Characterization of Air Quality During the 2016 Horse River Wildfire Using Permanent and Portable Monitoring

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The authors thank technical staff in the Monitoring Observation branch of the Environmental Monitoring and Science Division (Marty Collins, Shane Taylor, and Charlene Puttick) for data collection, deploying and operating the additional portable monitoring platforms during the 2016 Horse River Wildfire. Also thank you to Wood Buffalo Environmental Association personnel for managing the permanent continuous air monitoring stations and data quality assurance.

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Reviewer 1 holds a Ph.D. in Environmental Engineering and Sciences and has substantial experience and understanding in Fort McMurray's air quality and air quality statistical analysis.

Reviewer 2 holds a Ph.D in Atmospheric Science and has over 13 years of experience analyzing and reporting ambient air quality data.

Executive Summary

The 2016 Horse River Wildfire was first discovered approximately seven kilometers southwest of Fort McMurray on May 1st, 2016. Several days later, evacuation orders were issued to Fort McMurray and surrounding areas due to the close proximity of the wildfire. The wildfire was not declared under control until July 4th, 2016.

The wildfire smoke plume consisting of particulate matter and trace gases caused degradation of ambient air quality in Fort McMurray and surrounding areas. In response, Alberta Environment and Parks, in partnership with the Wood Buffalo Environmental Association, assessed air quality data from permanent continuous air monitoring stations. Alberta Environment and Parks also deployed four Beta-attenuation Particulate Monitoring (EBAM) units and the Mobile Air Monitoring Laboratory (MAML) to fill spatial gaps between air monitoring stations and to inform decisions around the safety of emergency response personnel and community members upon re-entry.

In both the permanent and portable air monitoring datasets, the largest impact from the wildfire smoke was observed in May 2016 at locations within the Horse River Wildfire boundary. At the Athabasca Valley and Patricia McInnes stations, the monthly median hourly $PM_{2.5}$ concentrations were 5 to 8 times larger than the concentrations measured outside of the wildfire period (2013-2015; and 2017 data), and the 24-hour average $PM_{2.5}$ concentrations exceeded the Alberta Ambient Air Quality Objective (AAAQO) for 17 and 18 days, respectively. This is similar to the 20 days of AAAQO exceedances observed at a nearby population centre during the 2011 Richardson Wildland Fire. Elevated $PM_{2.5}$ concentrations during the wildfire with exceedances of the AAAQO/AAAQG were also measured by the EBAM and MAML, which demonstrated the widespread impact of the wildfire on air quality in the area. Therefore, $PM_{2.5}$ is a good indicator of wildfire smoke and, based on the health-based AAAQO exceedances, $PM_{2.5}$ measurements were suitable to support decisions to protect human health. The EBAM, which measures $PM_{2.5}$ concentrations continuously and can be deployed fairly quickly, is a suitable platform to assess the spatial variation of air quality and support health-based risk assessments during emergency response to wildfire smoke episodes.

Elevated levels of other air quality parameters were also observed during the wildfire. A total of 13 episodes of 1-hour carbon monoxide (CO) concentrations exceeding the AAAQO were recorded at the Athabasca Valley station, and the median hourly concentration was 2 times higher than during the non-wildfire impacted period. Elevated ammonia (NH_3) concentrations were observed during the wildfire at the Bertha Ganter station and Patricia McInnes station, but the concentrations did not exceed the hourly AAAQO. The monthly median hourly concentrations for nitrogen dioxide (NO_2), and sulphur dioxide (SO_2) were comparable to non-wildfire impacted periods. These data suggest that monitoring of additional parameters such as CO and NH_3, as provided by the MAML, added valuable information to support the safety decisions for the emergency response personnel and the public. However, the MAML requires more time to deploy than the EBAM units. Therefore, the MAML was deployed after the largest impact of the wildfire smoke plume (i.e., early May). Furthermore, the MAML was moved to multiple locations with the goal of measuring the spatial variation of air quality; due to the rapid changes in air quality in time, the MAML data could not be used to assess spatial variation of air quality during the wildfire.

Overall, the additional air monitoring deployed by Alberta Environment and Parks provided valuable information during the wildfire used to protect the health of emergency response personnel and the public. The EBAM and MAML are suitable for emergency response during wildfires. The EBAM provides continuous measurements of $PM_{2.5}$ concentrations and several units can be deployed to assess spatial variation of air quality. The MAML provides complementary information with other air quality parameters, such as NH_3 and CO, which were also elevated during the wildfire. However, based on the analysis of the data collected, several recommendations were proposed to improve future air monitoring activities during wildfire events. These recommendations were to facilitate public communication on the available air quality monitoring data, to minimize the relocation of the portable monitoring platforms, to assess the existing air monitoring network for the detection of wildfire smoke, and to evaluate the data collected by EBAM units through comparisons with other Federal Equivalence Method $PM_{2.5}$ monitoring platforms.

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Acronyms and Abbreviations

Acronym	Definition
AAAQG	Alberta Ambient Air Quality Guidelines
AAAQO	Alberta Ambient Air Quality Objectives
AEP	Alberta Environment and Parks
ASERT	Alberta Environment Support & Emergency Response
CAAQS	Canadian Ambient Air Quality Standards
CO	Carbon Monoxide
EBAM	Beta-attenuation Particulate Monitors
EPA	Environmental Protection Agency
FEM	Federal Equivalent Method
GOA	Government of Alberta
MAML	Mobile Air Monitoring Laboratory
NH_3	Ammonia
NO_2	Nitrogen Dioxide
PAH	Polycyclic Aromatic Hydrocarbons
PDF	Portable Document Format
$PM_{2.5}$	Fine Particulate Matter
POC	Provincial Operations Center
ppb	Parts Per Billion
REOC	Regional Emergency Operations Center
SO_2	Sulphur Dioxide
TRV	Toxicity Reference Values
VOC	Volatile Organic Compounds
WBEA	Wood Buffalo Environmental Association

1.0 Introduction

The Horse River Wildfire was first discovered in a forested area approximately seven kilometers southwest of Fort McMurray on May 1st, 2016 (MNP LLP, 2017). The wildfire had a final estimated burn area of 589,552 hectares, and caused fire damage in Fort McMurray and surrounding areas (MNP LLP, 2017). A mandatory evacuation order was issued on the afternoon of May 3rd, 2016 for all residents within the Urban Service Area of Fort McMurray (MNP LLP, 2017). On May 4th, 2016, an evacuation order was issued to communities of Saprae Creek, Anzac, Gregoire Lake Estates and Fort McMurray First Nation (Government of Alberta, 2017c). Due the concerns of fire smoke inhalation, the community of Fort McKay was issued a voluntary evacuation order on May 7th, 2016 (Government of Alberta, 2017c). All evacuation orders were lifted for voluntary re-entry on June 1st, 2016. The Horse River wildfire was declared to be under control on July 4th, 2016 (MNP LLP, 2017).

During the Horse River Wildfire, Alberta Environment and Parks (AEP), in partnership with the Wood Buffalo Environmental Association (WBEA), used the data from permanent continuous air monitoring stations and portable air monitoring platforms as part of ongoing risk assessments to inform health and safety decisions around emergency response personnel and the public re-entry to Fort McMurray and surrounding areas. Portable air monitoring platforms included four Beta-attenuation Particulate Monitor (EBAM) units and the Mobile Air Monitoring Laboratory (MAML).

During wildfire events, a smoke plume consisting of water vapour, particulate matter and trace gases is released into the atmosphere and can bring adverse health effects (Burling et al., 2010; Government of Alberta, 2017c) and increase atmospheric ion deposition to sensitive vegetation (Bytnerowicz et al., 2016). Several studies have already reported on air quality during the Horse River Wildfire, including a preliminary health risk assessment (Government of Alberta, 2017b), and several journal articles (i.e., Landis et al., 2018; Wentworth, Aklilu, Landis, & Hsu, 2018). The preliminary risk assessment was contracted by the Government of Alberta (GOA) and compared data collected at permanent continuous air monitoring stations, as well by the portable air monitoring instruments against Toxicity Reference Values[1] (TRV) and Alberta Ambient Air Quality Objectives and Guidelines (AAAQO; AAAQG) (Government of Alberta, 2017b). Landis et al. (2018) analyzed data collected at ten permanent continuous air monitoring stations and found 188 fire-related exceedances of 1-hour and 24-hour AAAQOs for a variety of species. Landis et al. (2018) also found strong correlation between gaseous emissions (e.g., carbon monoxide, non-methane hydrocarbons, total reduced sulphur, ammonia) and fine particulate matter during the

[1] Toxicity Reference Values: based on various government agencies (i.e., AEP, Health Canada, Canadian Council of Ministers of the Environment, United State National Ambient Air Quality Standards) or maybe derived directly from literature (Government of Alberta, 2017b)

Horse River Wildfire event. Wentworth, Aklilu, Landis, & Hsu (2018) examined the impacts of the Horse River Wildfire on ground level atmospheric concentrations of speciated 24-hour integrated samples of polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs) within Fort McMurray and surrounding areas. On average, the sum of PAHs were 17 times higher in wildfire impacted influenced samples than in non-wildfire influenced samples, while the sum of VOCs in both wildfire influenced and non-wildfire influenced samples were similar.

In this report, air quality during the Horse River Wildfire was characterized using data collected by the EBAM and MAML, alongside the data from permanent continuous air monitoring stations. Fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), ammonia (NH_3), sulphur dioxide (SO_2) and carbon monoxide (CO) are the parameters presented because they were measured by the permanent and the portable air monitoring, can potentially be emitted during wildfires (Burling et al., 2010), and have associated AAAQO and/or AAAQG on hourly and 24-hour time-scales. Based on the spatial and temporal variability of air quality in the collected data, this report provides recommendations for the deployment and use of portable air monitoring during wildfire events.

2.0 Air Quality Monitoring

Figure 1 shows the estimated total burn area of the Horse River Wildfire and the locations of air quality monitoring stations used in this report. The Horse River Wildfire boundary was estimated from aerial photography by Alberta Agriculture and Forestry[2], and the spatial wildfire data is publicly available for download through http://wildfire.alberta.ca/resources/historical-data/spatial-wildfire-data.aspx.

Air quality data were collected at six permanent continuous air monitoring stations, as well as portable air monitoring platforms, including four EBAM units and the MAML, which were deployed to various locations in Fort McMurray and surrounding areas, as shown in Figure 1. Note that the markers for the portable monitoring platforms denote temporary monitoring locations and were not sampled for the entire measurement period. Details of the monitoring methods and sampling are given in following subsections. The monitoring locations for the EBAM and MAML were at heavily impacted areas identified by the Provincial Operations Centre (POC) of GOA. During the Horse River Wildfire, the POC used the data from both permanent and portable air monitoring

[2] Estimated Horse River Wildfire Boundary provided by Alberta Agriculture and Forestry through inter-government request on October 10th, 2018.

stations as part of ongoing risk assessments to inform health and safety decisions around emergency response personnel and the public re-entry to Fort McMurray and surrounding areas.

The reported values from permanent continuous air monitoring stations are publicly available in near real-time through http://airquality.alberta.ca/map. The data then undergo quality assurance and quality checks according to the Air Monitoring Directive (Alberta Environment and Parks, 2016) before submission to the Alberta Air Data Warehouse[3] at http://airdata.alberta.ca/. The data collected at the portable monitoring platforms were publicly available on a daily basis online at http://environmentalmonitoring.alberta.ca/air/fort-mcmurray-fire-updates/, but due to the time lag in posting these data, the data reported sometimes did not represent current air quality. Section 4.0 further discusses recommendations to improve data reporting during wildfires.

2.1 Permanent Continuous Air Monitoring Stations

The six permanent continuous air monitoring stations included in this report and are shown in Figure 1. These stations were selected because of their close proximities to the Horse River Wildfire and impacted communities, and because they measured the air quality parameters relevant to this report, including $PM_{2.5}$, NO_2, NH_3, SO_2 and CO.

Table 1 lists the parameters monitored at each permanent continuous air monitoring station. The detailed information about each station, including parameters measured, station coordinates and gas analyzer models used for monitoring, is shown in Appendix A1. During the Horse River Wildfire, all permanent continuous air monitoring stations were operational with the exception of Anzac station. Measurements at the Anzac station were interrupted from May 6th to 13rd, 2016 (i.e., 8 days), when the wildfire caused a power outage. As a result, the data completeness for May 2016 at the Anzac station was only at 75%.

[3] The 2013-2016 data were downloaded on or before April 25th, 2017. The 2017 data were download on or before November 9th, 2017.

