequent towards the end of the sampling period. The sensor output also was unclear with regard to exact time stamping. Specifically it was not clear when the averaging at intervals were occurring and/or if the time stamps were correct, as some time stamps did not indicate 5 minute intervals. The time stamp issue may mean that the TZOA values were not always being compared to the correct reference data. Both of these issues may have reduced correlations. Data were lost due to sensor failure and a power outage that caused the time stamp to reset, rendering some of the data after the power outage to be unusable (Figure 6). While the sensor was still collecting data, the reset time stamp with the sensor's inexact time stamping meant it was not possible to estimate the correct time stamp. The TZOA_0080 hourly data collection was only 37% of possible and TZOA_0010 had hourly data collection of 72% of possible This data loss meant no valid data were collected during the period when smoke from forest fires (the first two weeks of August of 2017) throughout British Columbia were affecting air quality in Metro Vancouver.

Table 2: Pearson's correlation for TZOAs and Reference

	TZOA_0010	TZOA_0080	TZOA Average	SHARP
TZOA_0010	1	0.954	0.986	0.748
TZOA_0080	0.954	1	0.990	0.664
TZOA Average	0.986	0.990	1	0.689
SHARP	0.748	0.664	0.689	1

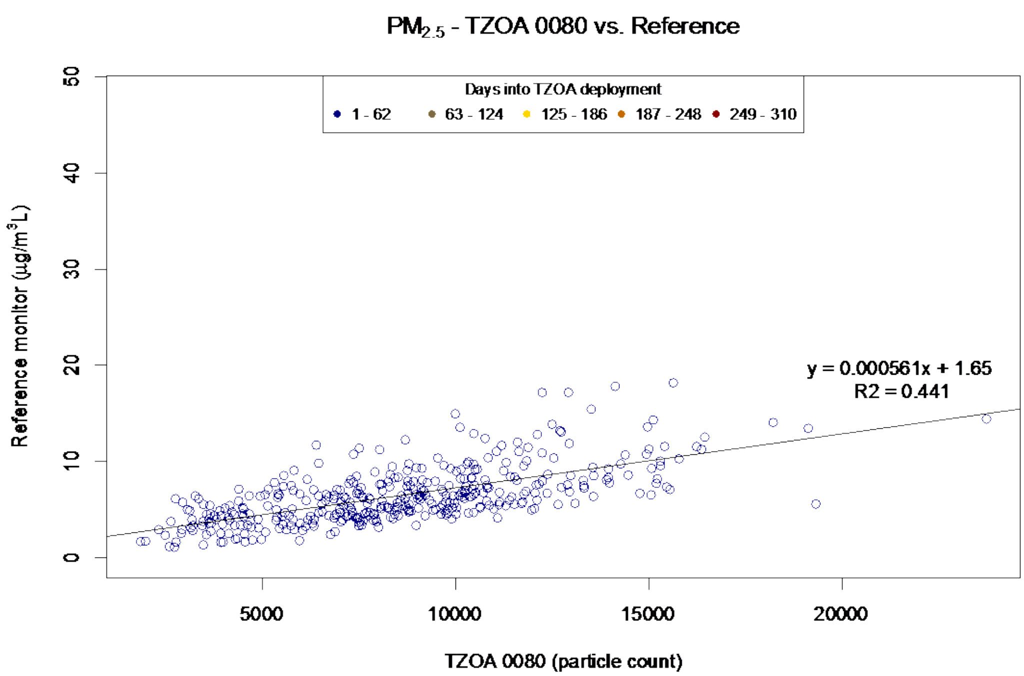

Figure 4 Scatterplot comparing TZOA 0080 and the reference monitor (Tzoa particle counts >25,000 removed)

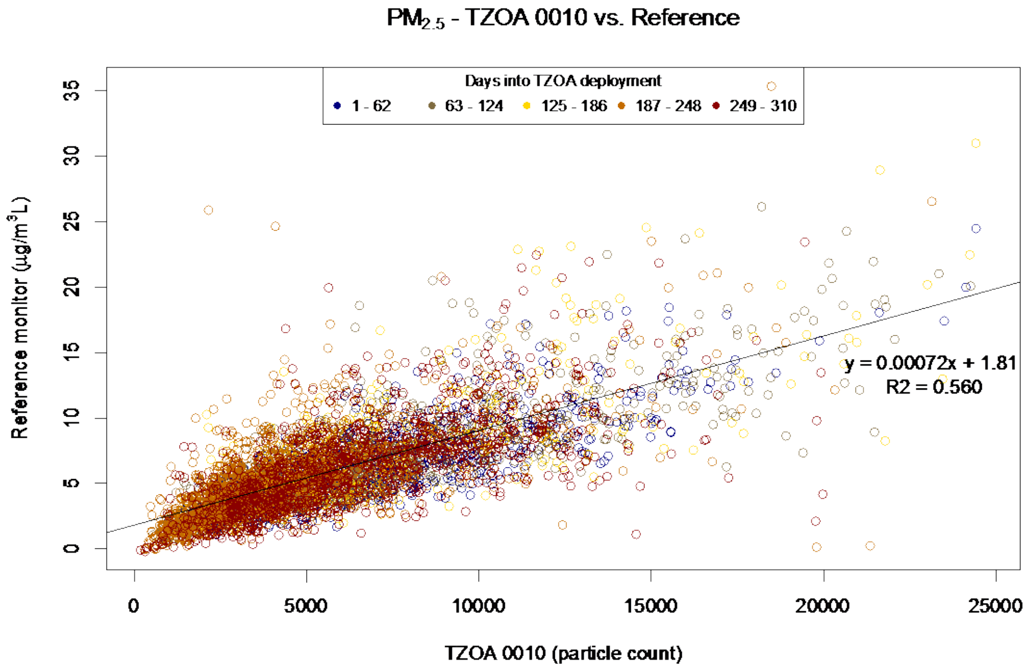

Figure 5 Scatterplot comparing TZOA 0010 and the reference monitor (Tzoa particle counts >25,000 removed)

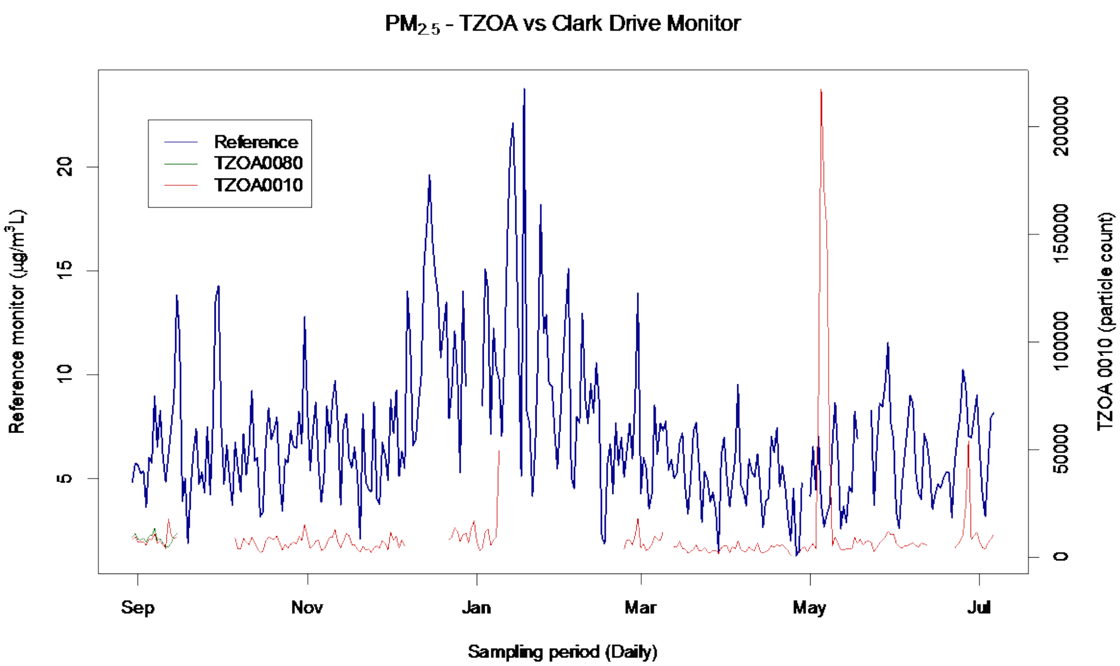

Figure 6 Time series plot of TZOA monitors and reference monitor

<u>PurpleAir 1003</u>

Correlations amongst the PurpleAir sensors and the reference monitor were greater than r > 0.94 during the 44.3 week deployment (Table 3). Averaging the three sensors

PurpleAir , using the period when they were simultaneously deployed, produced a slightly higher correlation with the reference sensor. During deployment of the individuals sensors, hourly data capture was 81% for PA1, 86% for PA2, and 85% for PA3. Data loss was due to power loss or the Wi-Fi hotspot turning off. The relationship between the PurpleAir sensors and the reference monitor was not completely linear, particularly during the two-week period affected by forest fire smoke (Figure 7-10). Removal of the higher values from the first two weeks of August 2017 when the area was affected by forest fire smoke slightly reduced the correlation (Figures 11-13).

Table 3 Pearson's correlation for PurpleAir and Reference

	PA1	PA2	PA3	PA Average	SHARP
PA1	1	1.000	0.999	0.999	0.935
PA2	1.000	1	0.999	0.999	0.950
PA3	0.999	0.999	1	0.999	0.970
PA Average	1.000	0.999	0.999	1	0.971
SHARP	0.935	0.950	0.970	0.971	1