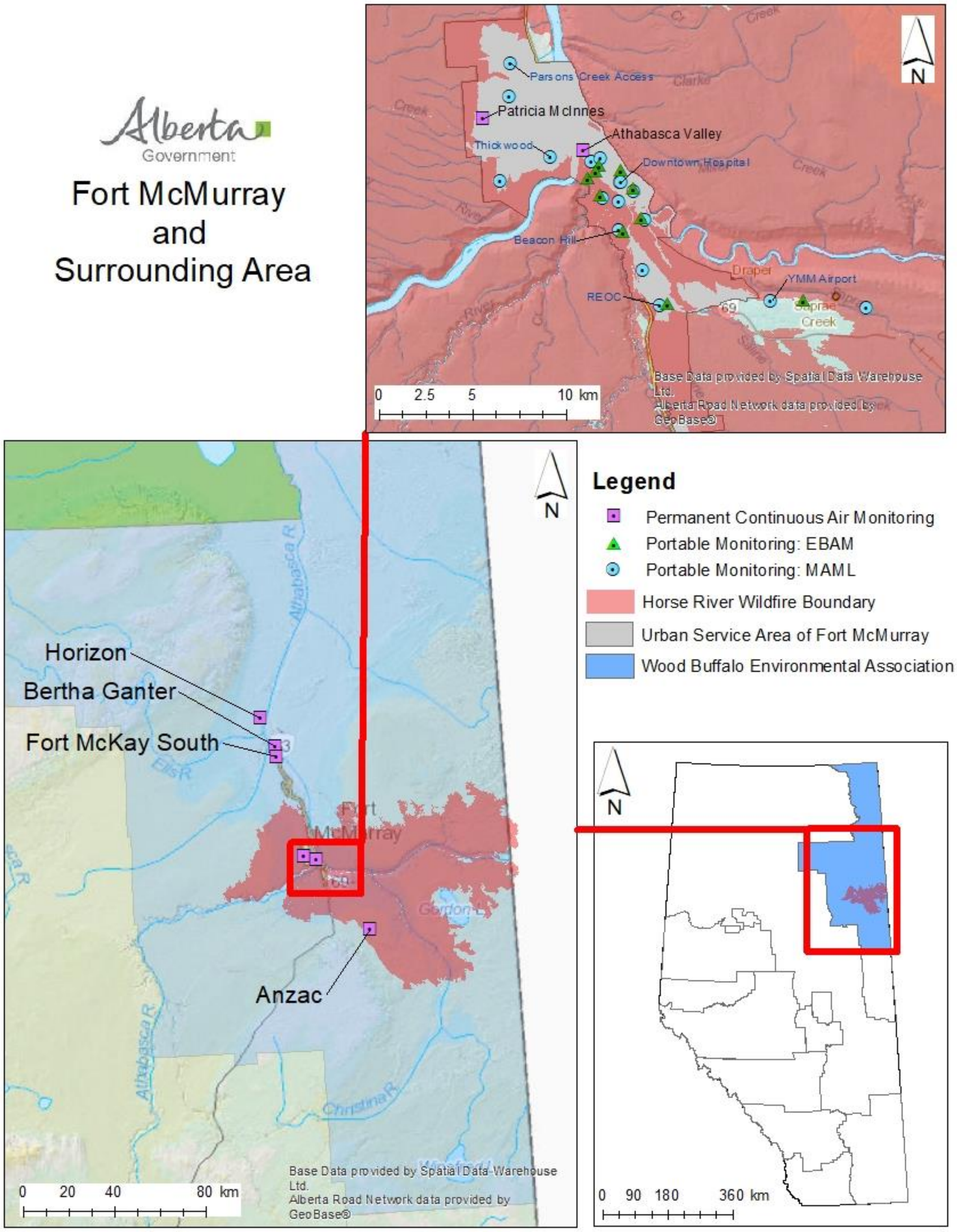

Figure 1: Fort McMurray and Surrounding Area with Air Quality Monitoring Stations and Horse River Wildfire Boundary Indicated

Table 1: Monitored Parameters at Permanent Continuous Air Monitoring Stations

Stations	Parameters Considered in this Report				
	$PM_{2.5}$	NO_2	NH_3	CO	SO_2
Anzac[4]	✓	✓	×	×	✓
Horizon	✓	✓	×	×	✓
Bertha Ganter	✓	✓	✓	×	✓
Fort McKay South	✓	✓	×	×	✓
Athabasca Valley	✓	✓	×	✓	✓
Patricia McInnes	✓	✓	✓	×	✓

2.2 Beta-attenuation Particulate Monitor (EBAM)

The EBAM units are portable monitors that report only hourly average $PM_{2.5}$ concentrations in near real-time. EBAM units are relatively easy to transport and can be deployed rapidly, which makes them suitable for quick deployment during emergency response. The EBAM $PM_{2.5}$ units are not designated a U.S. Environmental Protection Agency (EPA) Federal Equivalent Method (FEM); therefore, the data are not considered equivalent to the data collected by the FEM analyzers at the permanent air monitoring stations and in the MAML. AEP deployed four EBAM units to eleven locations in Fort McMurray and surrounding areas from May 7th to November 7th, 2016. The locations of the EBAM monitors are shown in Figure 2. A photo and details of EBAM monitoring locations are listed in Appendix A2. Data collected by AEP with EBAM as part of

[4] Monitoring was interrupted from May 6th – 13rd, 2016 due to power outage caused by wildfire

emergency response monitoring during the 2016 Horse River wildfire is available through the GOA Open Data Library (Government of Alberta, 2019a).

Due to logistical reasons, the EBAM units were not deployed for monitoring at the very beginning of the wildfire event (i.e., May 1st to May 7th, 2016). In Section 4.0, recommendations are proposed for future wildfire monitoring.

During the first phase of EBAM monitoring, from May 7th to June 21st, 2016, the EBAM units were deployed to assess the air quality risk for emergency response personnel and to inform the safety for public re-entry of Fort McMurray and surrounding areas. Therefore, the EBAM units were distributed to assess the spatial variation of air quality within Fort McMurray and surrounding areas. The EBAM units were relocated by small distances several times during this period due to security reasons and to reduce possible interference from localized anthropogenic sources (i.e., vehicle emissions) on the data.

During the second phase of EBAM monitoring, from June 21st to November 7th, 2016, the EBAM units were deployed to assess the impact of cleanup and recovery effects on air quality in neighborhoods that had been impacted by the wildfire. Therefore, three EBAM units were relocated to several neighborhoods (e.g., Abasand, Beacon Hill, Waterways) within Fort McMurray. One EBAM unit remained at the Fort McMurray Regional Emergency Operation Centre (REOC).

2.3 Mobile Air Monitoring Laboratory (MAML)

The MAML is a 27 foot (8.2 meter) vehicle that houses a variety of instruments that measure ambient air quality. The MAML was deployed in various impacted communities within Fort McMurray from May 16th to June 9th, 2016. Due to logistical reasons, the MAML was not deployed for monitoring at the very beginning of the wildfire event (i.e., May 1st to May 16th, 2016). In Section 4.0, recommendations are proposed to address the monitoring gaps in future wildfire monitoring.

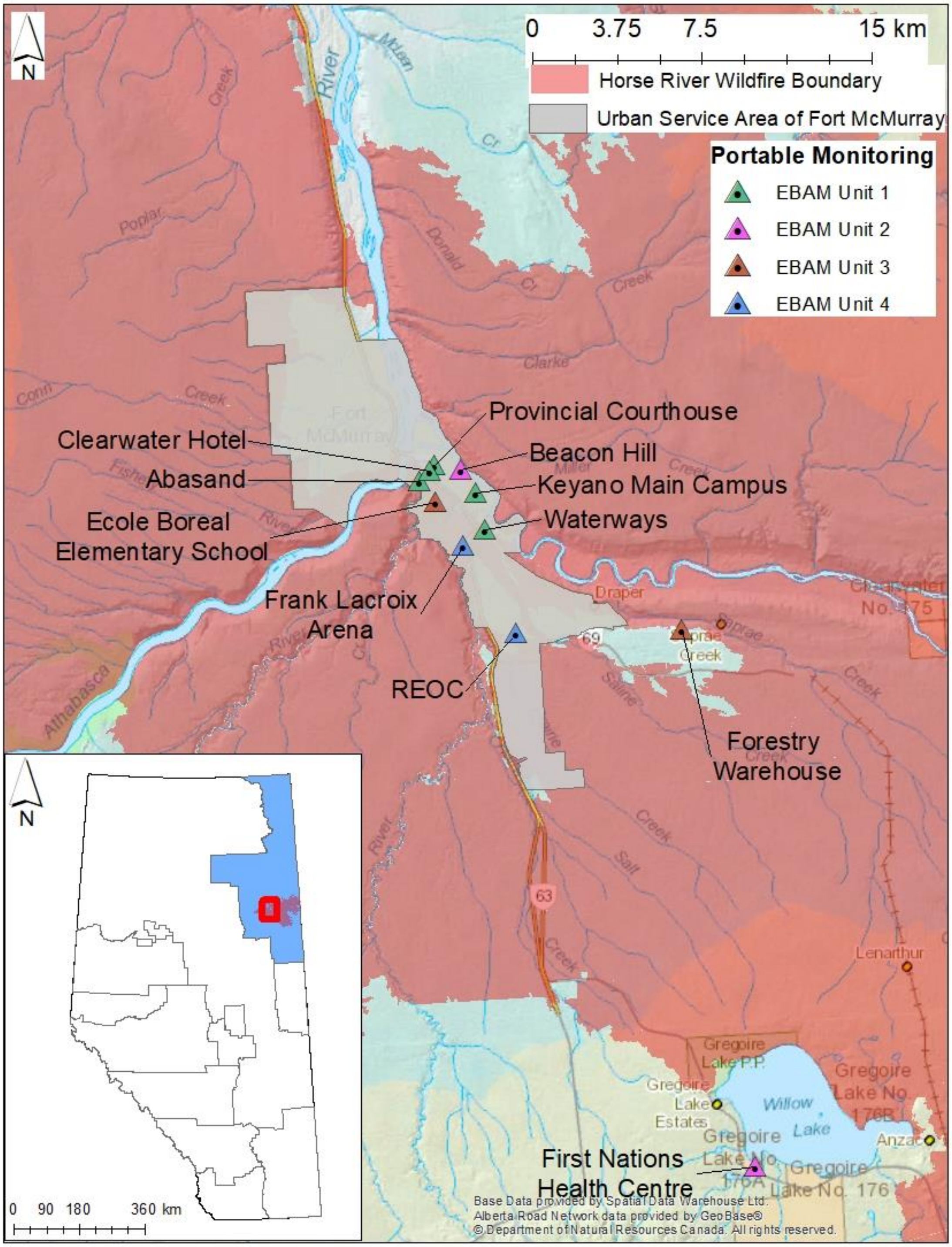

Figure 2: Fort McMurray and Surrounding Area with EBAM Monitoring Locations Indicated

The MAML houses a variety of instruments that measure ambient air quality as shown in Table 2, which are comparable to the quality and types of analyzers used at the continuous air monitoring stations. The MAML analyzers provide data at a 1-minute average frequency, and hourly averages were calculated with the requirement that at least forty-five 1 minute measurements were available to create a valid 1-hour average. Data collected by AEP with MAML as part of emergency response monitoring during the 2016 Horse River wildfire is available through the GOA Open Data Library (Government of Alberta, 2019b).

Table 2: Summary of MAML Analyzers Included in this Study

Parameters	Instrument Used
$PM_{2.5}$	Grimm aerosol model 180
NO_2	Thermo Scientific Model 17i gas analyzer
NH_3	Thermo Scientific Model 17i gas analyzer
SO_2	Thermo Scientific Model 43i
CO	Thermo Scientific Model 48i (trace-level)

The locations and duration of the MAML monitoring varied day-to-day, and were informed by POC, which identified heavily impacted areas. The MAML moved to various locations within Fort McMurray, sampling 1 to 2 locations for several hours per day (2 to 8 hours) in three monitoring phases. Phase I took place between May 16th to May 22nd, 2016, while Fort McMurray was under an evacuation order. During this period, the MAML was located to measure air quality in areas that were heavily impacted by the wildfire smoke in order to assess risk to emergency personnel in the area. For Phase II, the MAML was deployed to monitor air quality in neighborhoods during the voluntary re-entry of residents between May 31st and June 4th, 2016 to ensure that air quality was safe for the public. In Phase III, from June 7th to June 9th, 2016, the MAML was located to sample areas that had been destroyed by the wildfire and were restricted to the public. The intention was to monitor the air quality in the most wildfire-impacted neighborhoods during clean-up operations. The MAML monitoring locations are shown in Figure 3. A photo and a detailed list of monitoring locations are provided in Appendix A3.

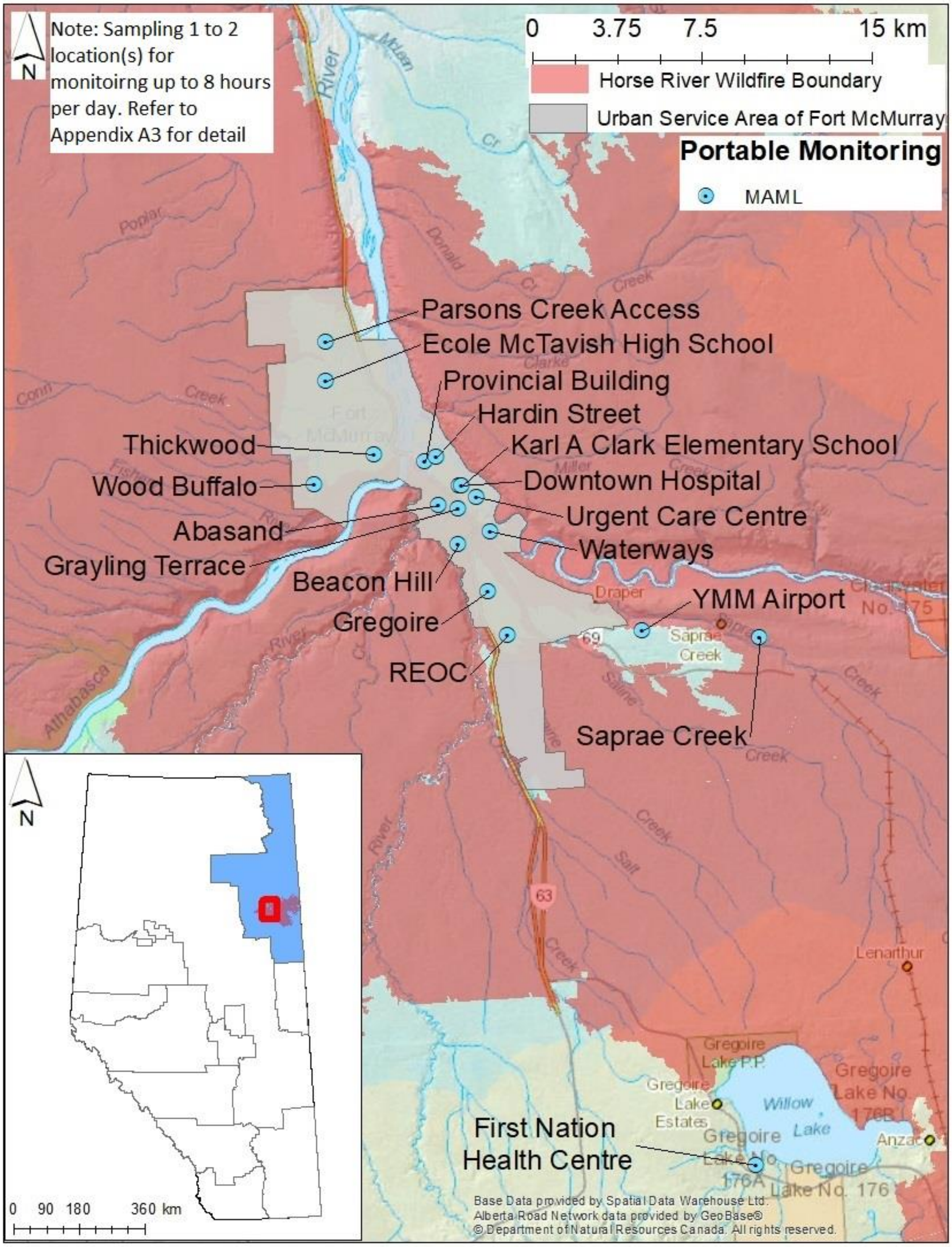

Figure 3: Fort McMurray and Surrounding Area with MAML Locations Indicated

3.0 Characterization of Air Quality during the Wildfire

To assess air quality during the Horse River Wildfire, data collected at permanent continuous air monitoring stations, and portable air monitoring platforms are compared with air quality guidelines and objectives and data collected prior to and after the Horse River Wildfire event.