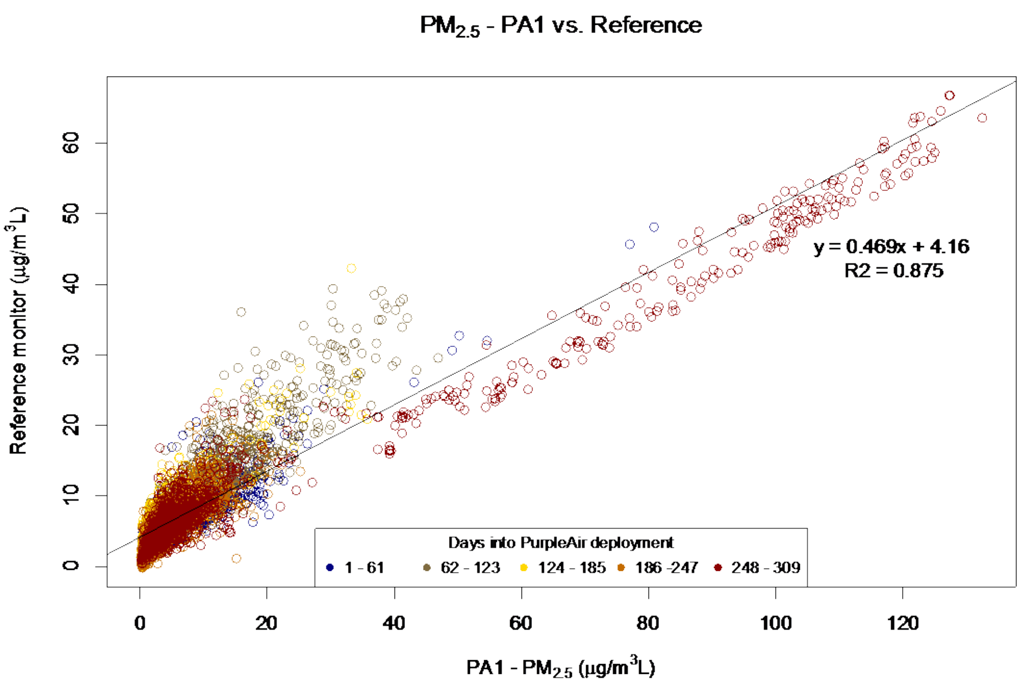

Figure 7 Scatterplot comparing PA1 and the reference monitor

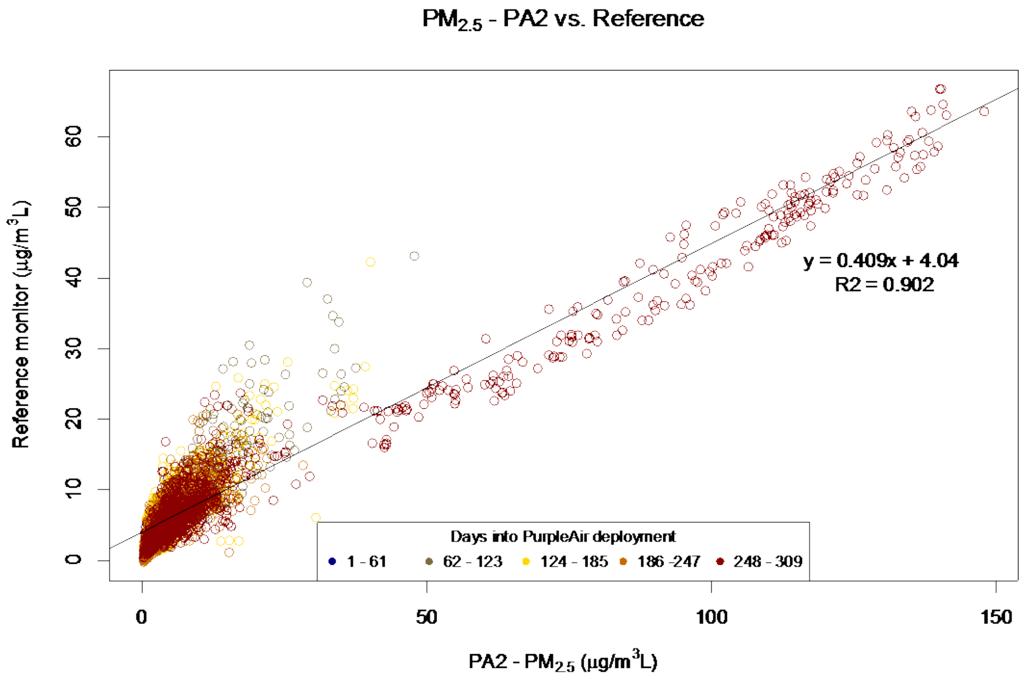

Figure 8 Scatterplot comparing PA2 and the reference monitor

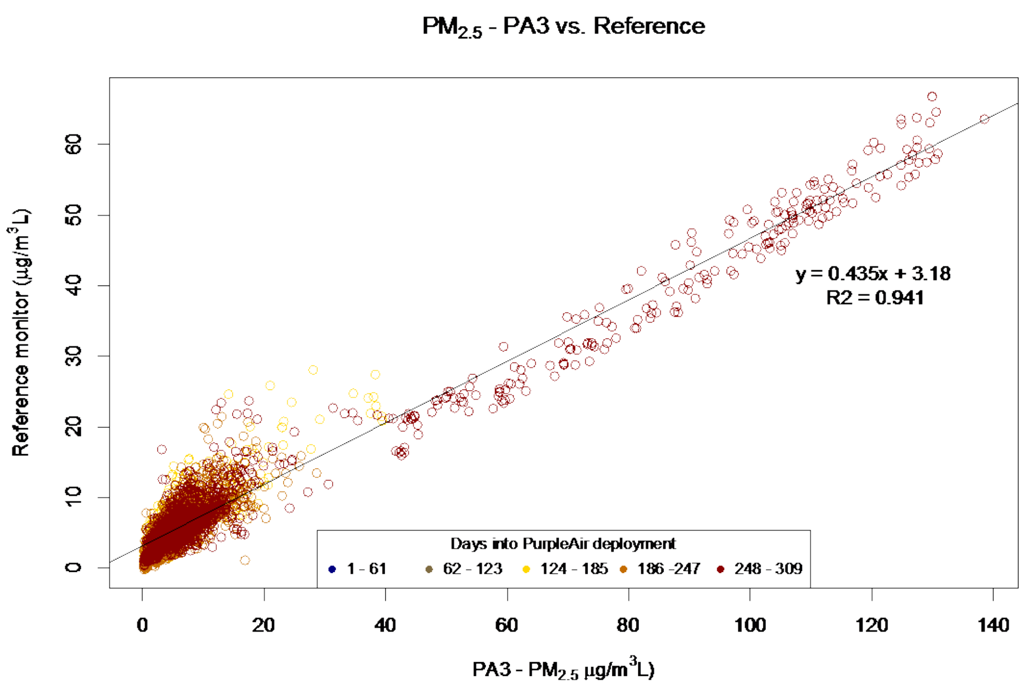

Figure 9 Scatterplot comparing PA3 and the reference monitor

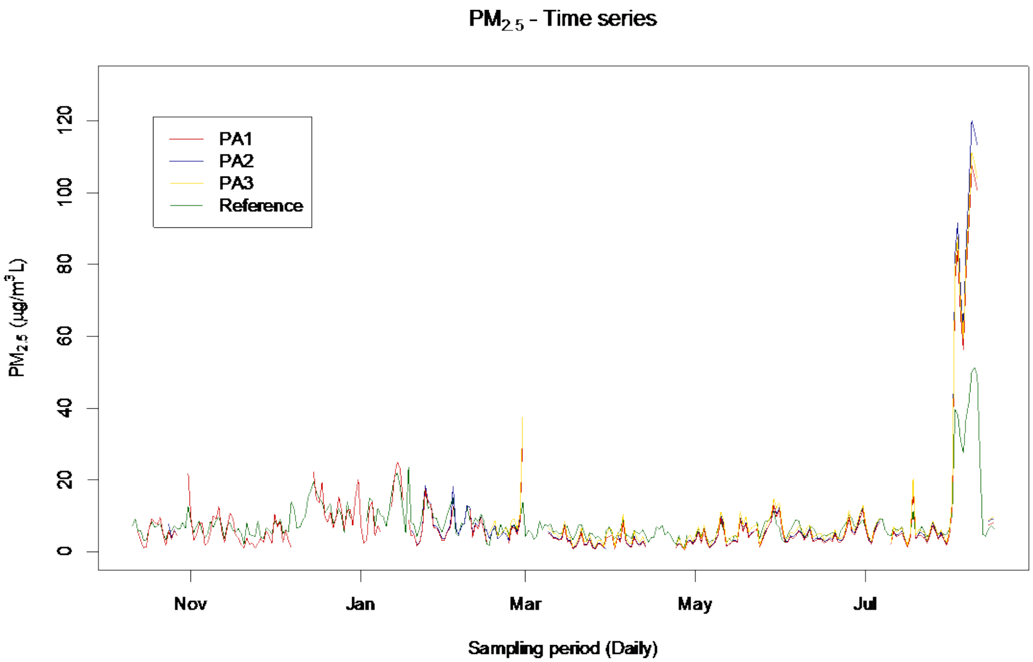

Figure 10 Time series plot of PurpleAirs and reference monitor

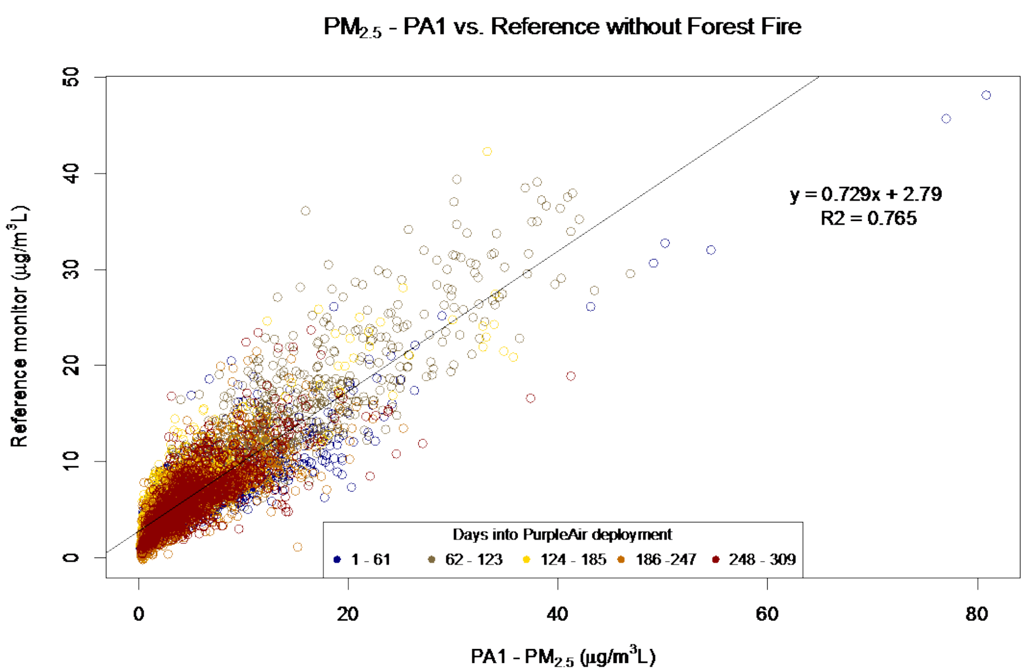

Figure 11 Scatterplot comparing PA1 and the reference monitor with first two weeks of August 2017 removed

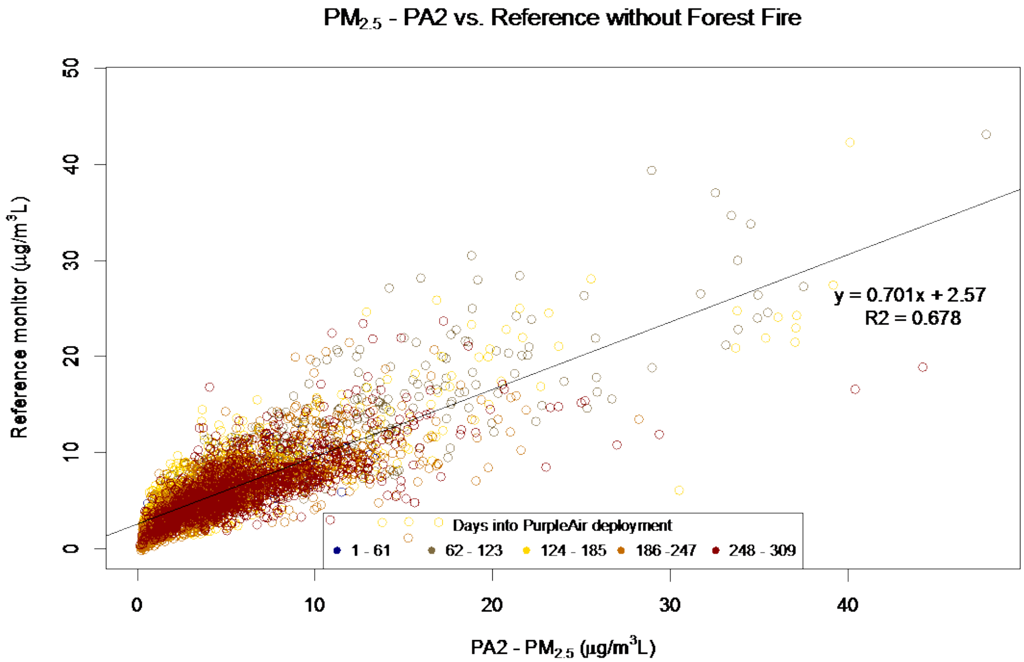

Figure 12 Scatterplot comparing PA2 and the reference monitor with first two weeks of August 2017 removed

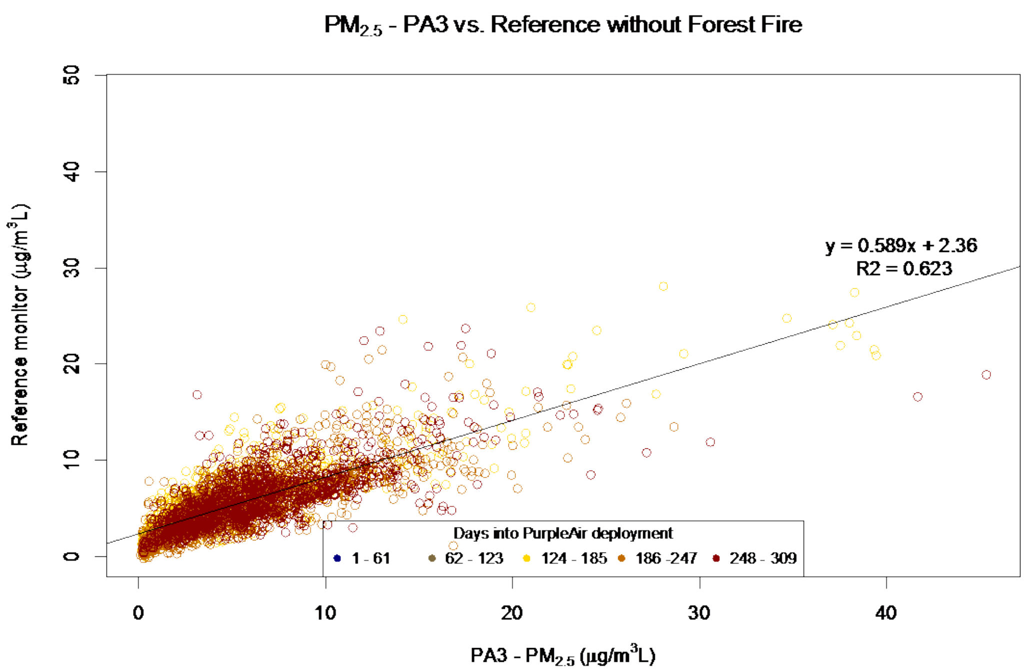

Figure 13 Scatterplot comparing PA3 and the reference monitor with first two weeks of August 2017 removed

<u>Met-One ES-642</u>

The correlation between the ES-642 monitor and SHARP reference monitor was r = 0.95, R^2 = 0.90 during the 20.0 week deployment (Figure 14). During this deployment period hourly data capture was 100%. There did not appear to be a drift with time during the deployment period, however, the correlation appeared to be anchored by high concentration values. Due to smoke from forest fires during the first two weeks of August 2017, the ES-642 recorded elevated PM concentrations (~100 μg/m^3) over this period. Outside of this two week period, hourly concentrations only exceeded 20 μg/m^3 on two occasions When the two weeks of high concentrations were removed, the R^2 was reduced to 0.38 (Figure 15). On average the ES-642 overestimated PM concentrations relative to the SHARP reference monitor (Figure 16).

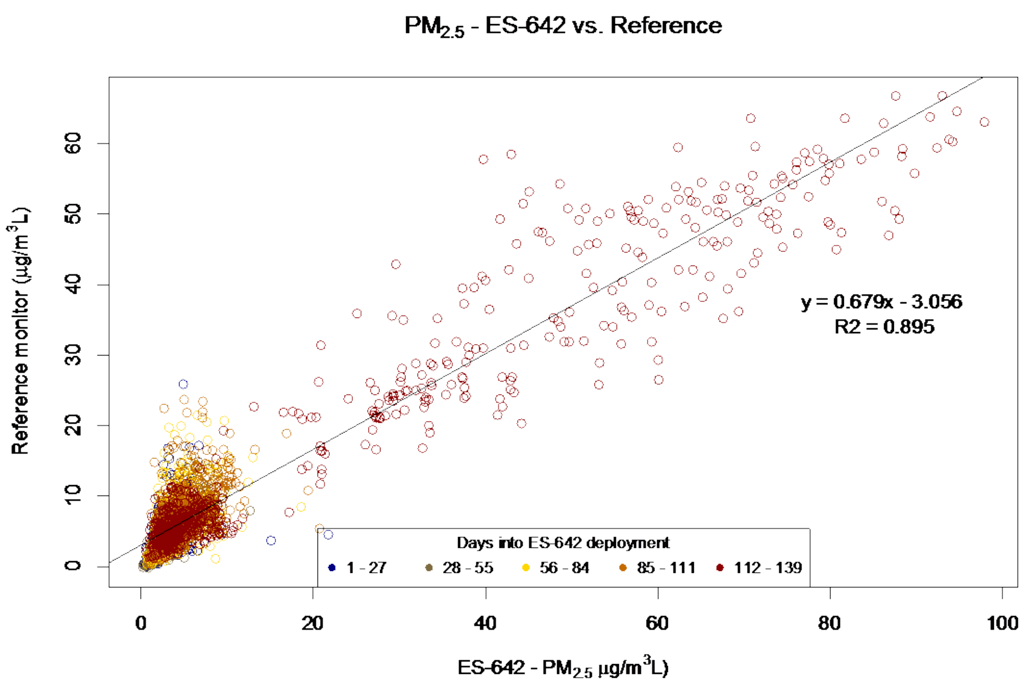

Figure 14 Scatterplot comparing ES-642 and the reference monitor

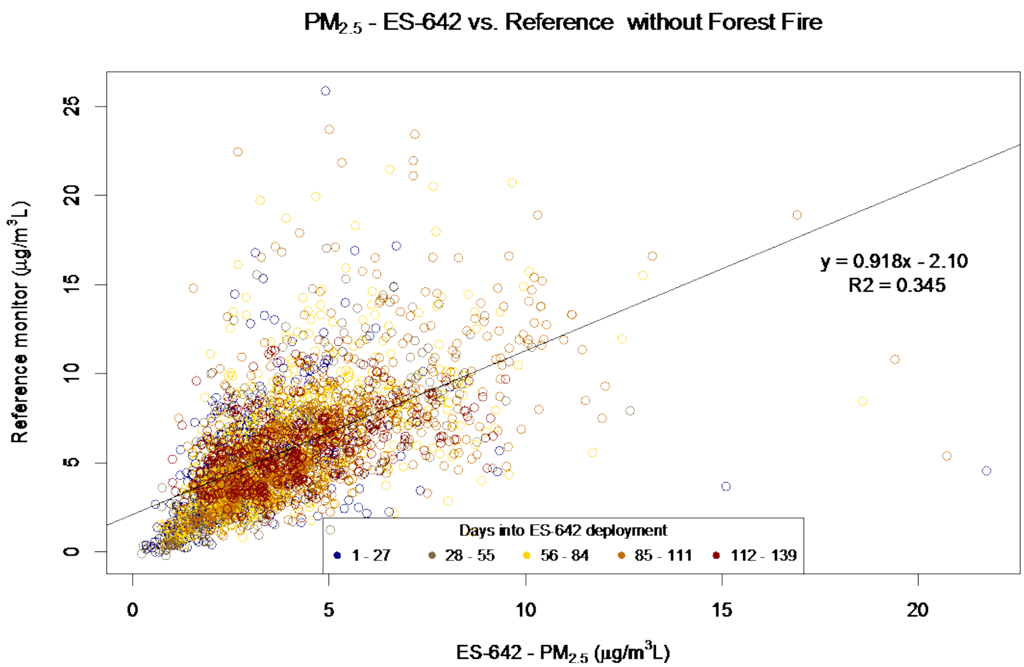

Figure 15 Scatterplot comparing ES-642 and the reference monitor after excluding the first two weeks of August 2017

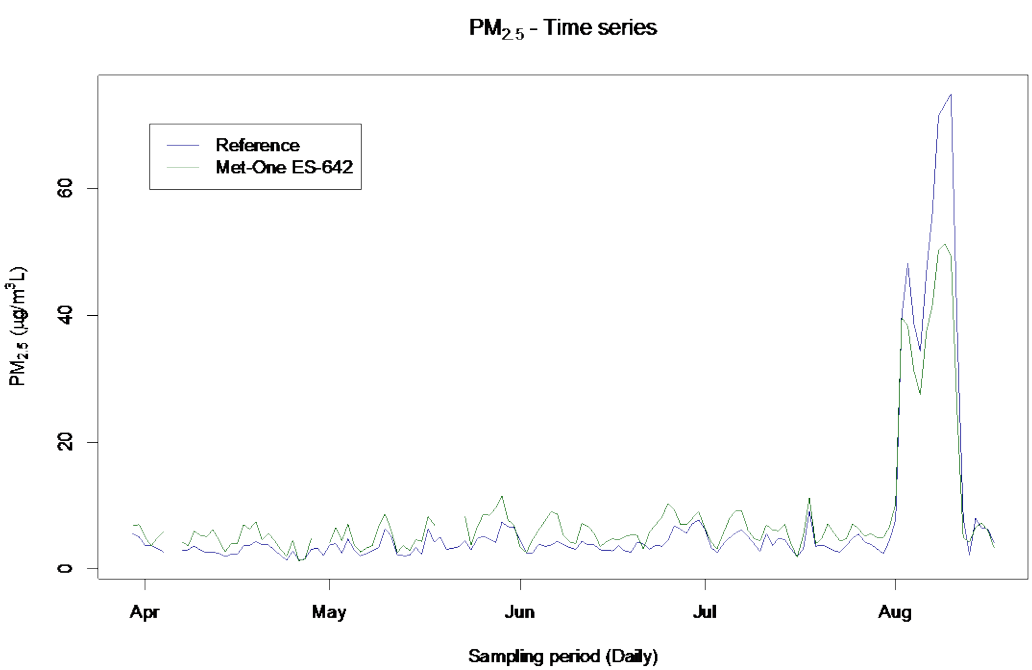

Figure 16 Time series plot of ES-642 and reference monitor

Aeroqual O_3 sensors

The correlation between the O_3 Aeroqual sensors and the reference monitor ranged from r = 0.92 to 0.97 - R^2 = 0.84 to 0.94 (Table 4) during the 19.4 week deployment. Averaging

Aero4 and Aero5 values did not improve correlation with the reference monitor. The internal correlation between units ranged from r = 0.96 to 0.98. This high level of correlation between the Aeroqual O_3 sensors and the reference O_3 monitor was similar to the result found of Lin et al. (2015) who compared the same type of O_3 Aeroqual to a EnviroTechnology Model 400E photometric analyser ($R^2 = 0.91$). While deployed, valid data capture was 100% for all three sensors. This excluded times when the sensors were taken down for data downloading.

Table 4: Pearson's correlation for O_3 Aeroquals and Reference

	Aero4	Aero5	Aero6	Aero Average[1]	Reference
Aero4	1	0.959	0.983	0.990	0.916
Aero5	0.959	1	-	0.990	0.945
Aero6	0.982	-	1	-	0.967
Aero Average	0.990	0.990	-	1	0.938
Reference	0.916	0.945	0.967	0.938	1

There appeared to be calibration drift in the Aeroqual sampling and reduced precision with time (Figures 17 - 19). This was mostly clearly seen in the results from Aero4. Correlation decreased with the deployment time of the sensors, with Aero6 (1.5 week deployment) having the highest correlation and Aero4 (18.5 week deployment) having the lowest correlation. In the study by Lin et al. (2015), the sampling campaign ran for ten weeks. Their finding of $R^2 = 0.91$ is consistent with our observation of temporal drift.

Initially, Aero4 consistently overestimated concentrations relative to the reference sensor (Figure 20). However, this trend began to switch ~¾ of the way through the deployment period. By the end of the sampling period, the Aero4 underestimated the hourly average data. Aero6 overestimated the hourly average data for its full deployment, however this was a short deployment period. Aero5 consistently underestimated the hourly average data during its sampling period relative to the reference monitor but also relative to Aero4, even when it was oversampling.

In their study, Lin et al. (2015) found their O_3 Aeroqual generally overestimated reference values at concentrations greater than ~0.0215 ppm and underestimated at concentrations less than ~0.0215 ppm relative to the photometric analyser. A study by Afshar-Mphajer et al. (2017) found O_3 Aeroquals (2 units) underestimated concentrations at all reference values by amounts ranging from 0.025 ppm to 0.150 ppm relative to an ultraviolet absorption (Model 1008-PC, Dasibi Environmental Co., Glendale, CA USA) reference monitor. The authors noted controlled changes in temperature (~25 - ~30°C) and RH (45% to 65%) in the test chamber as contributors to underestimation as semi-conduction oxidizing samplers are sensitize to environmental changes. Lin et al. (2015) reported that ambient RH (~30 to 100%) only explained 1% ($R^2 = 0.01$) of the deviation in O_3 concentrations relative to the reference monitor.

[1] Average of Aero4 and Aero5

Given this, it is unclear what may be responsible for over/underestimation of the O_3 Aeroquals. This may have been due to to environmental changes, as temperature and RH differ from spring to summer, and/or O_3 concentrations thresholds as suggested by Lin et al. (2015). The lag in Aero4's overestimation relative to the underestimation of Aero5 which continued until the very end of the sensor period may have been due to inter-sensor variation and the drift caused by sensor ageing. Unlike the $PM_{2.5}$, removal of data from the first two weeks of August when the area was impacted by forest fire smoke did not affect the performance of the Aero4 and Aero5, the two sensors deployed during that time (Figure 21 & 22).