The wildfire impacted period is 2016 and the focus indicators are $PM_{2.5}$, NO_2, NH_3, SO_2, and CO. These parameters were considered because they (1) are measured by the permanent continuous air monitoring stations and the portable air monitoring platforms; (2) can potentially be emitted during wildfire events (Burling et al., 2010) and; (3) have associated AAAQO/AAAQG on the hourly and 24-hour time-scales.

$PM_{2.5}$ is one of the largest components of wildfire smoke, and can travel relatively long distances affecting air quality and decreasing the visibility (Government of Alberta, 2017c). When a high concentration is present in ambient air, $PM_{2.5}$ can penetrate deep into the respiratory system, resulting in decreased lung function (Alberta Environment, 2007; Canadian Council of Ministers of the Environment, 2007). NO_2 and SO_2 can cause adverse effects on forest ecosystems (Bytnerowicz, Omasa, & Paoletti, 2007), and lung health (Ciais et al., 2013; WBK & Associates Inc., 2003). NH_3 contributes to nitrogen deposition where it can adversely impact sensitivity vegetation (Bytnerowicz et al., 2016). Exposure to CO can affect the blood oxygen carrying capacity and damages the nervous systems (Reisen, Duran, Flannigan, Elliott, & Rideout, 2015). Data analysis for some other air quality parameters (e.g., PAHs, VOCs) are examined for the Horse River Wildfire in other published work (e.g., Landis et al., 2018; Wentworth et al., 2018).

The results for the Horse River Wildfire were compared against air quality observed during the Richardson Wildland Fire (Bytnerowicz et al., 2016). The Richardson Wildland Fire started on May 15th, 2011 and burned into August, consuming over 700,000 hectares of forest (Bytnerowicz et al., 2016). There are similarities between the Richardson Wildland Fire and the Horse River Wildfire. Both wildfires are considered “mega-wildfires”, affecting more than 10,000 hectares, and occurred in the Alberta Athabasca Oil Sands Region during the summer months (May-August) in recent years (Bytnerowicz et al., 2016; Landis et al., 2018).

3.1 Comparison to Alberta Ambient Air Quality Objectives and Guidelines

In this section, data collected by the permanent continuous air monitoring stations and portable air monitoring platforms during the Horse River Wildfire are presented and compared against the AAAQOs and AAAQGs. The AAAQOs and AAAQGs for the parameters considered in this study, for shorter averaging periods (24-hour or less) are summarized in Table 3. The data are presented on bar charts and time series plots generated in Microsoft Excel and MATLAB.

Table 3: Summary of Ambient Air Quality Objectives and Guidelines Considered in this Study

Parameters	AAAQO	AAAQG
Particulate Matter- Fine ($PM_{2.5}$)	24-hour average[5]: 30 µg/m^3	1-hour average: 80 µg/m^3
Nitrogen Dioxide (NO_2)	1-hour average: 159 ppb	N/A
Ammonia (NH_3)	1-hour average: 2,000 ppb	N/A
Sulphur Dioxide (SO_2)	1-hour average: 172 ppb 24-hour average: 48.0 ppb	N/A
Carbon Monoxide (CO)	1-hour average: 13,000 ppb	N/A

3.1.1 Fine Particulate Matter ($PM_{2.5}$)

Elevated $PM_{2.5}$ concentrations were observed during the Horse River Wildfire period, with the largest impact of the wildfire smoke observed in May 2016. Hourly average $PM_{2.5}$ exceeded the AAAQG at all permanent continuous air monitoring stations, as shown in Figure 4. At the Athabasca Valley station, a total of 192 hours exceeded the 1-hour AAAQG, with a maximum

[5] The 24-hour AAAQO for $PM_{2.5}$ has changed to 29 µg/m^3, last reviewed in November 2018.

measured concentration of 3261 µg/m^3. This was the most hourly exceedances recorded at all permanent continuous air monitoring stations considered. At the Patricia McInnes station, 174 hours exceeded the 1-hour AAAQG, with a maximum measured concentration of 5198 µg/m^3. This was the highest hourly $PM_{2.5}$ concentration recorded at all permanent continuous air monitoring stations considered. The other four permanent continuous air monitoring stations also observed 35 hours to 72 hours of AAAQG exceedances, with maximum concentrations of 2028 µg/m^3 to 3867 µg/m^3. At each station, the total possible monitoring hours for May 2016 is 744 hours.

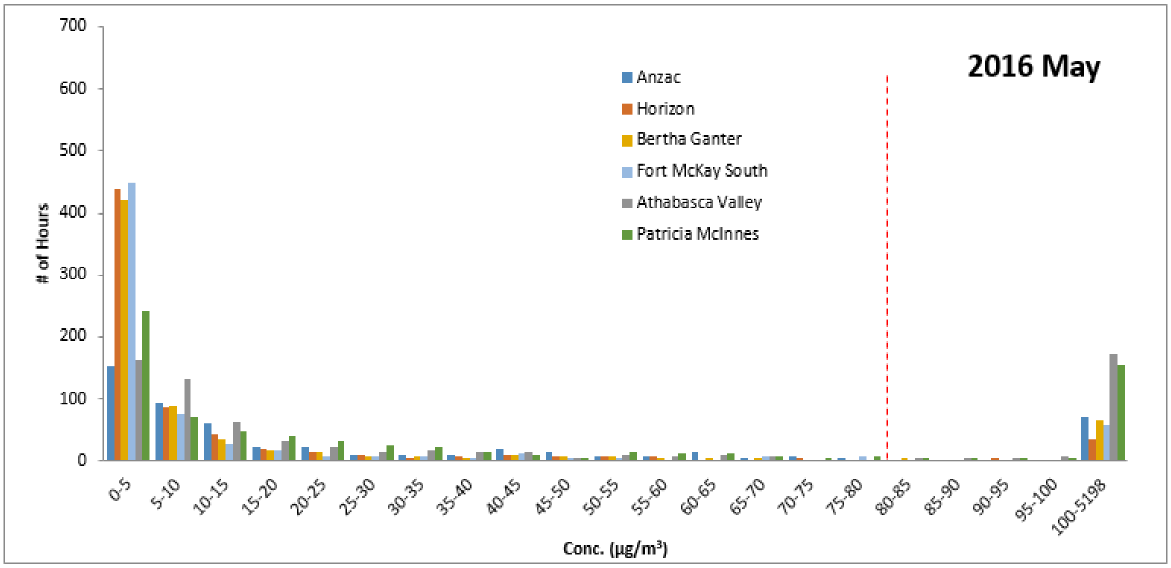

Figure 4: Histograms of 1-hour Average $PM_{2.5}$ Frequency Distribution for Permanent Continuous Air Monitoring Stations in May, with 1-hour AAAQG for $PM_{2.5}$ Indicated by the Red Dashed Line. Note: Due to a Power Outage, Data Completeness for the Anzac Station was 75%.

Figure 5 shows the distribution of 24-hour average $PM_{2.5}$ for permanent continuous monitoring stations for April to August 2016, with the AAAQO indicated.

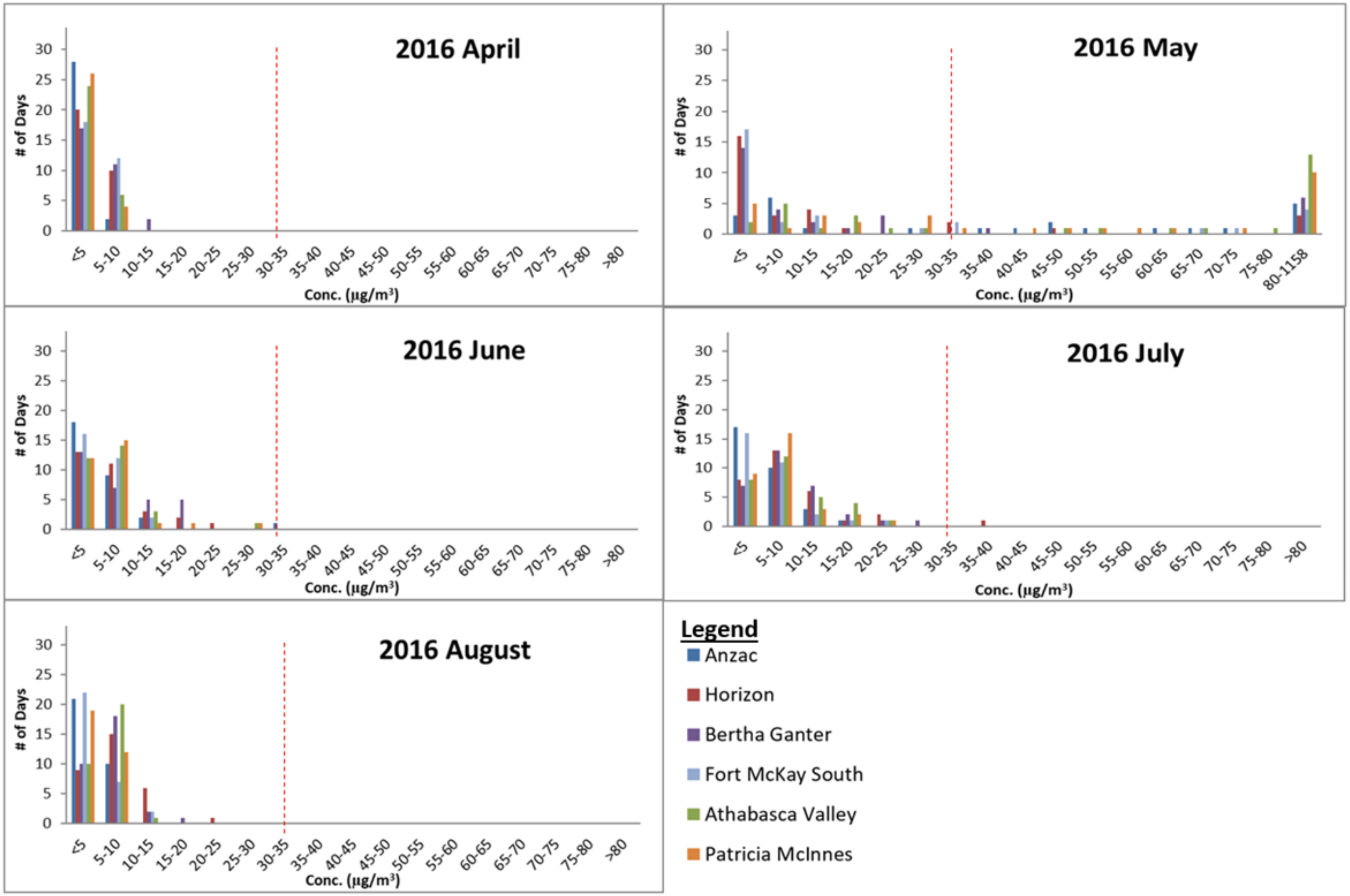

Figure 5: Histograms of 24-hour Average $PM_{2.5}$ for 2016 Permanent Continuous Air Monitoring Stations, with 24-hour AAAQG for $PM_{2.5}$ Indicated by the Red Dashed Line. Note: Due to a Power Outage, Data Completeness for the Anzac Station was 75%.

In May 2016, 24-hour AAAQO exceedances were observed at all six permanent continuous air monitoring stations. The Athabasca Valley and Patricia McInnes stations reported the largest number of exceedances, with 18 and 17 days of exceedances, respectively. This is similar to the 20 days of AAAQO exceedances observed at a nearby population centre during the Richardson Wildland Fire (Bytnerowicz et al., 2016). The maximum 24-hour average $PM_{2.5}$ concentrations recorded were 1035 µg/m^3 at the Athabasca Valley station on May 7th, 2016 and 1131 µg/m^3 at the Patricia McInnes station on May 4th, 2016. These concentrations were much higher than the 368 µg/m^3 observed during the Richardson Wildland Fire (Bytnerowicz et al., 2016). However, the maximum hourly maximum detection limit was set at 450 µg/m^3 during the Richardson fire, and therefore this value is likely underestimated (Bytnerowicz et al., 2016). The maximum 24-hour $PM_{2.5}$ concentrations observed during the Horse River Wildfire are comparable to the value of 1100 µg/m^3 observed for the 2006-2007 Victorian Alpine Fire (Reisen et al., 2015). In June and July 2016, there is one daily AAAQO exceedance each observed at the Anzac station (June 8th 2016 at 31.2 µg/m^3), and the Horizon station (July 17th 2016 at 39.5 µg/m^3). Therefore, the smoke plume from the Horse River Wildfire had the largest impact on air quality in the Fort McMurray area in May 2016. In Figure 6, the available 24-hour average $PM_{2.5}$ concentrations collected by the four EBAM units at various impacted neighborhoods within Fort McMurray and surrounding areas are shown.

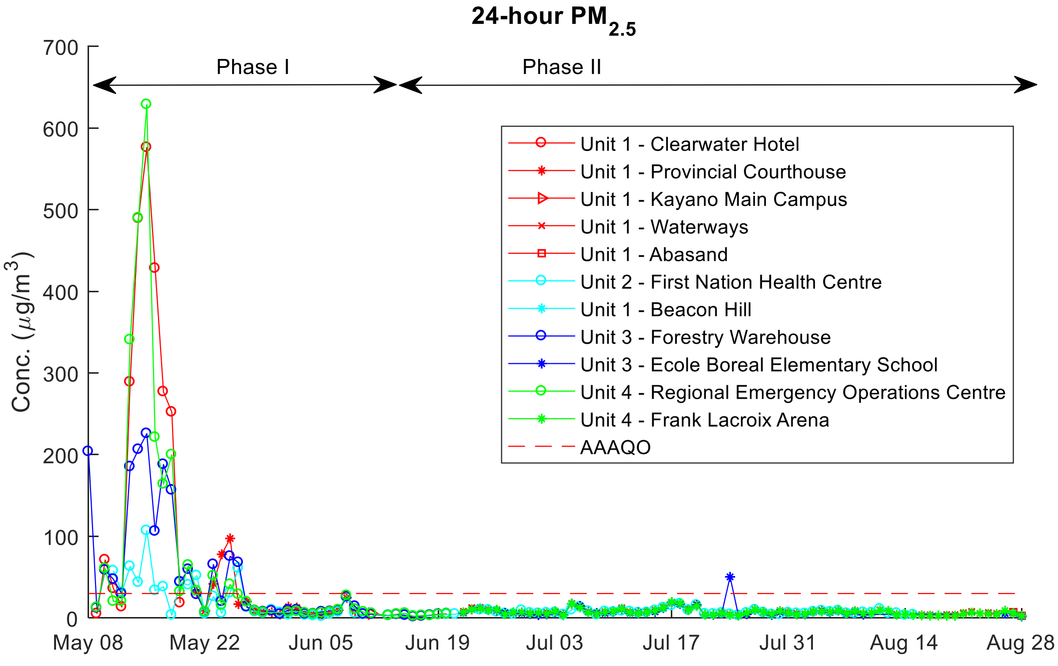

Figure 6: Time Series for EBAM 24-hour Average $PM_{2.5}$ Concentrations, with 24-hour AAAQO for $PM_{2.5}$ Indicated by the Red Dashed Line.

Exceedances of AAAQO were observed throughout the month of May for the EBAM units, which is consistent with observations at the permanent air monitoring stations and demonstrates that the wildfire smoke had the largest impact during this period. During the peak periods of ambient $PM_{2.5}$, the 24-hour average $PM_{2.5}$ concentrations ranges from 290 µg/m^3 to 629 µg/m^3, which were observed by the EBAM units located in downtown Fort McMurray (Unit #1) and at the REOC (Unit #4), suggesting that the fire had the highest impact on air quality in these areas. Lower levels of 24-hour average $PM_{2.5}$ concentrations of 44 µg/m^3 to 226 µg/m^3 were observed at the Fort McMurray Airport (Unit #3) and at Gregoire Lake Estates (Unit #2), which are located further from the downtown core of Fort McMurray. Although the impact of smoke at these locations was somewhat less than in the downtown core, it was still significant, as the two locations also observed $PM_{2.5}$ AAAQO exceedances for the same period.

The highest 24-hour average EBAM $PM_{2.5}$ concentration was recorded at the REOC on May 15th, 2016 at 629 µg/m^3 (Unit #4). Elevated $PM_{2.5}$ concentrations were also observed at the permanent continuous air monitoring stations at the Athabasca Valley station (725 µg/m^3; 9.25 km northeast of REOC) and Anzac (267 µg/m^3; 29.3 km southwest of REOC) on the same day.

Hourly average $PM_{2.5}$ from the MAML at various locations within Fort McMurray and surrounding areas are shown in Figure 7. In Phase I of monitoring, which took place when the wildfire plume was affecting Fort McMurray and surrounding areas, 18 hours out of total 45 hours of monitoring, exceeded the hourly average $PM_{2.5}$ concentrations of the AAAQG. The exceedances occurred between May 16th to May 20th, 2016, which is consistent with the timelines of enhanced $PM_{2.5}$ levels observed by the permanent continuous air monitoring stations and the EBAM units. During Phase II and Phase III of monitoring, which took place after the wildfire had moved away from the Fort McMurray area, no 1-hour average $PM_{2.5}$ concentrations were above the AAAQG. Note that the MAML was not deployed for monitoring when the wildfire smoke plume was thickest in the Fort McMurray area (i.e., early May). The spatial and temporal variation of the MAML data is explored in further detail in Appendix C. $PM_{2.5}$ concentrations reached high peak values that exceeded the AAAQOs and AAAQGs at all permanent continuous air monitoring stations, and at various portable air monitoring locations in May 2016. This demonstrates the widespread impact of wildfire smoke in Fort McMurray and surrounding areas.

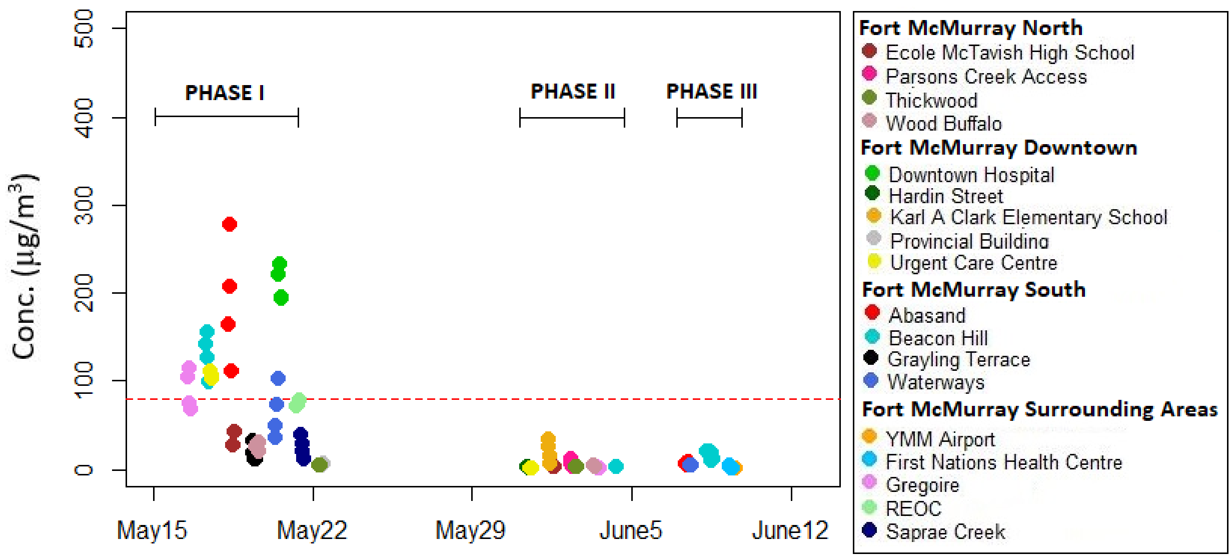

Figure 7: MAML 1-hour Average $PM_{2.5}$ Concentrations Prior to and During Public Re-Entry at Various Locations, with the 1-hour AAAQG for $PM_{2.5}$ Indicated by the Red Dashed Line

3.1.2 Nitrogen Dioxide (NO_2)

A time series plot of 1-hour average concentrations of NO_2 at permanent air monitoring stations is shown in Figure 8. The Anzac station recorded the only NO_2 AAAQO exceedance[6] for the hour of 22:00 May 5th, 2016 at a concentration of 291 ppb. At this time, the wildfire was in close proximately to the Anzac station, causing the loss of several structures and a power outage at the station from May 6th to May 13th, 2016.

No exceedances of the AAAQO for NO_2 were observed by the MAML NO_x analyzer, as shown in Figure 9. Furthermore, MAML NO_2 measurements did not vary like the $PM_{2.5}$ measurements, which were enhanced at several locations when the smoke plume influenced the area in mid-May (Figure 7). This is consistent with the minor influence of the smoke on NO_2 as observed at the permanent continuous air monitoring stations.

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[6] Note that the Alberta Health Preliminary Air Quality Assessment (Government of Alberta, 2017b) compares levels of NO_2 to a TRV of 100 ppb, which is based on the United State National Ambient Air Quality Standards for hourly NO_2. This is more stringent than the AAAQO of 159 ppb. Aside from the 1-hour exceedance at Anzac, the next highest NO_2 concentration at all six stations was 65 ppb and therefore comparison to the TRV yields the same results as comparison to the AAAQO.

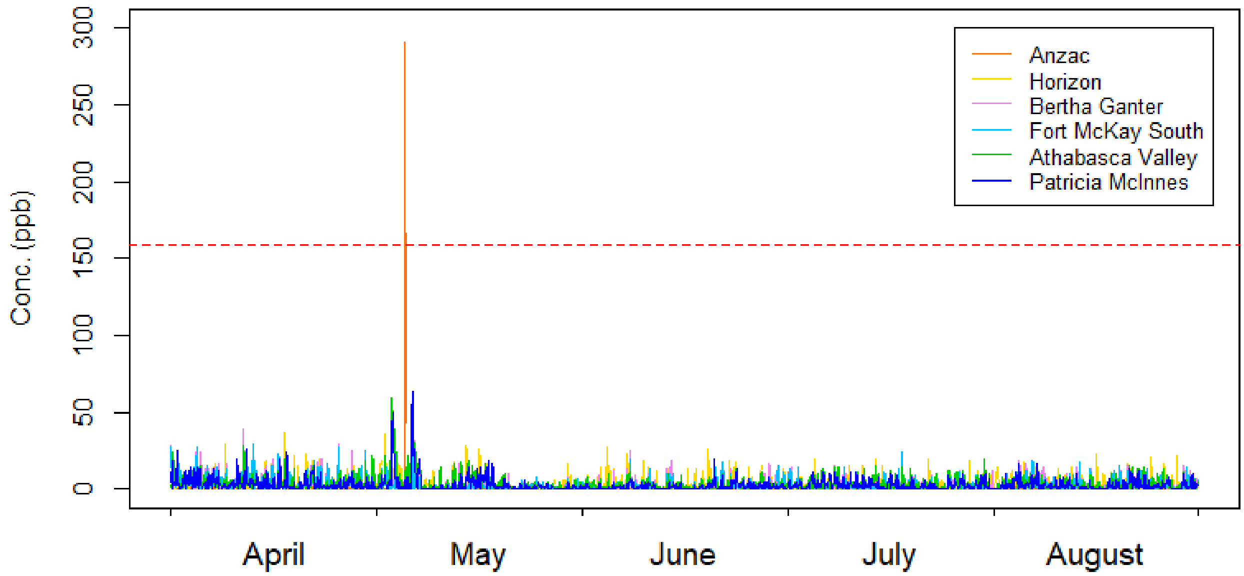

Figure 8: Time Series of 1-hour Average NO_2 Concentrations Monitored by Permanent Continuous Air Monitoring Stations, with the 1-hour AAAQO for NO_2 Indicated by the Red Dashed Line. Note: Due to a Power Outage, Data Completeness for the Anzac Station was 75% for May 2016.

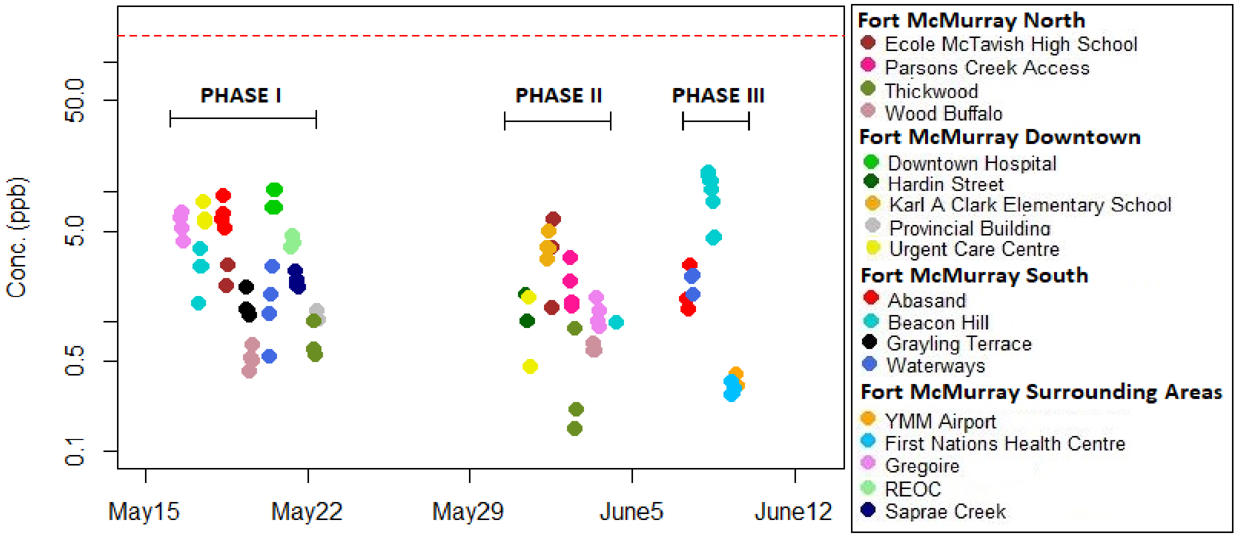

Figure 9: MAML 1-hour Average NO_2 Concentrations Prior to and During Public Re-Entry at Various Locations, with the 1-hour AAAQO for NO_2 Indicated by the Red Dashed Line

3.1.3 Ammonia (NH_3)

Figure 10 shows a time series plot of 1-hour average NH_3 concentrations from permanent continuous air monitoring stations at Bertha Ganter and Patricia McInnes stations. There were no exceedances of 1-hour AAAQO concentrations recorded during the study period. At these stations, NH_3 levels increased in May, over the same approximate time period as the highest $PM_{2.5}$ levels in the area. The maximum hourly concentration was 233 ppb at Bertha Ganter station on May 7th, 2016 at 10 am, and 1588 ppb at Patricia McInnes station on May 4th, 2016 at 1 am. As expected, the Patricia McInnes station, located within the Horse River Wildfire boundary, recorded higher NH_3 concentrations than the Bertha Ganter station, which is located downwind from the wildfire boundary.