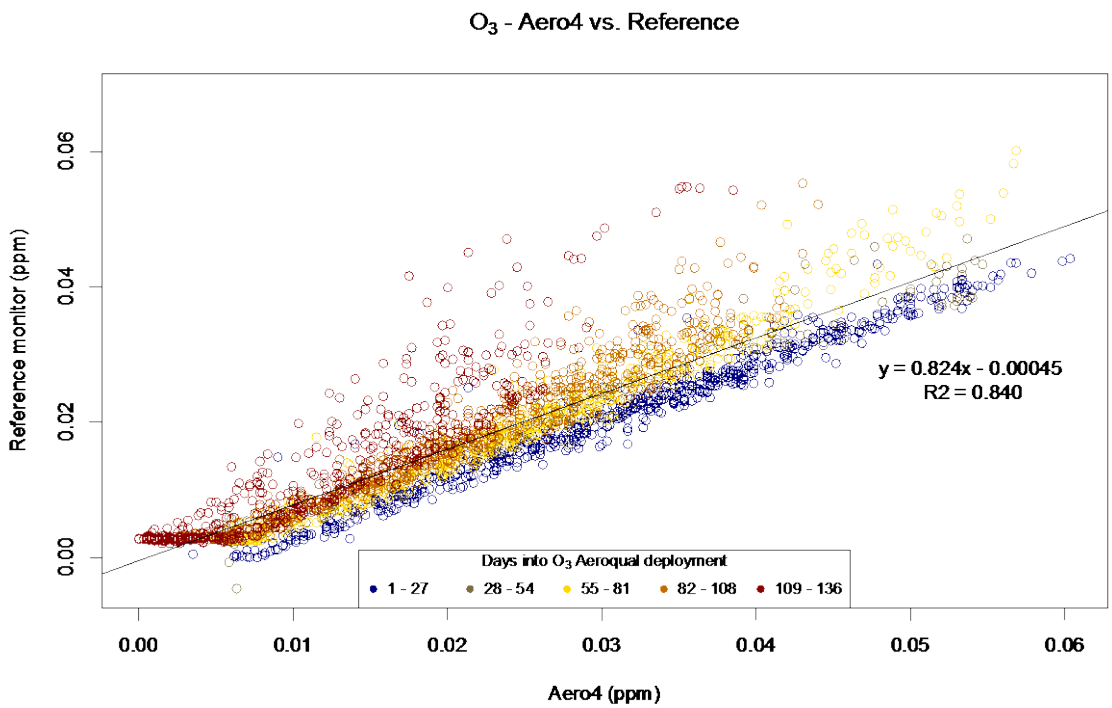

Figure 17 Scatterplot comparing Aero4 and the reference monitor

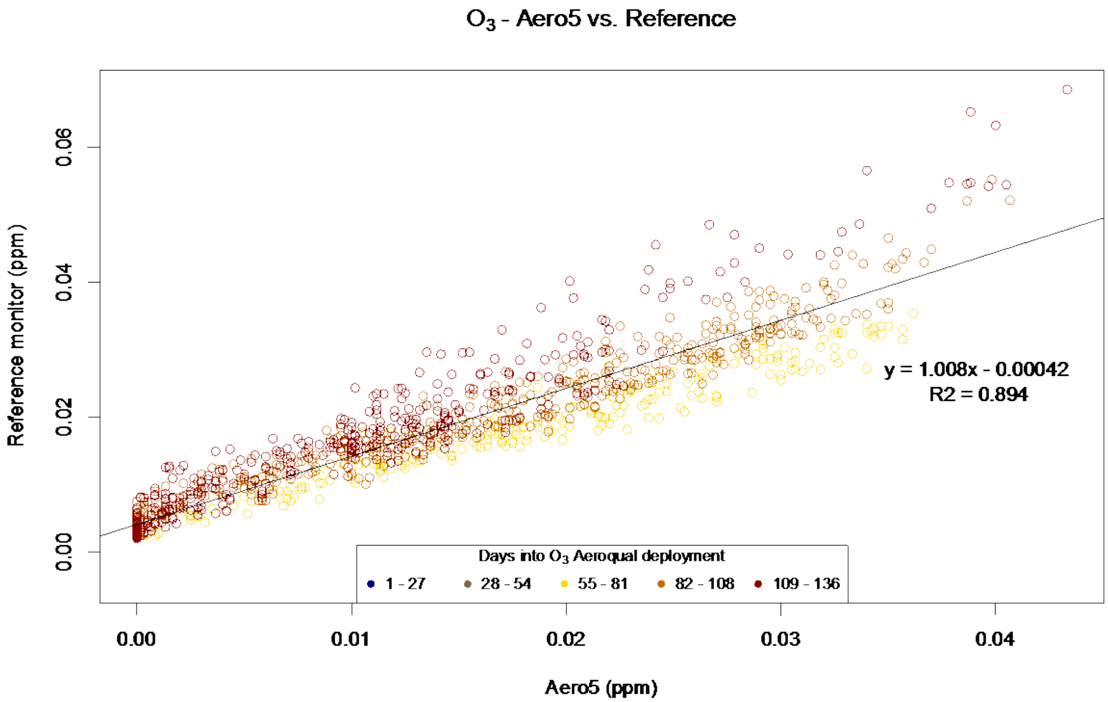

Figure 18 Scatterplot comparing Aero5 and the reference monitor

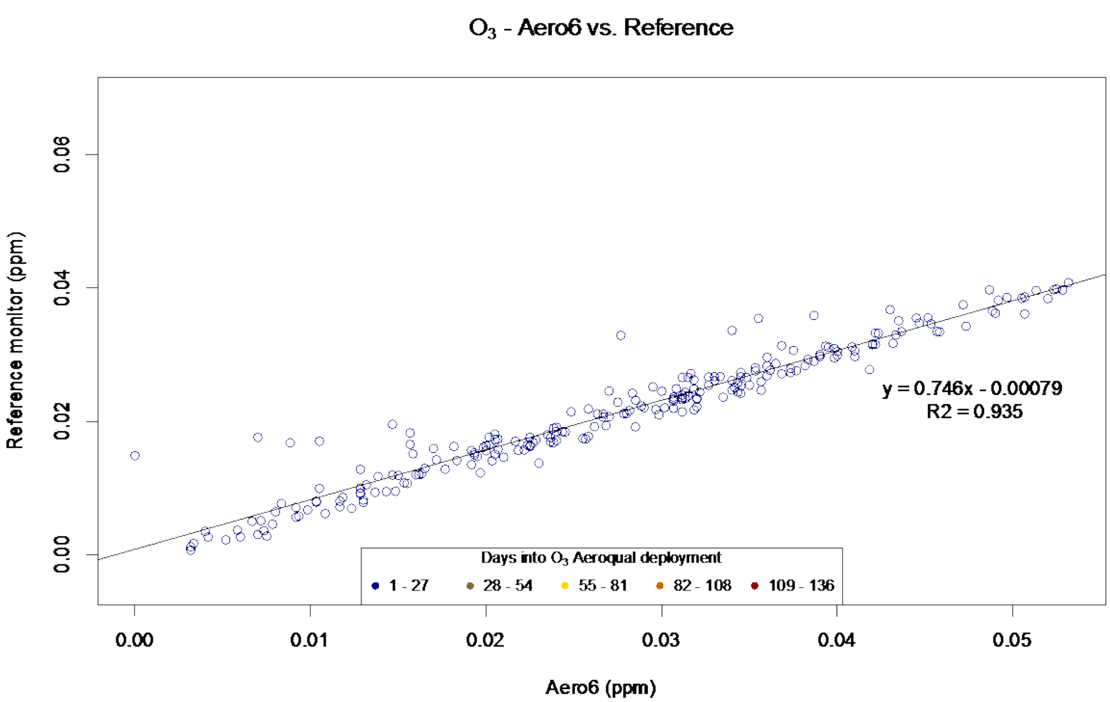

Figure 19 Scatterplot comparing Aero6 and the reference monitor

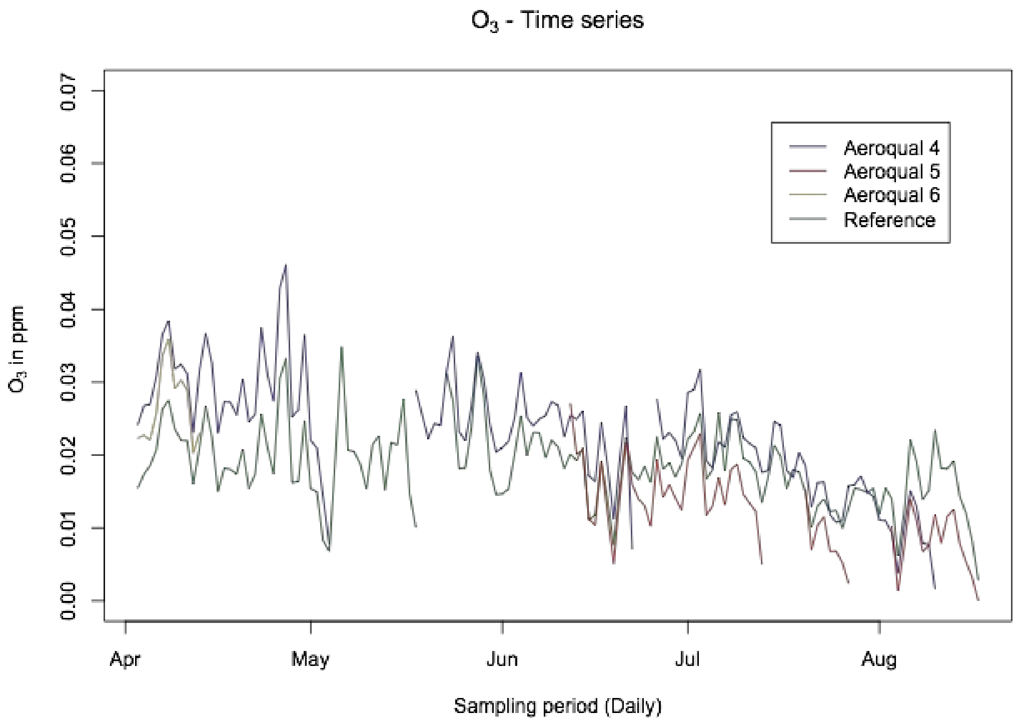

Figure 20 Time series plot of O_3 Aeroquals and reference monitor

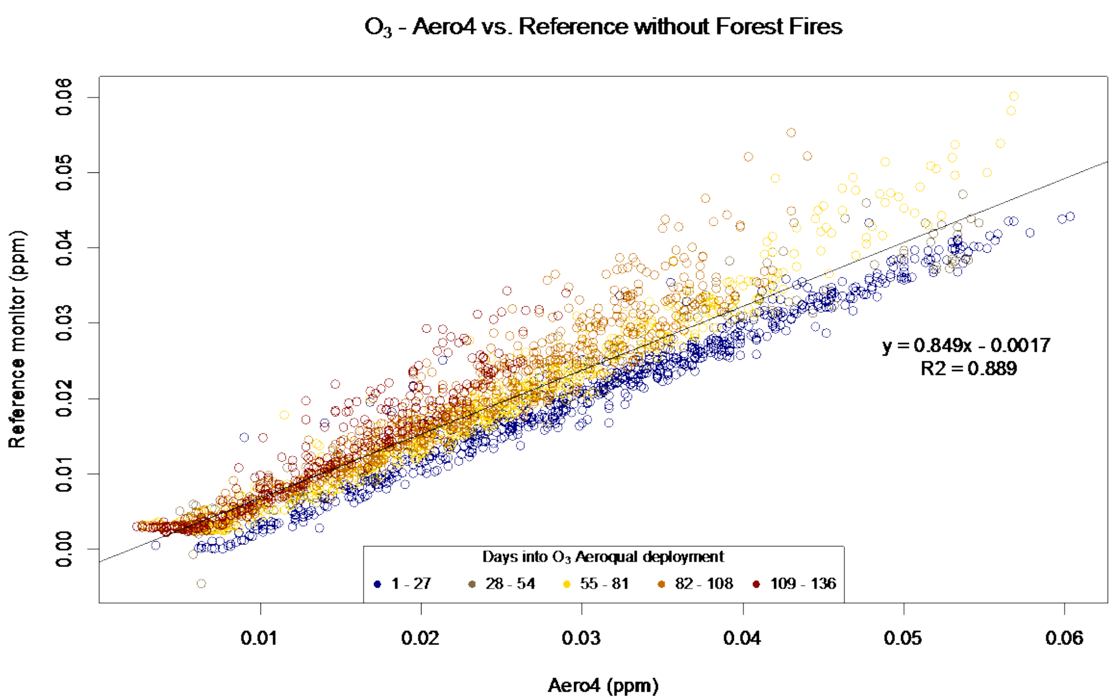

Figure 21 Scatterplot comparing Aero4 and the reference monitor with first two weeks of August 2017 removed

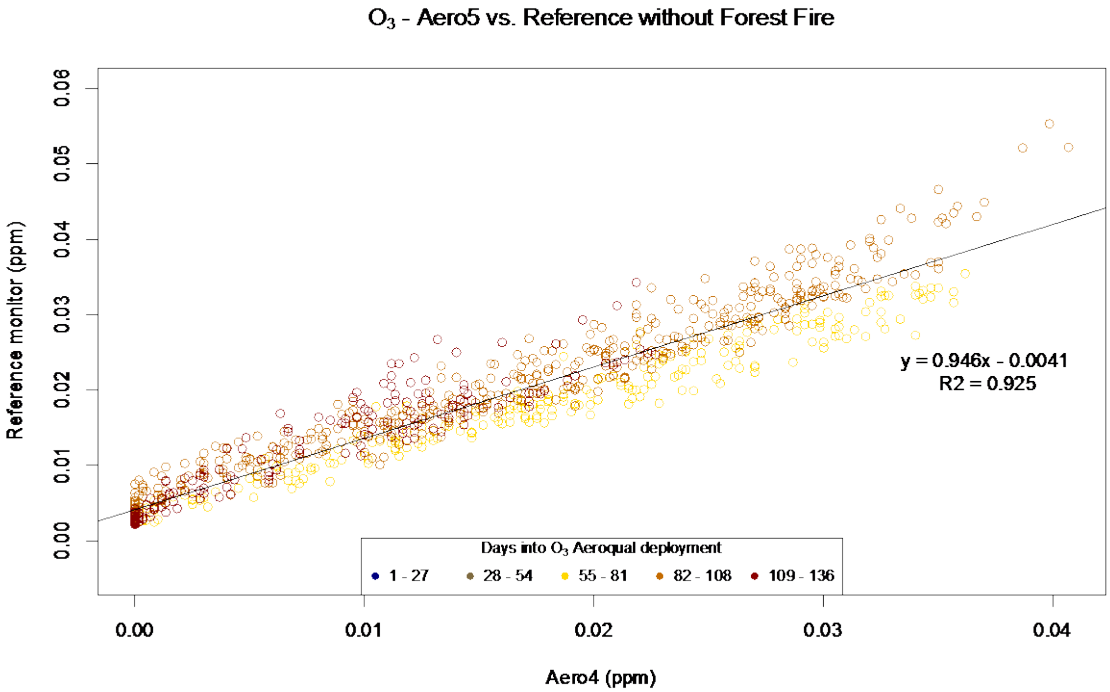

Figure 22 Scatterplot comparing Aero5 and the reference monitor with first two weeks of August 2017 removed

Aeroqual NO_2 sensors

Relative to the O_3 sensors, correlation was low between the NO_2 Aeroqual sensors and the reference sensor during the 49.3 week sampling period (Table 5, Figures 23-25). Correlation was strong between Aero1 and Aero2, however, Aero3 had a weak correlation with Aero1 and the weakest of all the NO_2 Aeroqual correlations with the reference. The Aeroqual agreement found at Clark Drive was similar to the correlation (R^2 = 0.02) noted by Lin et al. (2015) with a reference NO_2 chemiluminescence analyser y. Like the O_3 Aeroqual, data capture was 100% for all three sensors during their deployment when they were not taken down for data download and removal of the forest fire period data did not affect performance (Figure 26 & 27).

Table 5 Pearson's correlation for NO_2 Aeroquals and Reference

	Aero1	Aero2	Aero3	Aero Average[2]	Reference
Aero1	1	0.901	0.084	0.977	0.310
Aero2	0.901	1	-	0.973	0.372
Aero3	0.084	-	1	-	0.195
Aero Average	0.977	0.973	-	1	0.383
Reference	0.310	0.372	0.195	0.383	1

[2] Average of Aero1 and Aero2

The NO_2 Aeroquals consistently overestimated NO_2 concentrations relative to the reference by an average 6-fold difference. Lin et al. (2015) reported an average 3-fold difference. Both scatterplot and time series plots suggest drift with NO_2 as the Aeroqual sensor aged and the difference, on average increased (Figures 23-29).

In the Lin et al. (2015) study, the authors were able to correct for this apparent interference by O_3 by adjusting the NO_2 values. O_3 concentrations from the O_3 Aeroqual were correlated with the difference between the NO_2 Aeroqual and the reference sensor and this linear regressed relationship was used to correct the Aeroqual NO_2 values. This correction method was also applied to the Clark Drive dataset. In their paper, Lin et al. (2015) found a high correlation between the O_3 Aeroqual values and the difference between the NO_2 Aeroqual and reference NO_2 values ($R^2 = 0.92$). At Clark Drive the NO_2 difference relative to the Aeroqual O_3 values was lower, with an R^2 value of 0.62 for Aero 1 (Figure 30). The final correlation for the adjusted NO_2 and reference NO_2 was $R^2=0.17$ for Aero 1, which was significantly lower than the $R^2 = 0.88$ found in the Lin et al. (2015) study (Figure 31). The weak correlation in this study may be due to the aging of the Aero1 sensor prior to the O_3 Aeroqual deployment. Aero3 was deployed with the O_3 Aeroquals, but was not working correctly and was removed from further analysis.

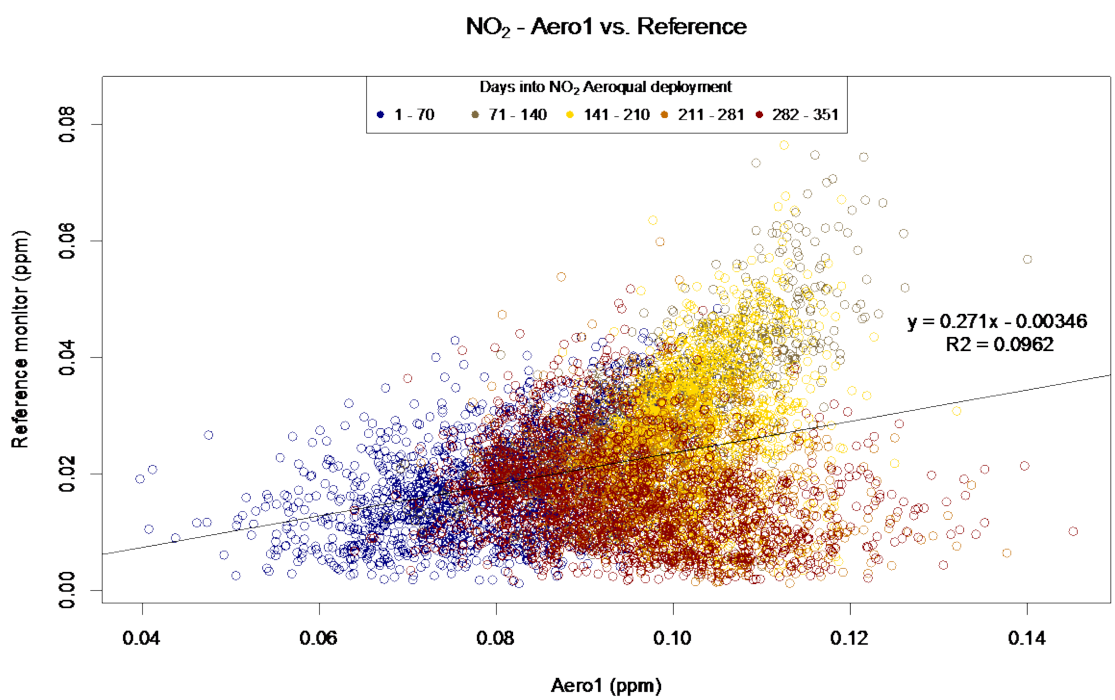

Figure 23 Scatterplot comparing Aero1 and the reference monitor

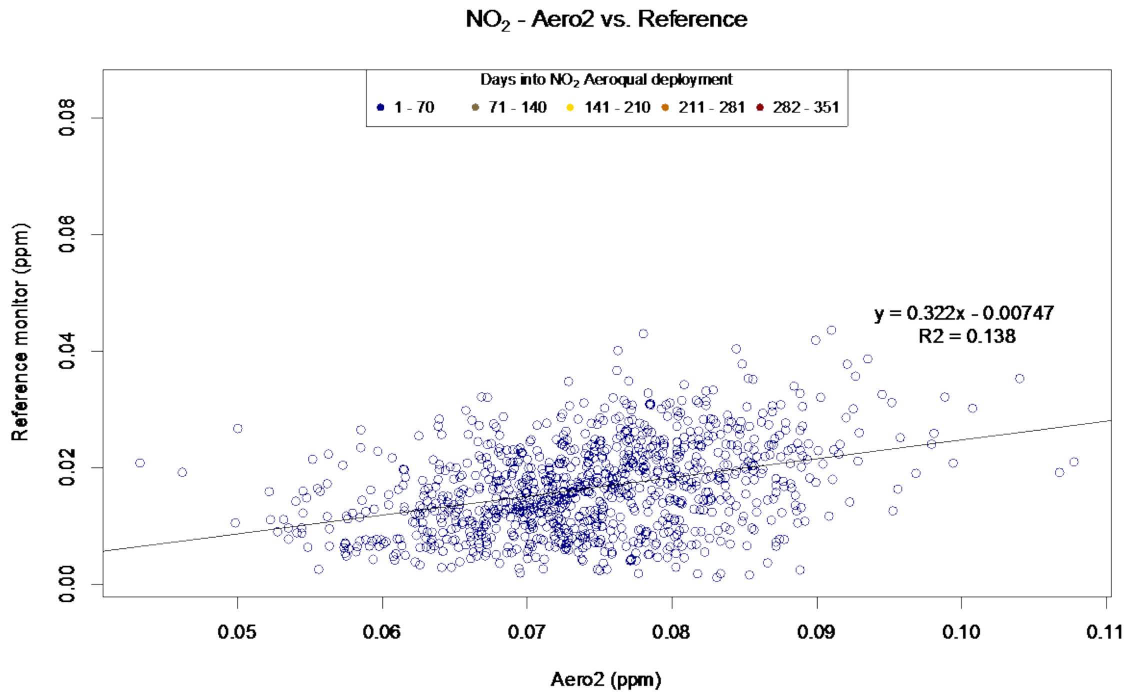

Figure 24 Scatterplot comparing Aero2 and the reference monitor

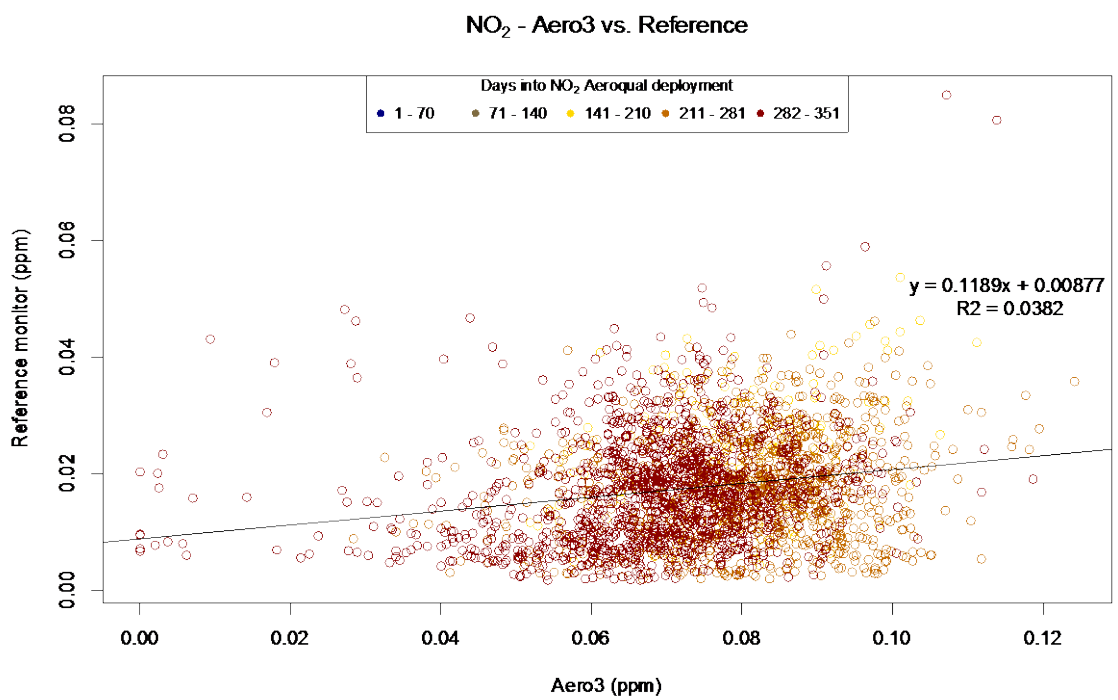

Figure 25 Scatterplot comparing Aero3 and the reference monitor

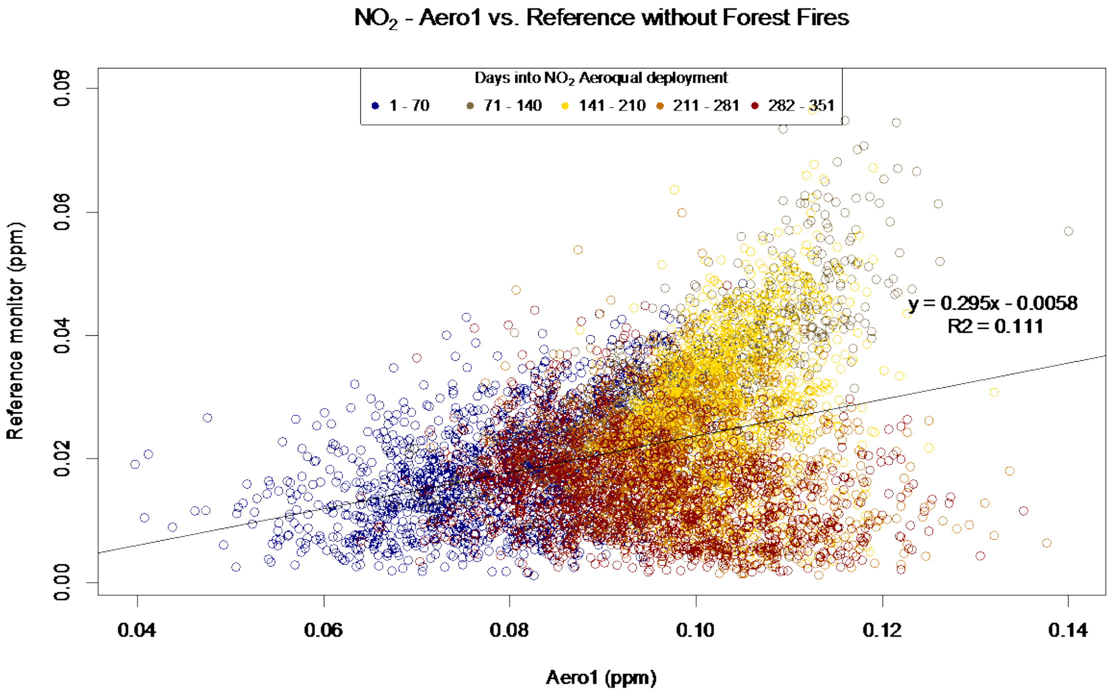

Figure 26 Scatterplot comparing Aero1 and the reference monitor with first two weeks of August 2017 removed

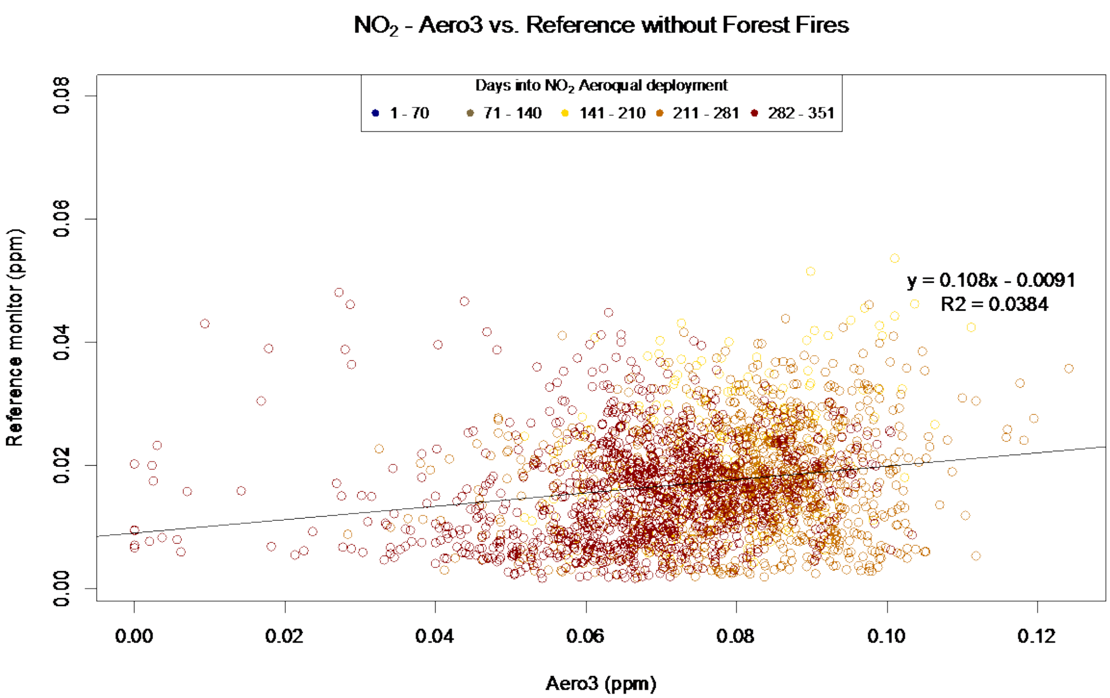

Figure 27 Scatterplot comparing Aero3 and the reference monitor with first two weeks of August 2017 removed