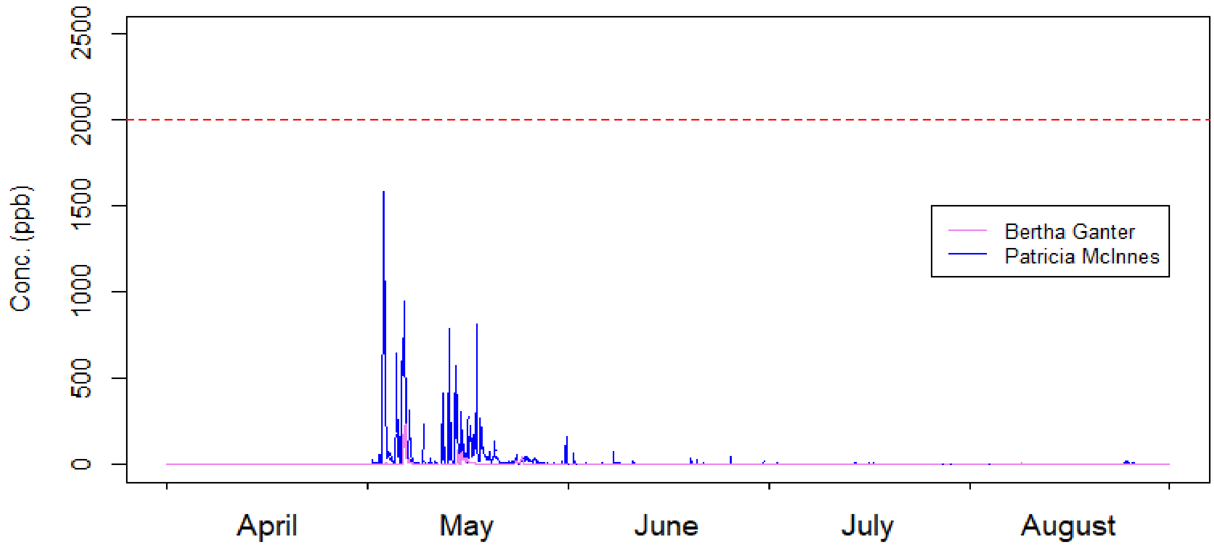

Figure 10: Time Series of 1-hour Average NH_3 Concentrations Monitored by Permanent Continuous Air Monitoring Stations, with 1-hour AAAQO for NH3 Indicated by the Red Dashed Line

As shown in Figure 11, no AAAQO exceedances were observed by the monitor on the MAML. However, higher levels of NH_3 in mid-May than in late-May and June were noted by the data. This is consistent with the timelines of enhanced $PM_{2.5}$ levels observed by the permanent continuous air monitoring stations.

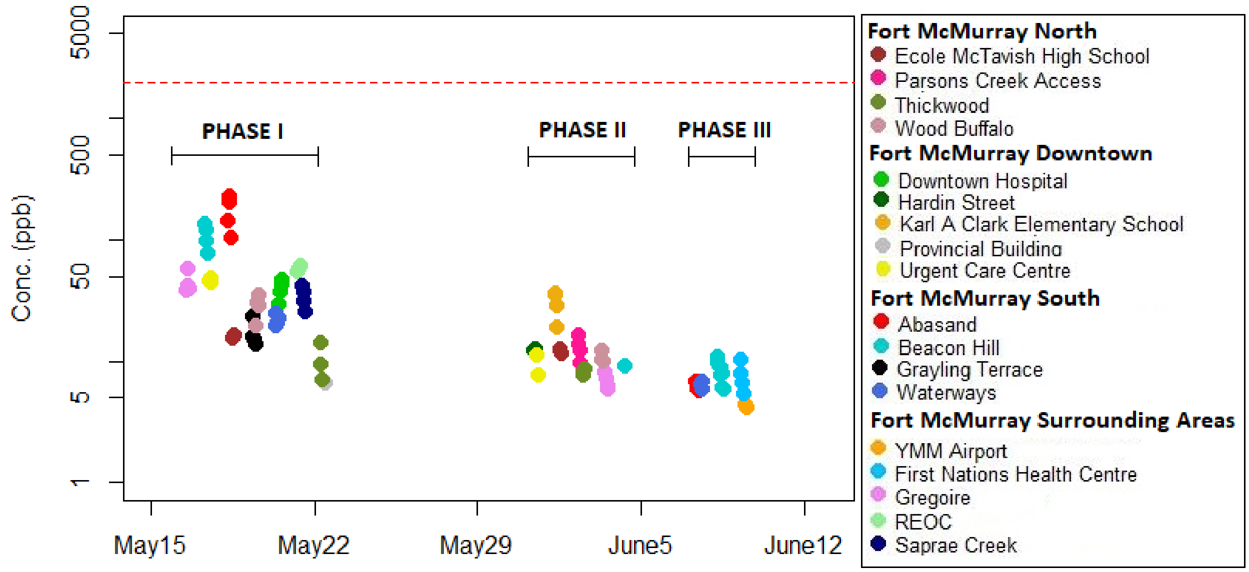

Figure 11: MAML 1-hour Average NH_3 Concentrations Prior to and During Public Re-Entry at Various Locations, with the 1-hour AAAQO for NH_3 Indicated by the Red Dashed Line

3.1.4 Sulphur Dioxide (SO_2)

For SO_2, no AAAQOs exceedances were recorded during the Horse River Wildfire at the permanent continuous air monitoring stations or by the MAML SO_2 analyzer, as shown in Figure 12 and Figure 13. The maximum hourly concentration was 87 ppb at the Fort McKay South station, and the maximum 24-hour average concentration was 10 ppb at the Athabasca Valley station. Neither of these maximum concentrations were observed during May 2016, when smoke plume most strongly influenced the area, suggesting that industrial SO_2 emission sources in the area may be responsible for some of the variability in SO_2. This is similar to the Richardson Wildland Fire observations, during which recorded SO_2 concentrations were below the level that can adversely affect human health or sensitive vegetation (Bytnerowicz et al., 2016).

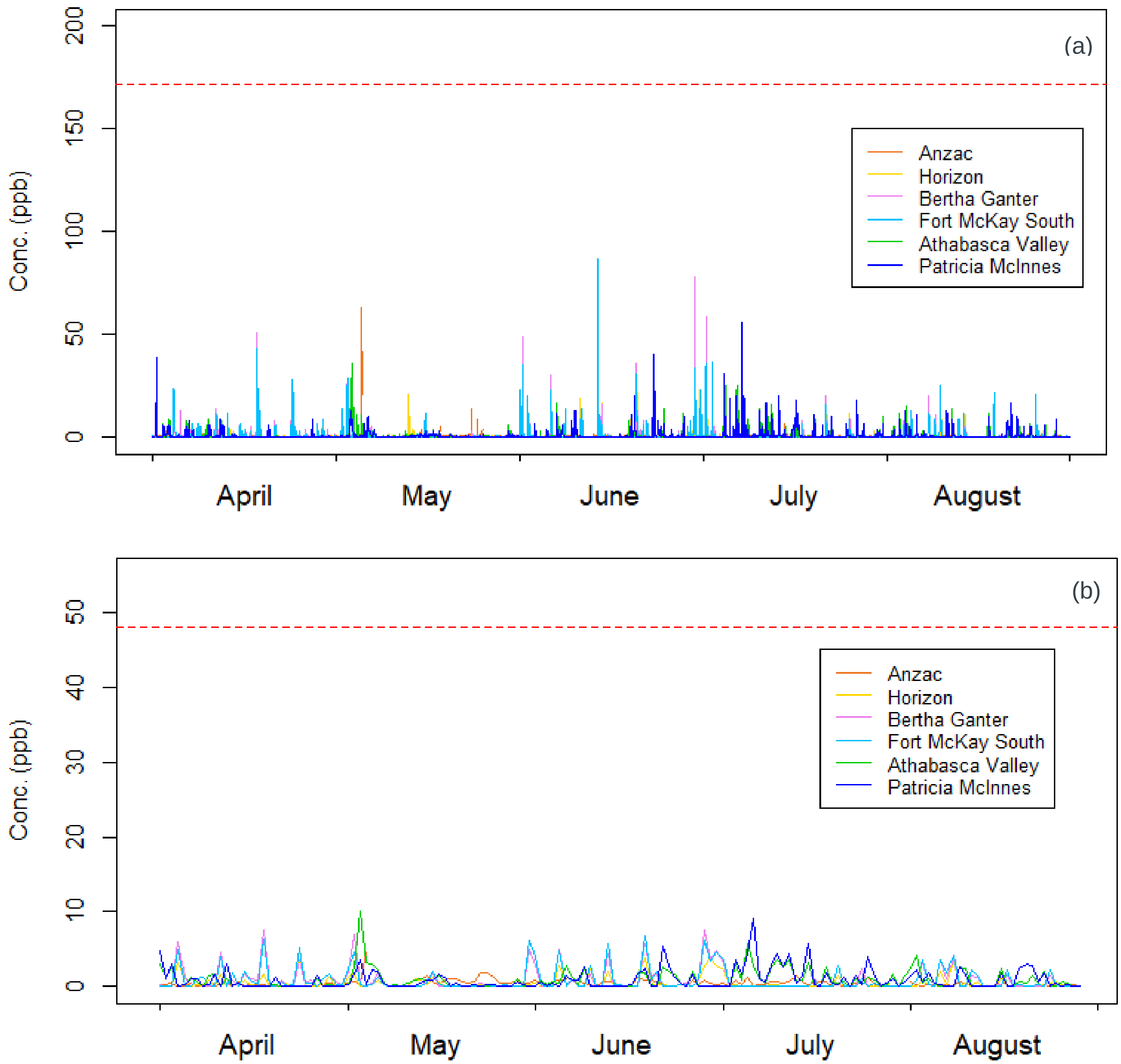

Figure 12: Time Series of SO_2 Concentrations Monitored by Permanent Continuous Air Monitoring Stations, with AAAQO for SO_2 Indicated by the Red Dashed Line: (a) 1-hour Average Concentrations; (b) 24-hour Average Concentrations. Note: Due to a Power Outage, Data Completeness for the Anzac Station was 75% for May 2016.

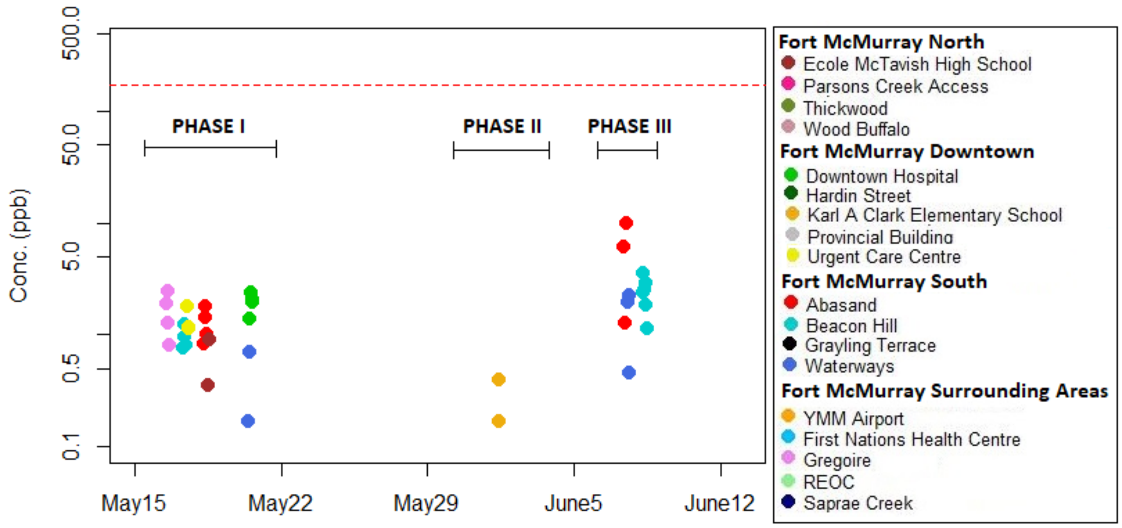

Figure 13: MAML 1-hour Average SO_2 Concentrations Prior to and During Public Re-Entry at Various Locations, with the 1-hour AAAQO for SO_2 Indicated by the Red Dashed Line

3.1.5 Carbon Monoxide (CO)

Figure 14 presents a time series plot of CO at the Athabasca Valley station, the only station monitoring CO in the study area. Enhanced CO concentrations were observed in May 2016, with 13 episodes of hourly CO AAAQO exceedances.

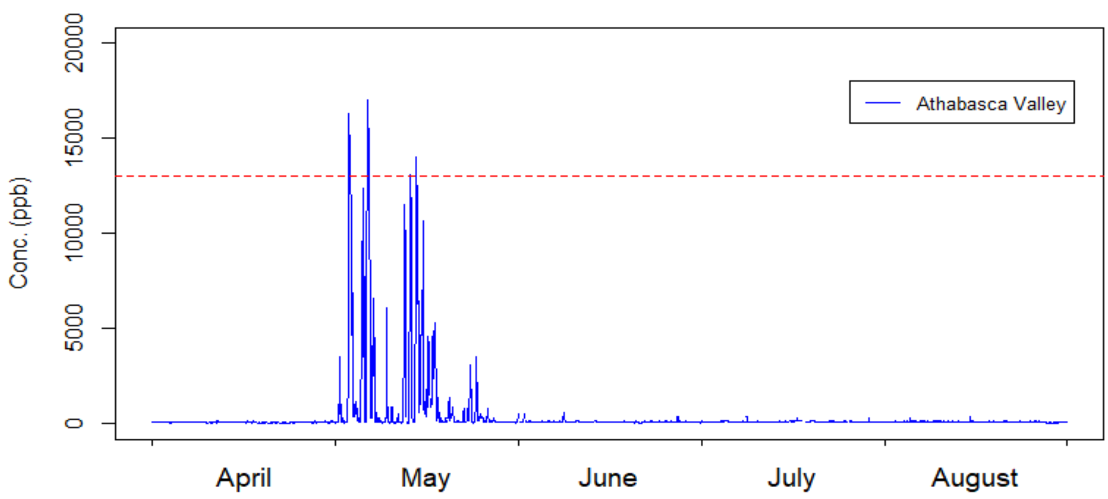

Figure 14: Time Series of 1-hour Average CO Concentrations Monitored by the Athabasca Valley station, with 1-hour AAAQO for CO Indicated by the Red Dashed Line

No CO AAAQO exceedances were observed by the MAML CO analyzer, as shown in Figure 15**.** However, higher peak CO concentrations were observed in mid-May than in June, which is consistent with observations at the permanent continuous air monitoring station. The exceedance episodes observed at the Athabasca Valley station and the elevated CO levels monitored by the MAML at various locations occurred during the same approximate time period (early and mid-May) as the increased levels of $PM_{2.5}$ and NH_3.

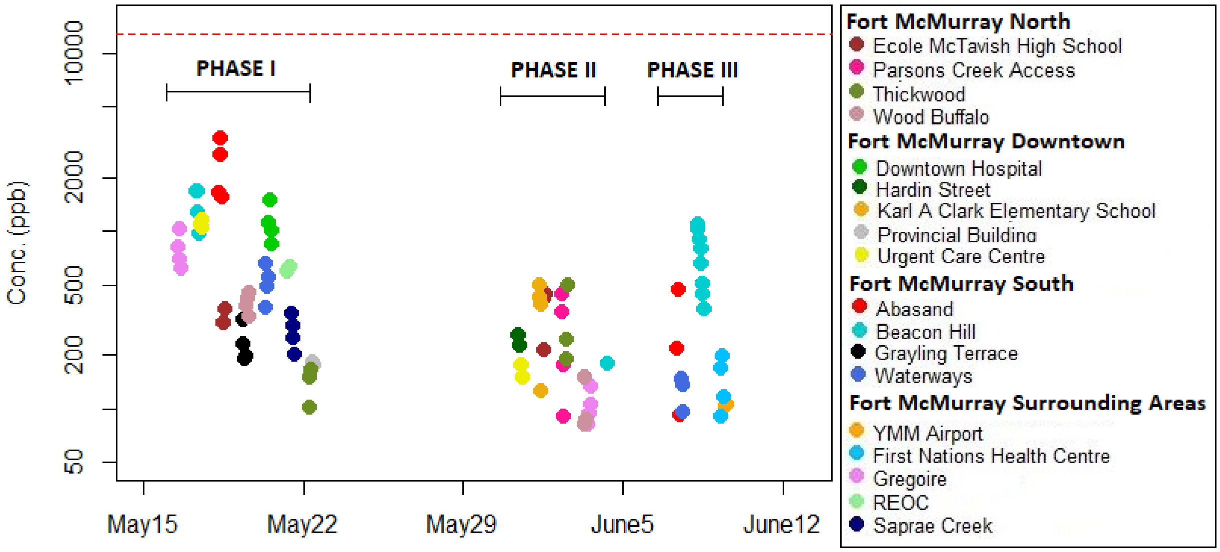

Figure 15: MAML 1-hour Average CO Concentrations Prior to and During Public Re-Entry at Various Locations, with the 1-hour AAAQO for CO Indicated by the Red Dashed Line

3.2 Comparison to Data Collected during Non-Wildfire Impacted Periods

The measurements during the Horse River Wildfire were compared with data collected during the non-wildfire impacted period. The term “non-wildfire impacted period” includes data collected between April to August in 2013, 2014, and 2015 (hereafter referred as historical data) and between April to August 2017 (hereafter referred to as post wildfire data). Smoke impacted data were excluded from the analysis of the historical period. Smoke impacted data were identified using the methodology for Canadian Ambient Air Quality Standards (CAAQS) assessments (Canadian Council of Ministers of the Environment, 2007). Therefore, the historical period represents typical air quality in the area when it is not affected by wildfire smoke. Wildfire smoke events were not removed for the data collected in 2017 because the CAAQS identification of smoke episodes had not been completed at the time of this study. However, in 2017, Fort

McMurray and surrounding areas were not significantly affected by wildfire smoke in 2017 data likely has negligible effect from the wildfire emissions.

Hourly average data are selected to characterize the air quality in Fort McMurray and surrounding areas prior to, during, and after the Horse River Wildfire. Box and whisker plots are used to compare the wildfire impacted period and non-wildfire impacted period. The box and whisker plots indicate the median (horizontal line in the middle for box), 25th percentile and 75th percentile (bottom and top of box), upper and lower 1.5 times inter-quantile range (whiskers) and outliers representing extreme concentrations, which are outside the upper and lower 1.5 times inter-quantile range (open circle marker). Pollution rose figures are also used to infer the source area for elevated levels of $PM_{2.5}$. The box and whisker plots and pollution roses were generated by using R.3.4.2, a statistical computing and graphics programming language.

Note that Landis et al. (2018) also quantify increases in $PM_{2.5}$ and other species. However, they define hours when air over the station is "fire-impacted", based on concentrations of $PM_{2.5}$ and other species, and compare that data to hours that were not fire-impacted. Therefore, their results focus on air quality at specific times when smoke influenced a station. The results presented in this report quantify the impact of the wildfire on monthly median and percentiles of $PM_{2.5}$ and other parameters. For example, if a station experiences only a few days of wildfire smoke influence, the median and quartiles will be lower than for a station which experiences many days of wildfire smoke influence.

3.2.1 Fine Particulate Matter ($PM_{2.5}$)

Figure 16 shows the $PM_{2.5}$ box and whisker plots for 1-hour average data collected from permanent continuous air monitoring stations for the historical data (2013-2015 averaged data with smoke influences removed), the 2016 data, and the 2017 post wildfire data from April to August. The highest levels of $PM_{2.5}$ were observed in May 2016 at all permanent continuous air monitoring stations, which is consistent with the proximity of the wildfire.

The Anzac station, Athabasca Valley station and Patricia McInnes station observed the highest median $PM_{2.5}$ concentrations during May 2016 (Figure 16a, Figure 16e, and Figure 16f). These stations are located within the Horse River Wildfire boundary and therefore this is consistent with the direct impacts of the wildfire smoke on these stations. The median hourly concentrations in May 2016 were 12 µg/m^3 for the Anzac station[7], 15 µg/m^3 for the Athabasca Valley station and 16 µg/m^3 for the Patricia McInnes station. These concentrations were 5 to 8 times larger than the

[7] Note: Due to a power outage, data completeness for Anzac station was 75% for May 2016.

hourly median concentrations measured during non-wildfire impacted period. For the monthly 75th percentile hourly concentrations, the $PM_{2.5}$ levels observed were 8 to 13 times larger than the concentrations measured outside of wildfire impacted period.

The Horizon station, Bertha Ganter station and Fort McKay South station are located about 30 to 40 kilometers north of the Horse River Wildfire boundary. These stations only observed the wildfire smoke plume when winds transported it over the stations. Furthermore, the smoke plume disperses as it is transported, resulting in lower $PM_{2.5}$ concentrations. Therefore, the enhancements in $PM_{2.5}$ levels during the wildfire impacted period are lower at these stations than at the stations which were located within the wildfire boundary. The median hourly concentrations in May 2016 were comparable to concentrations measured outside of the wildfire impacted period, which ranged from 2.0 $\mu g/m^3$ to 5.5 $\mu g/m^3$. However, the monthly 75th percentile hourly concentrations and outliers were somewhat higher than concentrations measured during the non-wildfire impacted period (Figure 16b, Figure 16c, and Figure 16d).

Figure 17 shows the pollution roses from May 2016 for Horizon station, Bertha Ganter station and Fort McKay South station with 1-hour average $PM_{2.5}$ concentrations higher than the AAAQG (80 $\mu g/m^3$) and excluding low wind speeds less than 1 m/s due to the uncertainty in wind direction at low wind speeds (Appendix B). Elevated $PM_{2.5}$ concentrations occurred for southerly winds at these stations, which is consistent with the transport of smoke plumes downwind.

As the Horse River Wildfire continued to move eastward, the smoke plume had less impact on levels of $PM_{2.5}$. In June, July and August 2016, levels of $PM_{2.5}$ were similar to the non-wildfire impacted period. The median hourly concentrations ranged from 2.0 $\mu g/m^3$ to 8.0 $\mu g/m^3$ for all permanent continuous air monitoring stations during both the wildfire impacted and non-wildfire impacted periods. As expected, wildfire smoke plume dispersed over time.

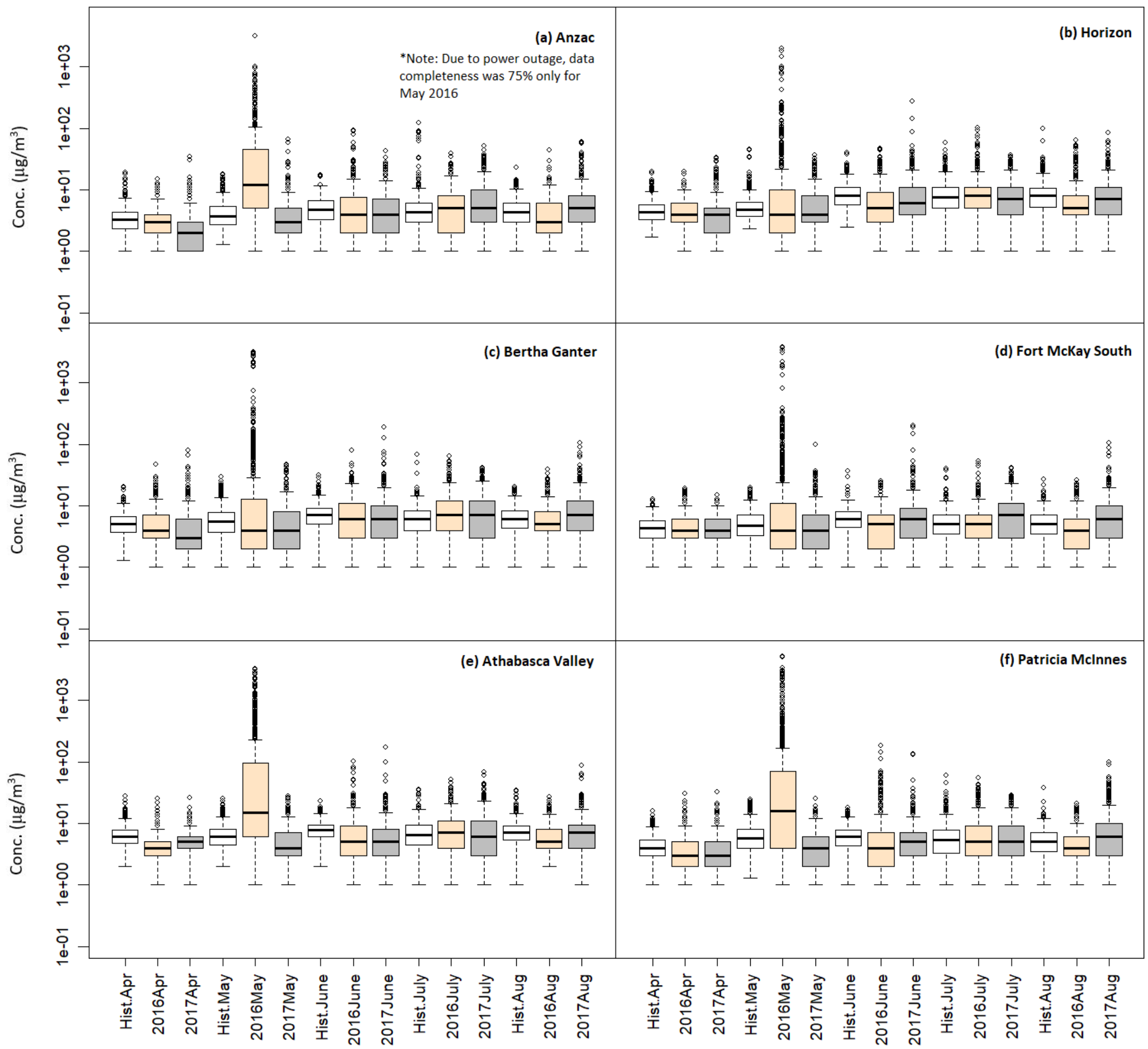

Figure 16: 1-hour Average $PM_{2.5}$ Box and Whisker Plots from Continuous Monitoring Stations showing Comparison of 2013-2015 Average Data with Smoke Influences Removed (Hist. indicated as white), During (2016 indicated as pink) and 1-Year After (2017 indicated as grey) the Horse River Wildfire Event