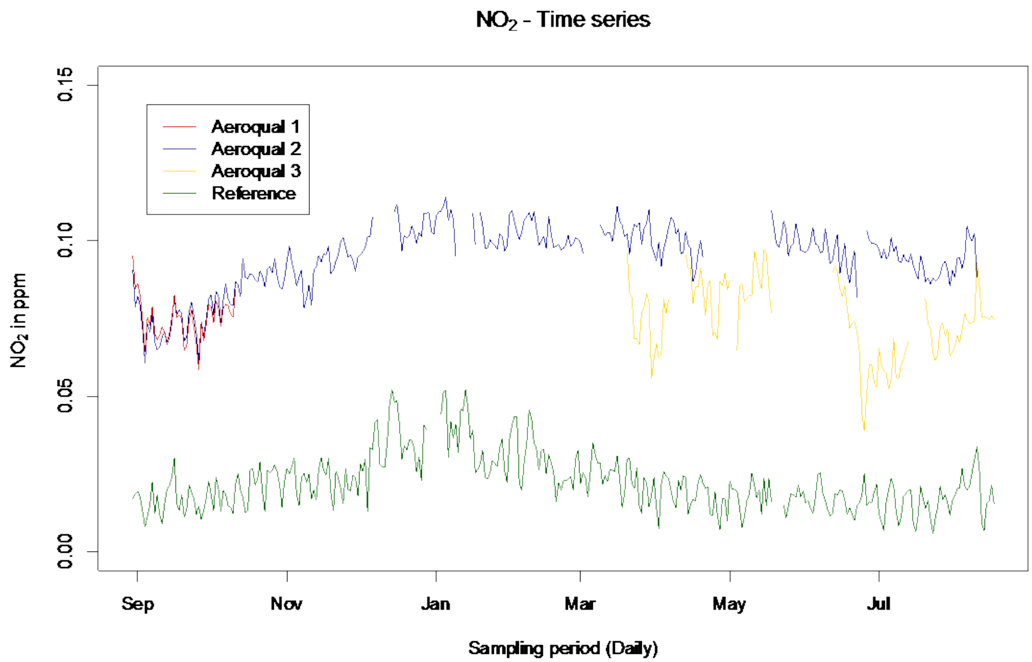

Figure 26 Time series plot of NO_2 Aeroquals and reference monitor

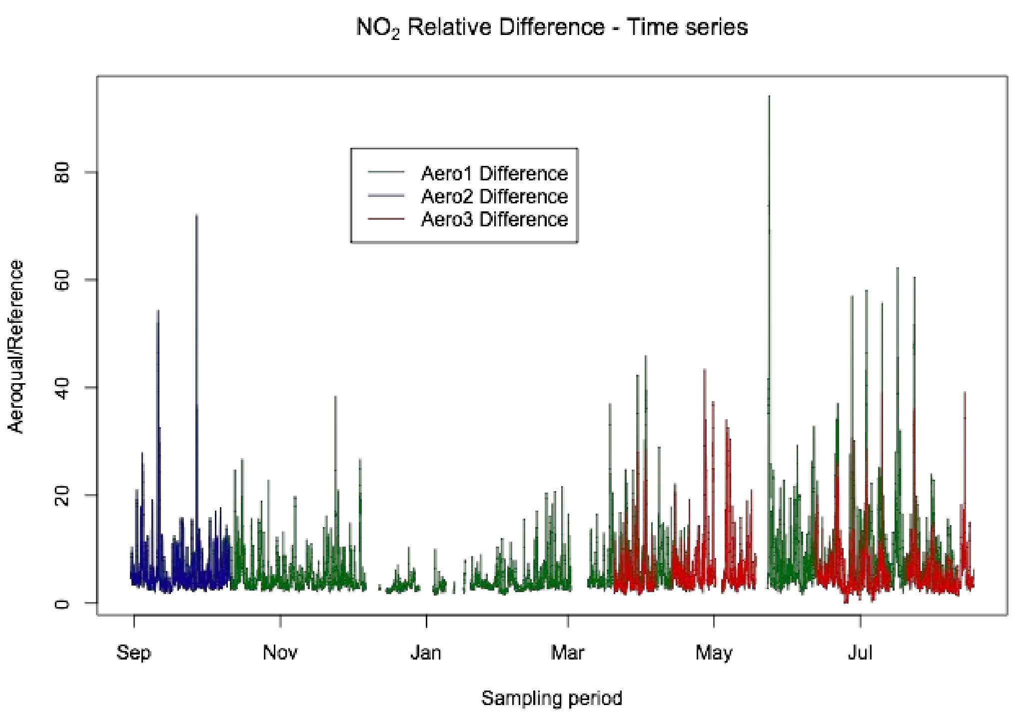

Figure 27 Time series plot of difference between NO_2 Aeroquals and reference monitor

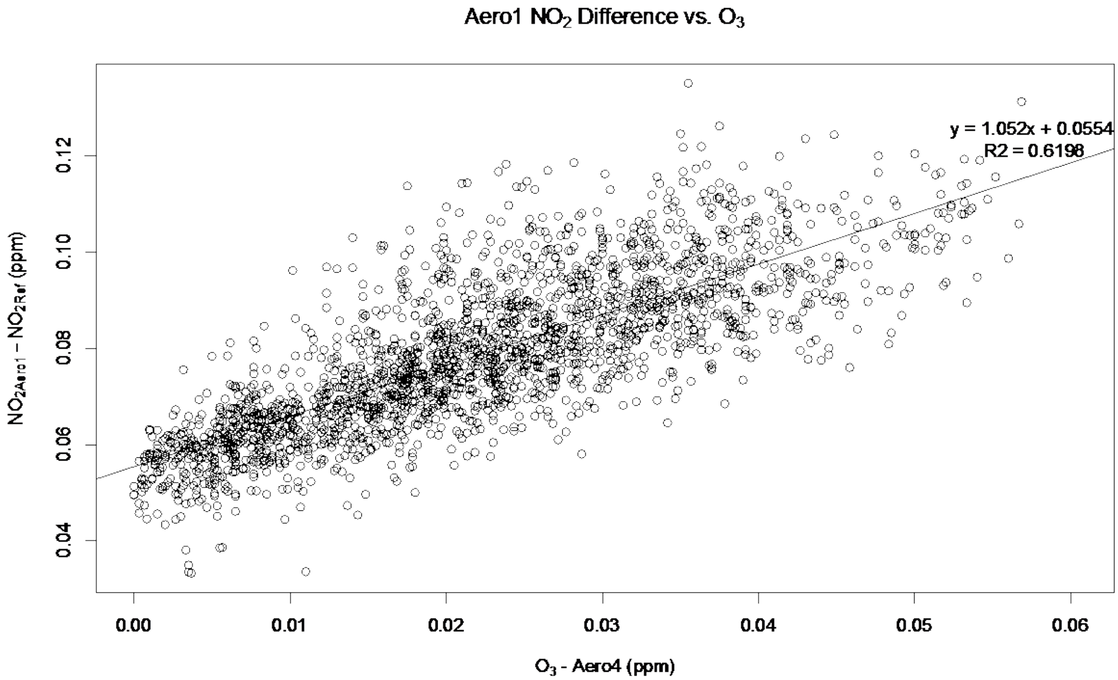

Figure 28 Scatterplot comparing the difference between Aero1 and reference and Aero4

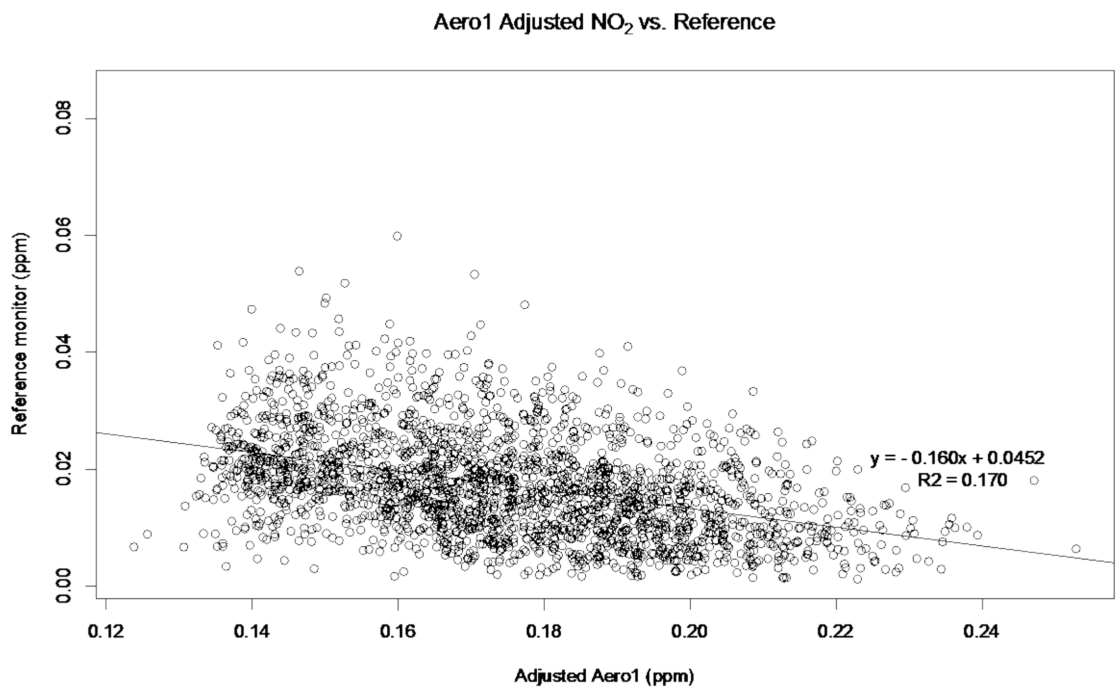

Figure 29 Scatterplot comparing adjusted Aero1 and the reference monitor

<u>microAeth AE51</u>

The correlations amongst the mircoAeth monitors and with the reference monitor (at 880nm wavelength) ranged from r = 0.73 to 0.99 during the 50.3 week deployment (Table 6). The average value from all sensors was not compared to the reference monitor due to the lack of overlap between the five sensors. AE189 was the oldest microAeth and had the lowest correlation with the reference (r = 0.88). The use of the microAeth is fairly common in the literature and other fixed site comparison tests have generally found strong correlation which these personal samplers. A study by Cheng and Lin (2013) comparing mircoAeth with the same type of reference monitor (at a traffic site) and data correction method found an $R^2 = 0.98$. Another study by Cai et al. (2013) noted R^2 values of 0.92 and 0.98 respectively for 1 minute and 24h averaged data relative to a full rack mounted AE22 Aethalometer (Magee Scientific Co.). The R^2 values from this study were lower but still suggest a strong correlation (Figures 32-36). The microAeth sensors did not appear to be systemically deviated from the reference values (Figure 37). Data capture for the hourly averaged data was 89% for AE189, 74% for AE929, 92% for AE1067, 88% for AE959, and 77% for AE963, during deployment of the sensors. Reasons for data loss included overloading of the filter during periods of high concentrations, power loss to the sensors, and in rain water in the case of AE929. Removal of data from the forest fire period did not have a strong impact on the correlation between the sensors and the reference monitors (Figure 38 & 39).

Table 6 Pearson's correlation for microAeths and Reference

	AE189	AE1067	AE959	AE963	AE929	BC6_880nm
AE189	1	0.985	-	0.835	-	0.875
AE1067	0.985	1	-	-	0.953	0.931
AE959	-	-	1	0.968	-	0.909
AE963	0.727	-	0.968	1	-	0.943
AE929	-	0.953	-	-	1	0.902
BC6_880nm	0.875	0.931	0.909	0.889	0.902	1