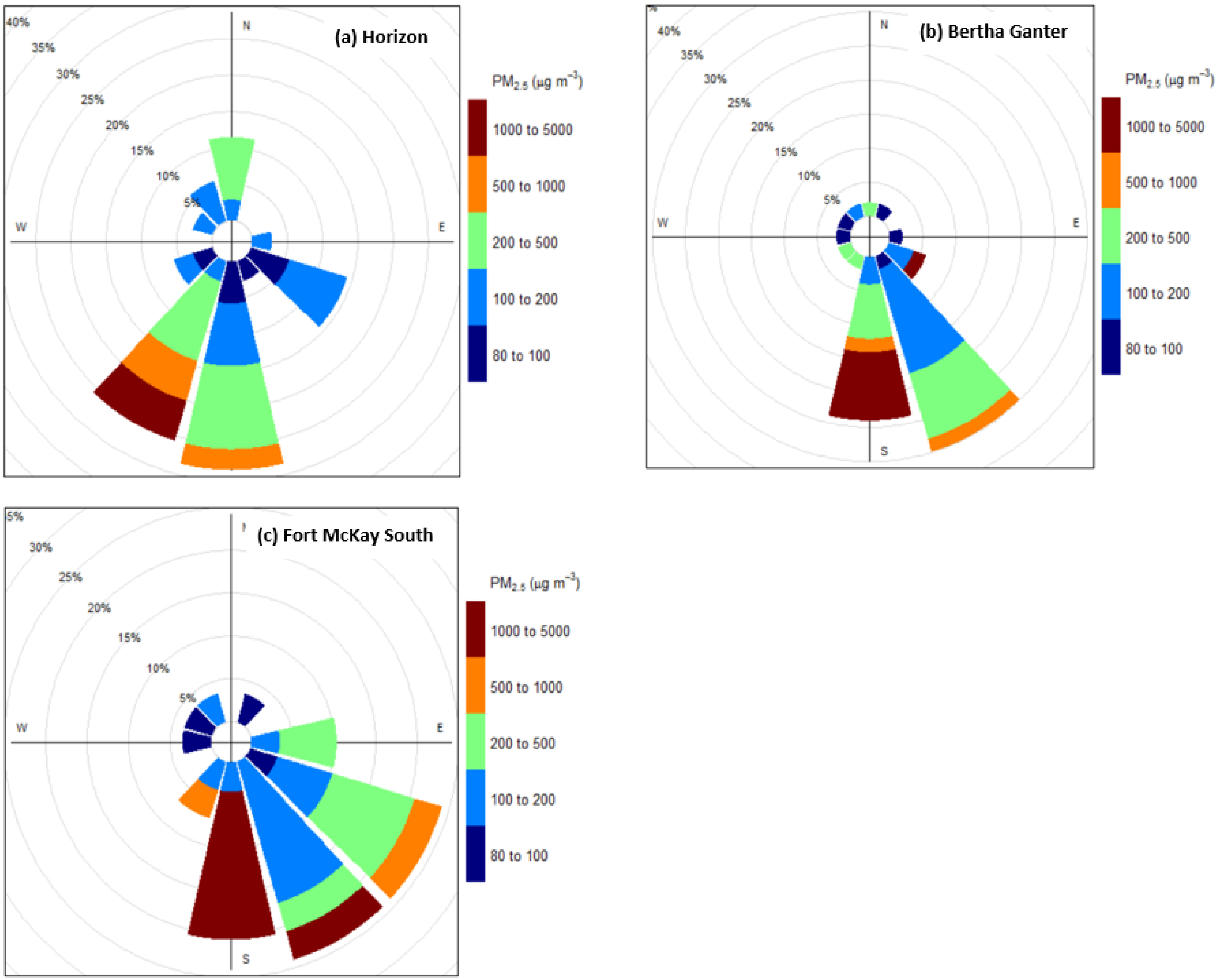

Figure 17: May 2016 Pollution Roses for $PM_{2.5} \geq 80$ µg/m^3 and Wind Speed ≥ 1 m/s: (a) Horizon Station; (b) Bertha Ganter Station; and (c) Fort McKay South Station

3.2.2 Nitrogen Dioxide (NO_2)

Figure 18 shows the NO_2 box and whisker plots for 1-hour average data collected from the permanent continuous air monitoring stations for the historical (2013-2015 averaged data with smoke influences removed), the 2016, and the 2017 post-wildfire periods from April to August. The highest 1-hour NO_2 concentration was recorded at the Anzac station with the concentration exceeding AAAQO at 291 µg/m^3. Note that this exceedance of episode is not shown in the Anzac NO_2 box and whisker plot because it is well above the y-axis scale.

In May 2016, the outliers for NO_2 at the Anzac station, Athabasca Valley station and Patricia McInnes station are higher than during non-wildfire impacted periods, suggesting that peak levels of NO_2 may have been influenced by the nearby active wildfire. The 95th percentile hourly concentrations (not shown on the box and whisker plots), were 5.8 ppb to 15 ppb at these stations, and were 1.5 times to 2.3 times larger than the 95th percentile concentrations for non-wildfire impacted period. This is consistent with Landis et al. (2018), who detected small, though perhaps statistically insignificant, increases NO_2 during hours impacted by the Horse River Wildfire. The median and 75th percentile hourly concentrations for Anzac station, Athabasca Valley station and Patricia McInnes station were similar to measurement outside of the wildfire impacted period. Therefore, the smoke plume only had a significant influence on peak levels of NO_2 (95th percentile) at these stations. The minor influence of the wildfire on NO_2 concentrations is consistent with observations during the Richardson Wildland Fire (Bytnerowicz et al., 2016).

For the Horizon station, the Bertha Ganter station and the Fort McKay South station, the median and 75th percentile hourly concentrations collected during the Horse River Wildfire fall broadly within the variability of other years. In fact, levels of NO_2 appear to be lower in May and June 2016 than in the non-wildfire impacted period. This might be related to reduced NO_2 emissions during the shutdown of mining and operation due to the wildfire and the evacuation of Fort McMurray and surrounding areas (Accenture, 2017; Alberta Energy Regulatory, 2018).

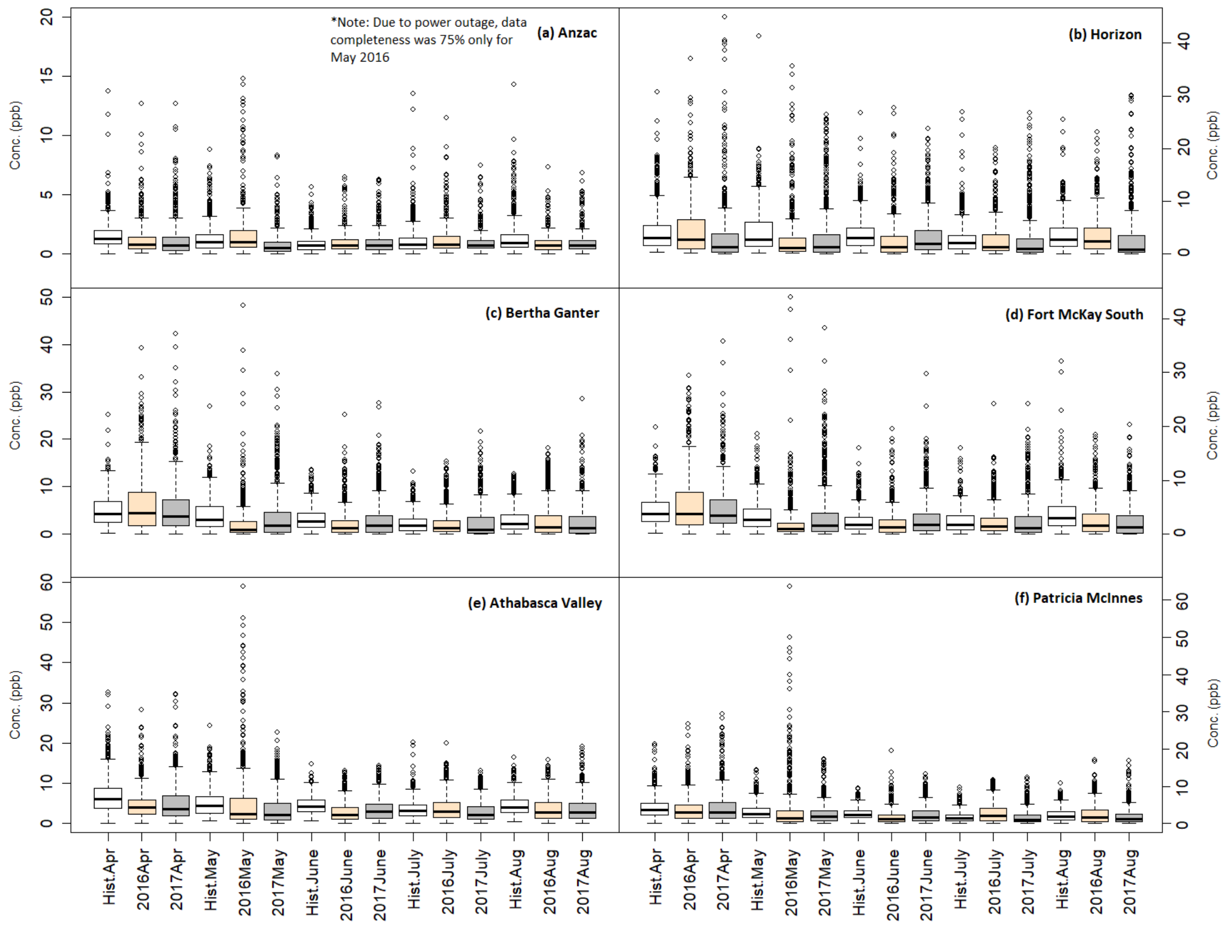

Figure 18: 1-hour Average NO_2 Box and Whisker Plots from Permanent Continuous Monitoring Stations Showing Comparison of 2013-2015 Average Data with Smoke Influences Removed (Hist. indicated as white), During (2016 indicated as pink) and 1-Year After (2017 indicated as grey) the Horse River Wildfire Event. (a) At Anzac Station, the Highest 1-hour NO_2 Concentration Recorded (291 $\mu g/m^3$) is not Shown as it is above the Y-Axis Scale. All other Data are within the Presented Y-Axis Scales.

3.2.3 Ammonia (NH_3)

Figure 19 shows the NH_3 box and whisker plots for 1-hour average data collected from Bertha Ganter station and Patricia McInnes station for historical data (2013-2015 averaged data with smoke influences removed), 2016 data, and 2017 post wildfire data from April to August. Elevated NH_3 concentrations were observed in May 2016 at both stations.

The Patricia McInnes station located within the Horse River Wildfire boundary, recorded higher NH_3 concentrations than the Bertha Ganter station, which is located outside of the wildfire boundary. At the Patricia McInnes station, the median NH_3 hourly concentration in May 2016 was 18 ppb, which is approximately 22 times larger than for the non-wildfire impacted period. The 75th percentile hourly concentration was elevated by at least 28 times when compare to concentrations outside of wildfire impacted period. The 75th percentile NH_3 hourly concentration at the Bertha Ganter station was approximately 4 times larger than the concentrations measured during the non-wildfire impacted period. None of the concentrations reported exceeded the AAAQO for NH_3 of 2000 ppb, as discussed in Section 3.1.3.

For June to August, NH_3 levels were comparable for the wildfire impacted period and non-wildfire impacted period at the Bertha Ganter station and the Patricia McInnes station, with monthly average median hourly concentrations and the 75th percentile hourly concentrations ranging from 0.3 ppb to 2 ppb and 0.7 ppb to 3 ppb, respectively. This is consistent with observations of enhanced NH_3 levels during the early phases of the Richardson Wildland Fire (Bytnerowicz et al., 2016).

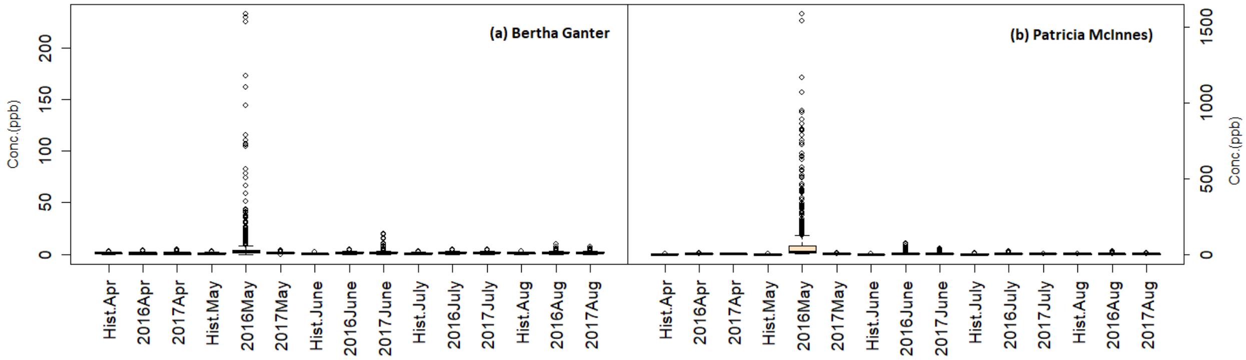

Figure 19: 1-hour Average NH_3 Box and Whisker Plots from the Bertha Ganter and Patricia McInnes Stations Showing Comparison of 2013-2015 Averaged Data with Smoke Influences Removed (Hist. indicated as white), During (2016 indicated as pink) and 1-Year After (2017 indicated as grey) the Horse River Wildfire Event

3.2.4 Sulphur Dioxide (SO_2)

Figure 20 shows the SO_2 box and whisker plots of 1-hour average data collected from the continuous air monitoring stations for the historical data (2013-2015 averaged data with smoke influences removed), the 2016 data, and the 2017 post wildfire data from April to August.