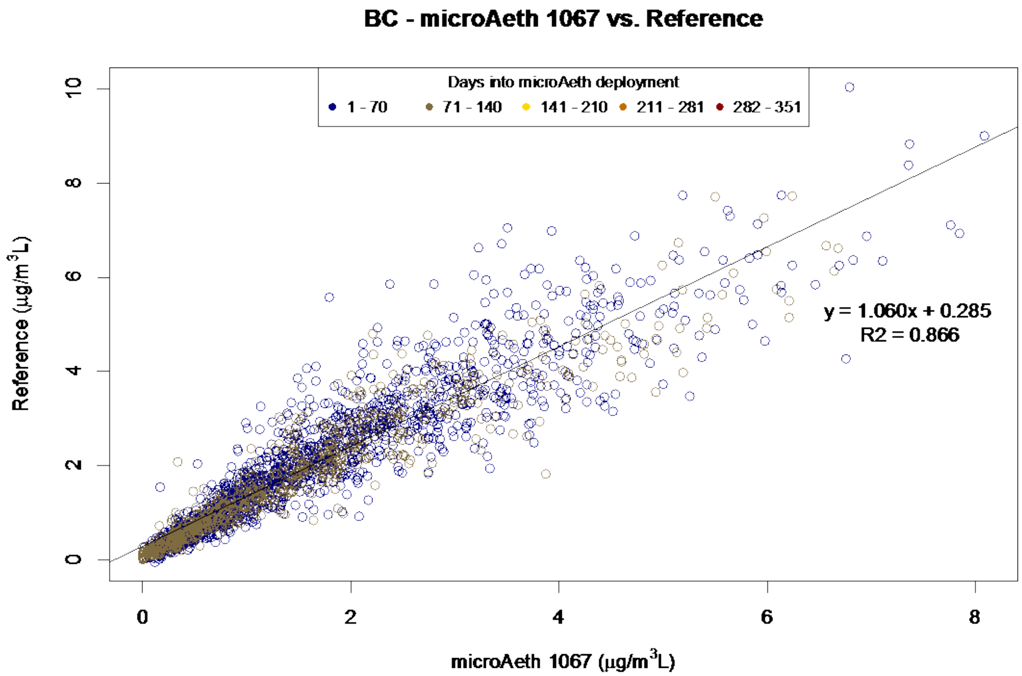

Figure 30 Scatterplot comparing AE1067 and the reference monitor

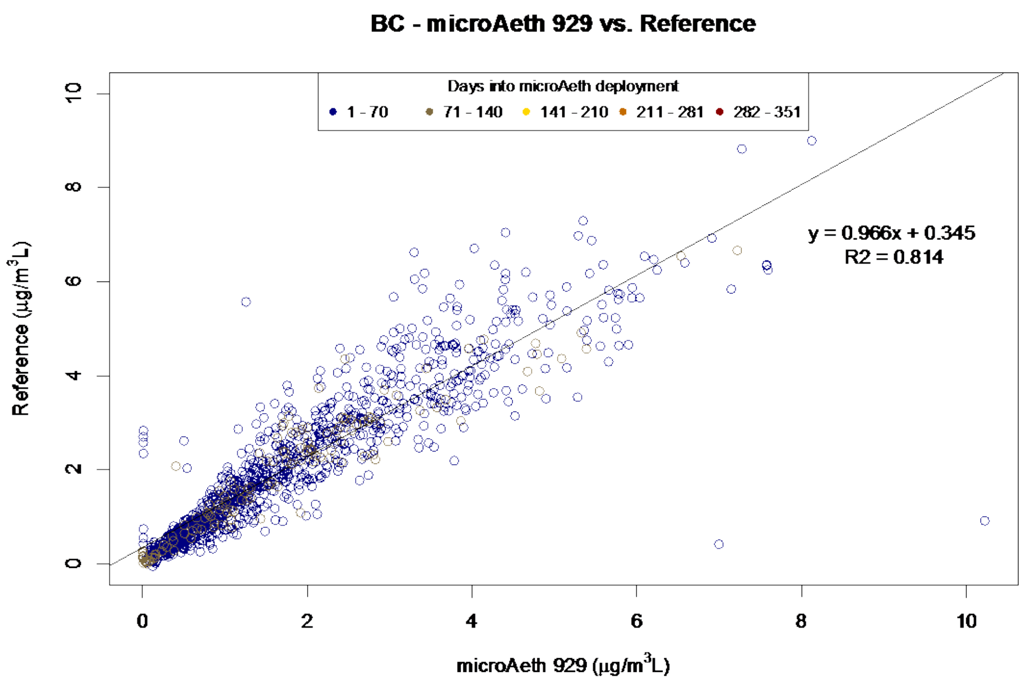

Figure 31 Scatterplot comparing AE929 and the reference monitor

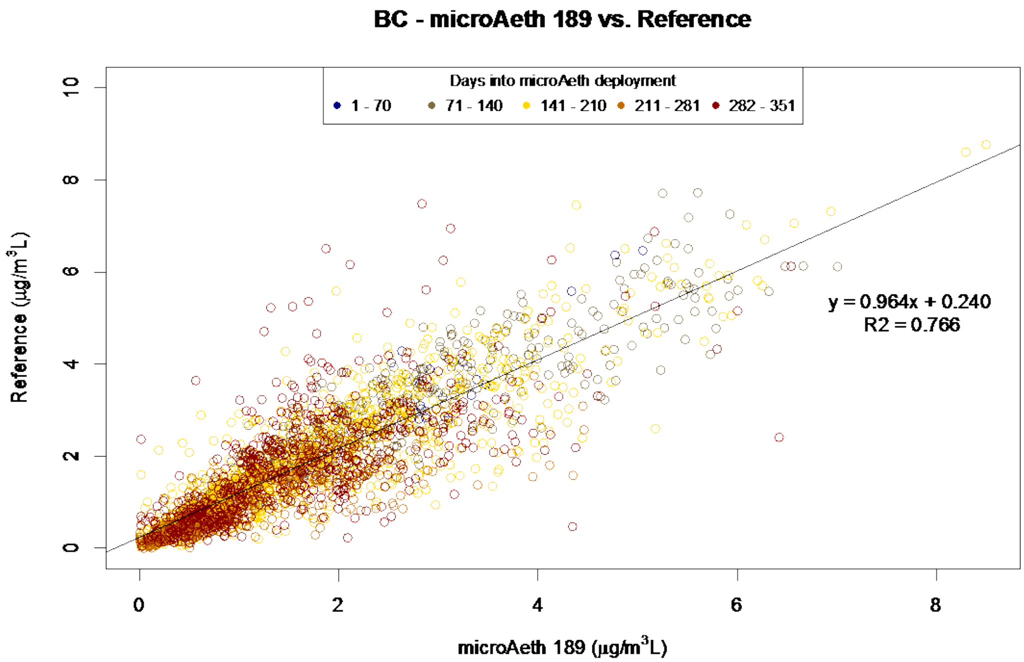

Figure 32 Scatterplot comparing AE189 and the reference monitor

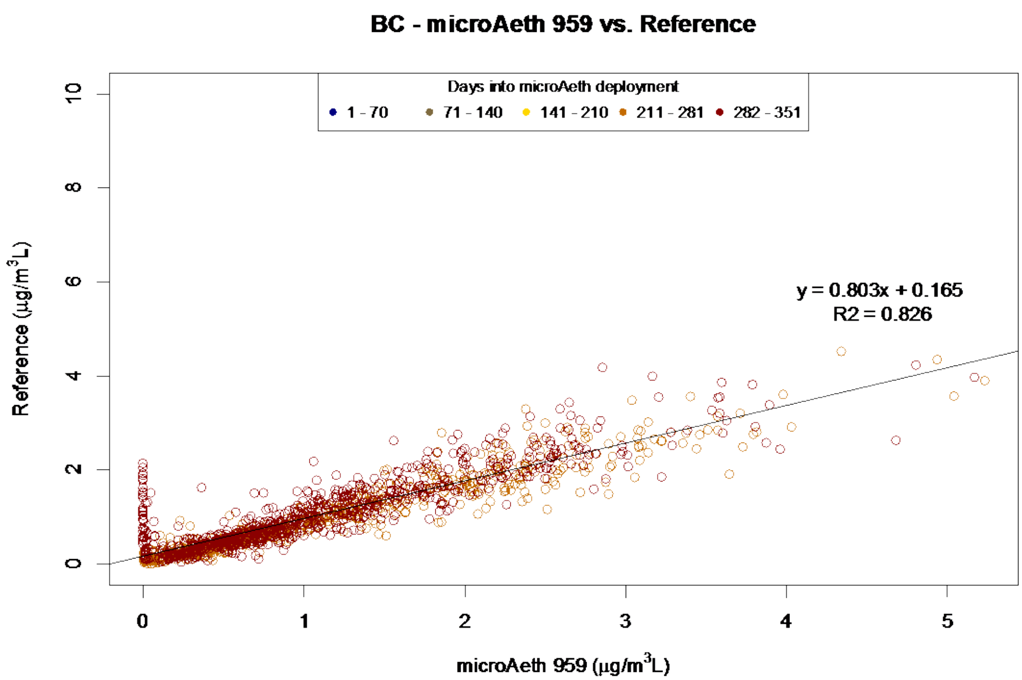

Figure 33 Scatterplot comparing AE959 and the reference monitor

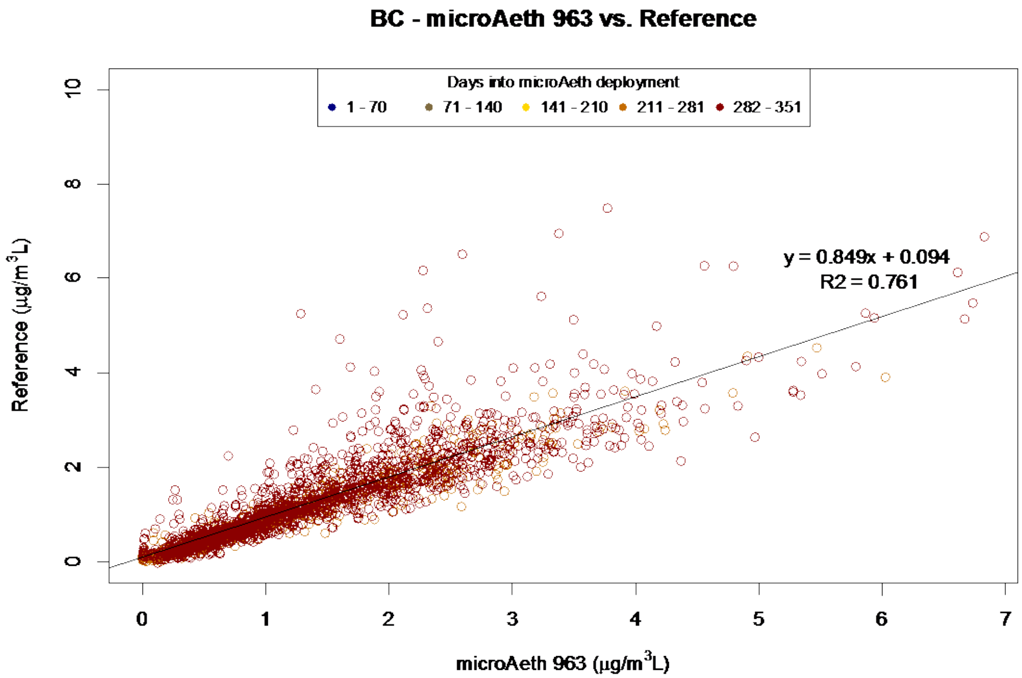

Figure 34 Scatterplot comparing AE963 and the reference monitor

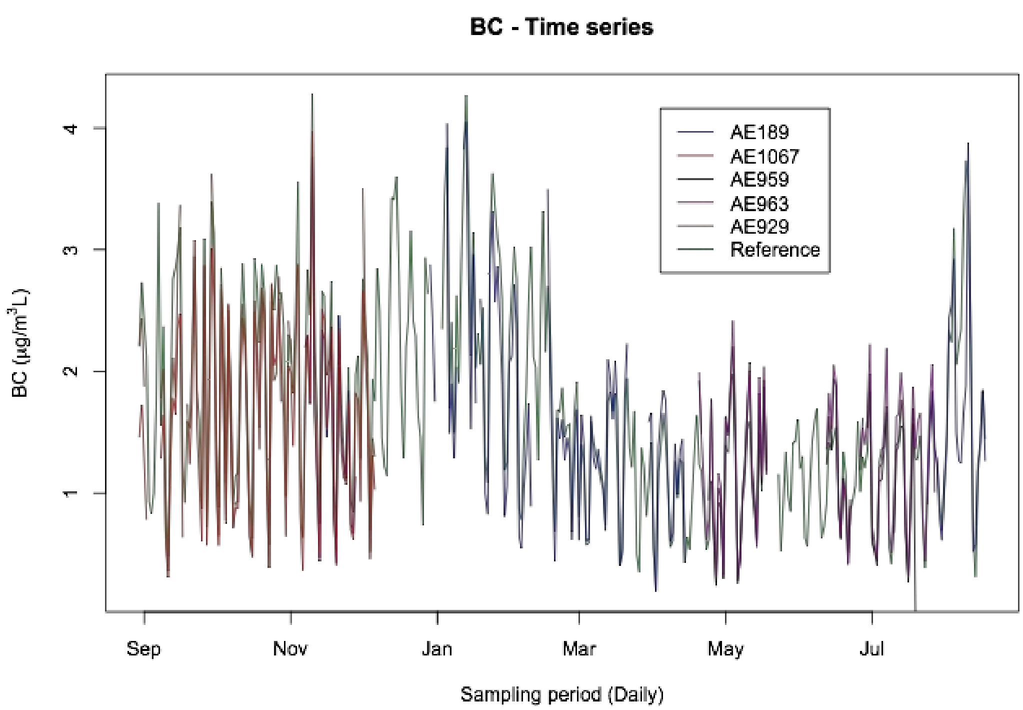

Figure 35 Time series plot of microAeths and reference monitor

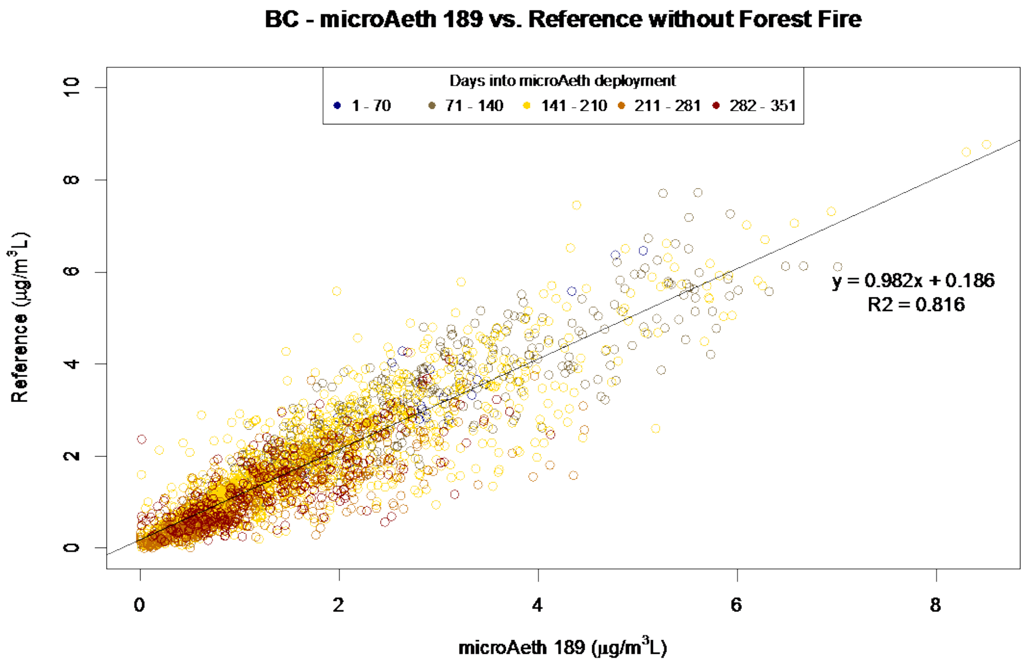

Figure 38 Scatterplot comparing AE189 and the reference monitor with first two weeks of August 2017 removed

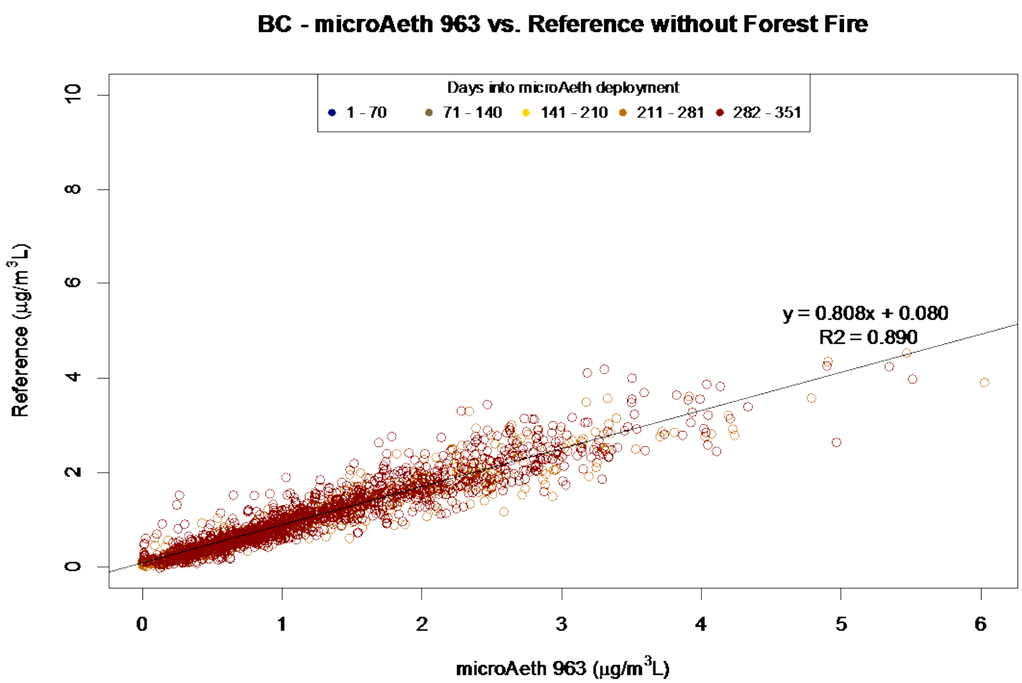

Figure 39 Scatterplot comparing AE963 and the reference monitor with first two weeks of August 2017 removed

Burnaby South Comparaison

The overall large-scale temporal trends for O_3, NO_2, BC, and $PM_{2.5}$ were similar between these four pollutants at the South Burnaby and Clark Drive locations. Correlations between the South Burnaby and Clark Drive monitoring stations were 0.82, 0.73, and 0.76 for O_3, NO_2, and $PM_{2.5}$ respectively. The correlation between these stations for BC was weaker, $r = 0.47$. This difference may have been due to O_3 and NO_2 being secondary pollutants which are not linked to local emissions sources as they form within the atmosphere and thus have a more homogeneous spatial distribution. $PM_{2.5}$ is both a primary and secondary pollutant that can be rather homogeneously distributed in the atmosphere while components (such as BC) may be more spatially heterogeneous. BC levels and spatial patterns were observed to be more closely tied to their emission sources. Generally, the Sunny Hill site correlations with Clark Drive were higher than with the South Burnaby site. This may be due to proximity to Clark Drive or due to the period of sampling (August 2016).

Table 7 Pearson's correlation for Clark Drive and other monitoring stations

	$PM_{2.5}$	BC	O_3	NO_2
Burnaby South	0.760	0.473	0.824	0.730
Sunny Hill	0.487	0.596	0.959	0.816

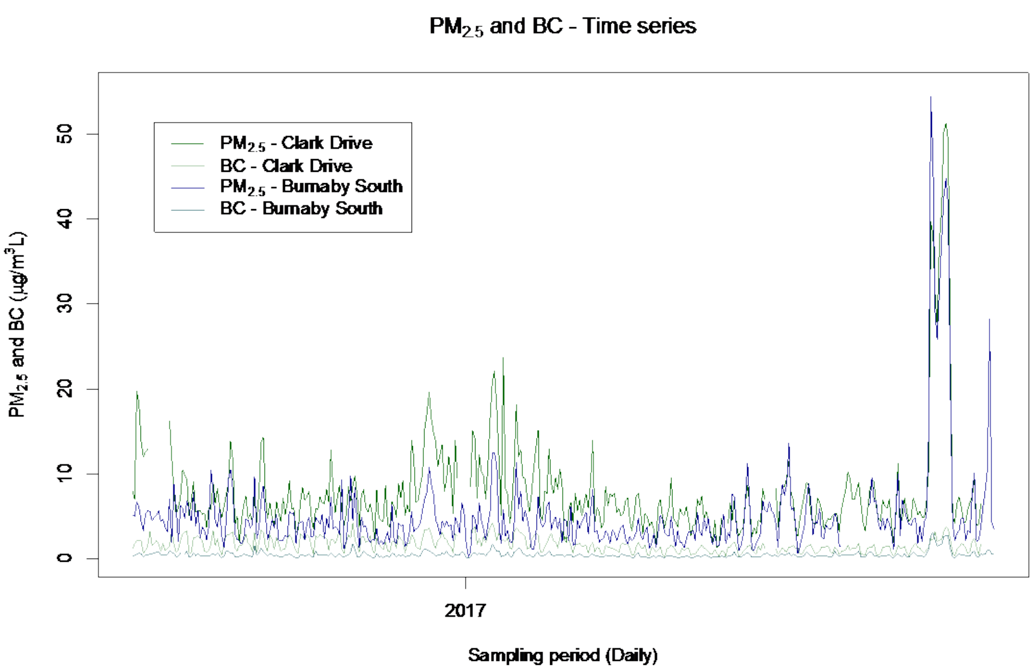

Figure 40 Time series plot of Burnaby South and Clark Drive – $PM_{2.5}$ and BC

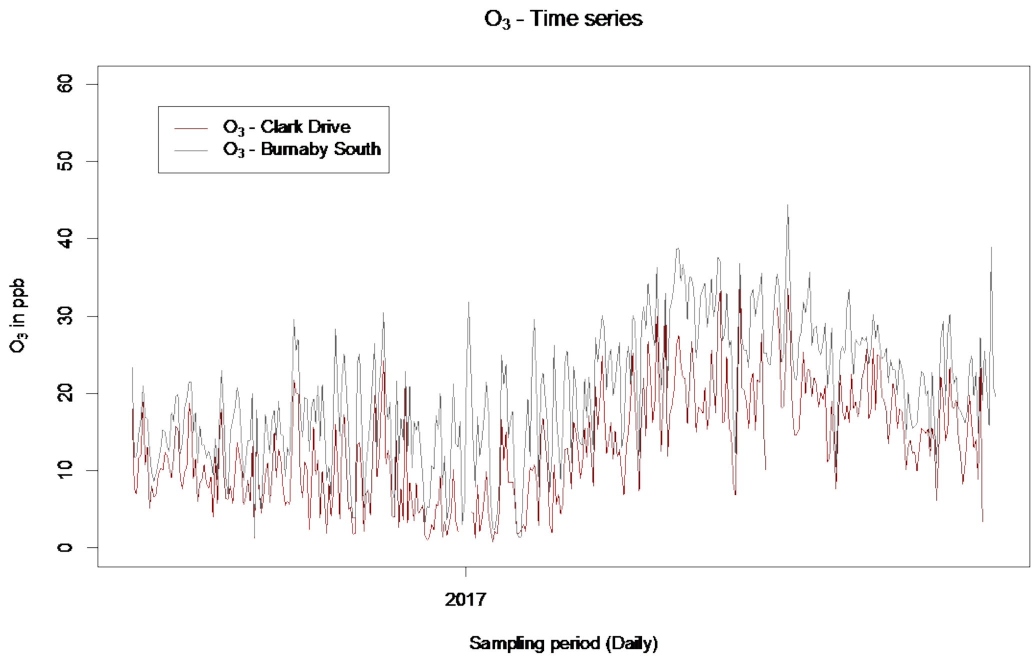

Figure 41 Time series plot of Burnaby South and Clark Drive – O_3

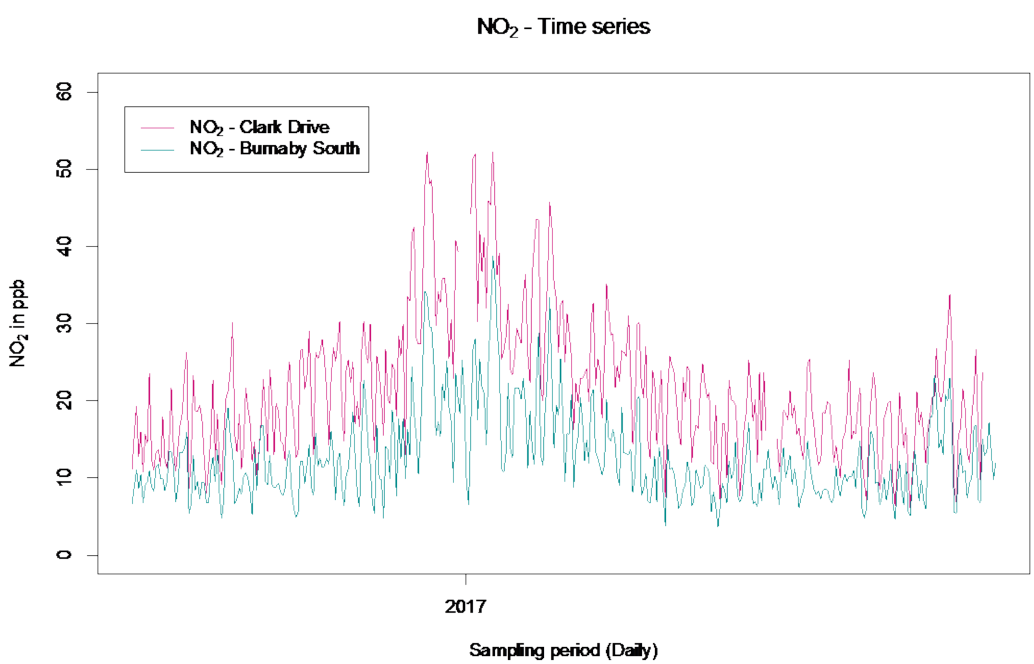

Figure 42 Time series plot of Burnaby South and Clark Drive – NO_2

The RMSE divided by the mean difference between the reference monitors from the Clark Drive and Burnaby South station provides an indication of the precision of the sensors at the Clark Drive Station compared to the spatial variation between locations (Table 8). This measure therefore is an indicator of the sensors' ability to detect the spatial variability in concentrations within an urban area, for example due to traffic-related air pollution as characterized by the near-roadway monitoring site. This measure is dependent on both the accuracy of the sensor and the variation in concentrations between sites. The Aeroquals and mircoAeths had values under one suggesting their precision was greater than the variation between the sites and that these devices may be useful for measuring spatial variability within an urban area such as Vancouver. The PurpleAir sensors and the ES-642 values were greater than one, suggesting that the error in the sensors was greater than the variability between sites.

Table 8 Sensor RMSE (with the difference between the sensor and the reference monitor) and RMSE divided by site difference

Sensor	RMSE[3]	$\frac{\text{RMSE}}{\text{mean difference between Clark Drive and Burnady South}}$
PA1	12.5	4.35
PA2	12.9	4.49
PA3	12.5	4.35
ES-642	5.67	1.97
Aero4	0.00683	-0.000962
Aero5	0.00572	-0.000807
Aero6	0.007378	-0.00104
Aero1	0.0735	0.00799
Aero2	0.0586	0.00637
Aero3	0.0590	0.00641
AE1067	0.689	0.597
AE929	0.749	0.649
AE189	0.695	0.602
AE959	0.391	0.339
AE963	0.367	0.318

Conclusion

In summary, of the potable low-cost sensors that were tested, the O_3 Aeroqual, microAeth AE51, and the PurpleAir provided the most promising results relative to the reference sensors. In addition to the relatively higher correlations, there is not a large logistical burden associated with use of these sensors, though the microAeth required frequent filter changes and both it and the O_3 require manual data download. They can however be connected to a wireless network via third party components to allow offsite data download.

The comparison between the South Burnaby ambient site and Clark Drive site, suggest that air pollution concentration variations were driven primarily by background trends

[3] Error represents the difference between the sensor and reference monitor

with relatively homogeneous concentrations, especially for secondary pollutants. Sensor precision relative to observed variability between sites suggested that only the Aeroqual ozone and microAeth units were adequate for measuring within-area spatial variation in pollutant concentrations.

Acknowledgments
We thank Ken Reid and Geoff Doerksen of Metro Vancouver, along with the entire Metro Vancouver air quality monitoring staff, for assistance with access to the Clark drive measurement site and for providing measurement data. We also thank Caleb Lee for assistance with switching filters and downloading data.

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