For May 2016, the stations within the wildfire boundary (i.e., the Anzac station, the Athabasca Valley station, and the Patricia McInnes station) are similar to previous years. For stations near the minable oil sands region, the 95th percentile hourly concentrations (not shown on the box and whisker plots) at Horizon, Bertha Ganter and Fort McKay South stations were 1.8 ppb, 2.0 ppb, and 1.0 ppb, respectively for May 2016, which were 1.6 times to 8 times lower than for the non-wildfire impacted period. The concentrations during non-wildfire impacted period ranged from 2.7 ppb to 8.0 ppb for these stations. This lower concentration may reflect reduced SO_2 emissions during the precautionary shutdown of oil sands facilities during the wildfire (Accenture, 2017; Alberta Energy Regulatory, 2018). However, more analysis would be required to determine whether this lower concentration was statistically significant. For June, July and August, SO_2 levels observed are comparable between wildfire impacted period and non-wildfire impacted period for all stations.

By focusing on the hours affected by the Horse River Wildfire smoke, Landis et al. (2018) detected small increases in SO_2 during fire impacted periods. However, as the present report shows, these increases have minimal effect on the monthly data. Similarly, during the Richardson Wildland Fire observations, SO_2 concentrations were below the level that can adversely affect human health or sensitive vegetation (Bytnerowicz et al., 2016). Wildfire emissions of SO_2 are often minor in comparison with other pollutants (Reisen et al., 2015).

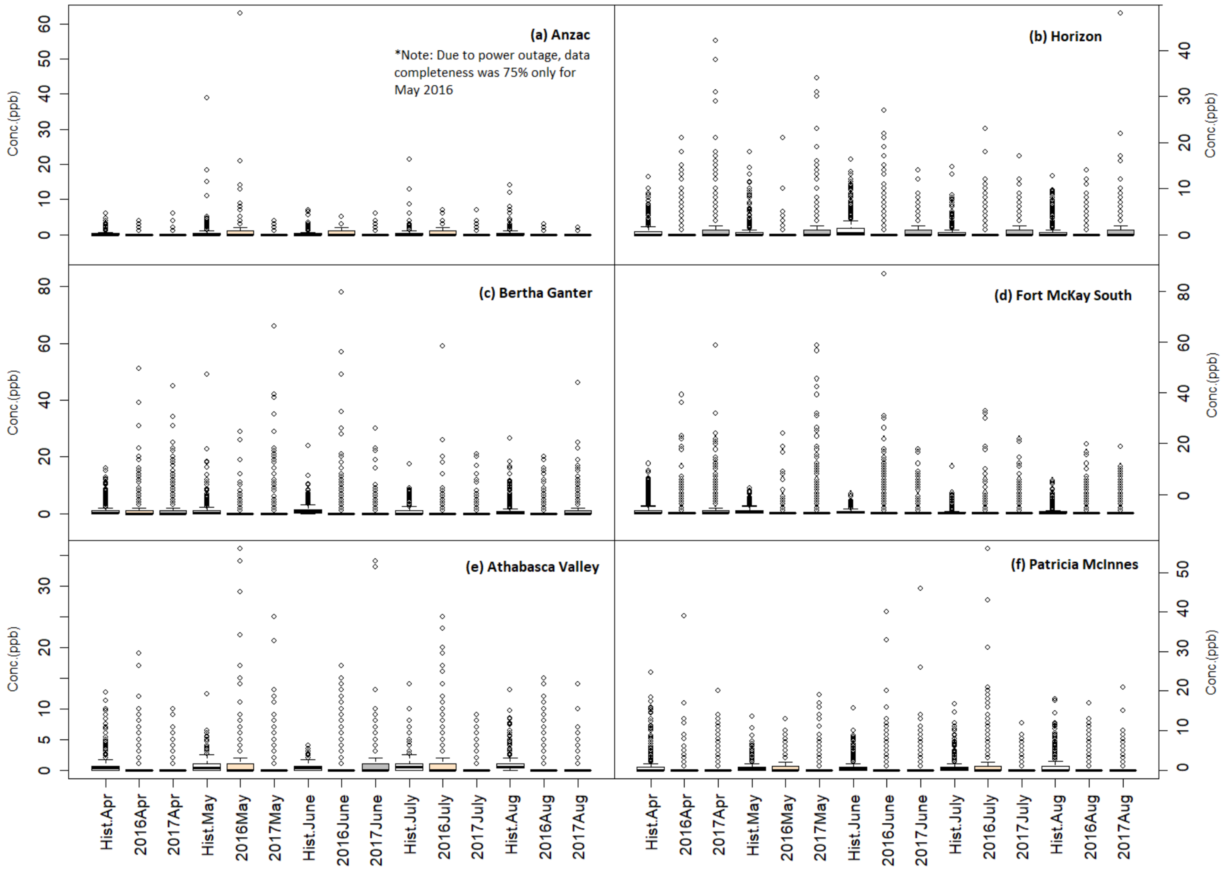

Figure 20: 1-hour Average SO_2 Box and Whisker Plots from Continuous Air Monitoring Stations Showing Comparison of 2013-2015 Averaged Data with Smoke Influences Removed (Hist. indicated as white), During (2016 indicated as pink) and 1-Year After (2017 indicated as grey) the Horse River Wildfire Event

3.2.5 Carbon Monoxide (CO)

The Athabasca Valley station is the only CO monitoring station within or near the Horse River Wildfire boundary. Figure 21 shows the CO box and whisker plots for 1-hour average data collected from the Athabasca Valley station for the historical (2013-2015 averaged data with smoke influences removed), the 2016, and the 2017 post wildfire periods from April to August. During May 2016, the median hourly concentration was 200 ppb, which was 2 times larger than concentrations outside of wildfire impacted period. The 75th percentile was 1000 ppb in May 2016, which is 8.7 times larger than the non-wildfire impacted period. Landis et al. (2018) also noted increases in CO during the fire-impacted period. For June, July and August, CO levels were comparable between the wildfire impacted and non-wildfire impacted periods.

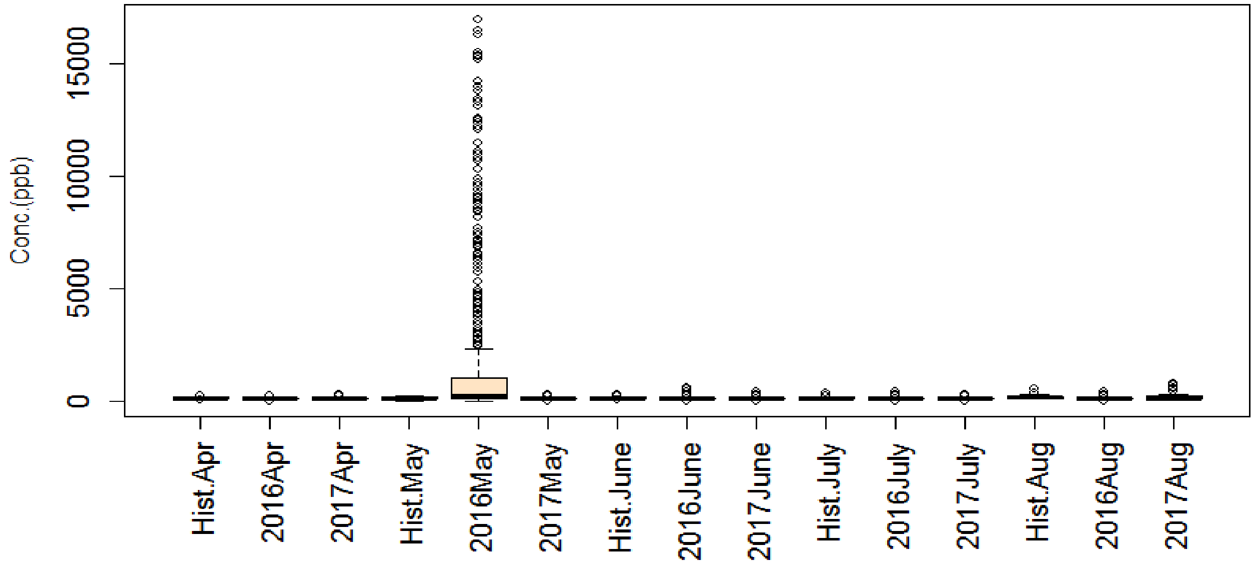

Figure 21: 1-hour Average CO Box and Whisker Plot from the Athabasca Valley Continuous Monitoring Station Showing Comparison of 2013-2015 Averaged Data with Smoke Influences Removed (Hist. indicated as white), During (2016 indicated as pink) and 1-Year After (2017 indicated as grey) the Horse River Wildfire Event

4.0 Discussion and Recommendations

During the Horse River Wildfire, many enhancements of $PM_{2.5}$ were observed and variability was consistent with the inferred location of the smoke plume based on fire hot spots and winds. Furthermore, $PM_{2.5}$ exceeded health-based AAAQO/AAAQG at many locations throughout the measurement period, demonstrating that $PM_{2.5}$ data provides useful information to support decisions to protect the health of emergency response personnel and the public. Therefore, $PM_{2.5}$ is a good indicator for the spatial and temporal variation of the smoke plume and possible health impacts. During emergency response monitoring, AEP often deploys EBAM units, which measure $PM_{2.5}$, to assess the spatial extent of smoke episodes and to inform health decisions. The EBAM units are a suitable platform for wildfire emergency response monitoring because they can be deployed at multiple locations relatively quickly and they collect continuous $PM_{2.5}$ measurements, which is a good indicator of wildfire smoke.

Other parameters, particularly CO and NH_3 were also elevated during the Horse River Wildfire, with multiple exceedances of health-based AAAQO for CO. This demonstrates the value of the suite of parameters that can be measured by the MAML analyzers, to provide complementary information on the composition of the smoke plume. The MAML can be deployed to multiple locations and the data can be used to support decisions to protect human health, for example related to CO exposure.

Therefore, AEP's strategy to deploy EBAM units to assess spatial and temporal variability of smoke and the MAML to measure smoke plume composition was suitable for emergency response during the Horse River Wildfire. In large part, the deployment of additional monitoring was successful – the data collected during the wildfire event informed decisions to protect the health of the public and emergency response personnel. However, some limitations of monitoring design and reporting were noted during the evaluation of the datasets and conversations with stakeholders. These limitations are discussed below, with recommendations for future air monitoring activities.

Recommendation #1: Build a web platform to automatically display air quality monitoring data from additional deployed portable monitoring instruments in near real-time for improved communication within the GOA (Alberta Health, Alberta Health Services, Alberta Labour), external agencies, emergency response personnel, and the public.

During the Horse River Wildfire, EBAM hourly data were available in near real-time to through a password-protected website, only allowing access to specific requested individuals within GOA. These data were used to inform decisions in near real-time. However, external public data users did not have access to the near real-time EBAM data.

Daily summaries of EBAM and MAML data were shared internally via email and posted publicly online at http://environmentalmonitoring.alberta.ca/air/fort-mcmurray-fire-updates/. The air quality during the wildfire event varied rapidly on an hourly and day-to-day basis (Appendix C), and therefore, due to the time lag in posting these data, the data reported in the PDFs did not represent current air quality and could only be used to infer typical fluctuations in air quality over the measurement period. Furthermore, this approach required human resources to generate the figures, create the document and post them to the website.

External agencies are also interested in accessing the near real-time data. For example, the additional portable monitoring data could be used in Environment and Climate Change Canada's Wildfire Smoke Prediction System. With current practice, this is not possible.

Therefore, it is proposed that hourly data from portable air monitoring platforms be presented on a website in near real-time. This would be similar to the public access to permanent continuous monitoring station data at the Air Quality Health Index Website (http://airquality.alberta.ca/map). This would minimize the delay in distributing time sensitive information internally, to other agencies, and to the public. Furthermore, full automation with a data logger connected to the online web server would reduce the required human resources.

Recommendation #2: When possible, consider factors such as site security and the spatial versus temporal variation of air quality prior to deployment to minimize of the number of times the portable air monitoring platforms are moved.

Portable monitoring platforms were deployed rapidly in response to an emergency during the Horse River Wildfire. Therefore, detailed scientific assessment of ideal site locations was not possible. Overall, the monitoring locations were determined using input from other agencies, such as Alberta Environment Support & Emergency Response (ASERT), Alberta Health, Alberta Health Services, and Health Canada. Site locations were chosen based on factors including human traffic, the spatial distribution of the smoke plume, and the location of other monitoring stations in the area. These general considerations are appropriate for site selection and are discuss in Table 4.

Table 4: General Considerations for Air Quality Monitoring Design during Wildfire Emergency

General Considerations	Comments
1. Monitoring goal(s) • support decisions to protect health of emergency personnel and the public • identify areas that are most heavily affected by smoke plume	Clearly identify the monitoring goal and monitoring duration for each monitoring phase.
2. Human traffic	Deploy monitoring where emergency response personnel and/or the public are located.
3. Smoke plume	Deploy monitoring where smoke plume is the thickest, based on best knowledge.
4. Proximity to existing air monitoring stations	Fill monitoring gaps between permanent continuous air monitoring stations to provide additional information on the air quality. Ensure that portable monitoring is far enough away from permanent stations so that it does not duplicate measurements.

Four EBAM units were used to measure the spatial variation of air quality during the wildfire. The EBAM units require ground power and a secure location. The EBAM was moved several times during the study period due to security reasons and potential influence from local anthropogenic sources. For example, EBAM unit #1 was first deployed at Clearwater Hotel on May 8th, 2018, and was relocated to Provincial Courthouse (one block north) on May 22nd, 2018 due to potential local anthropogenic inferences of increased vehicle traffic in the area. The EBAM unit was relocated again on June 10th, 2016 to Keyano Main Campus due to security reasons because of increased human activity in the area. If these factors were considered in advance, the need for re-location of the unit during the study period would be limited.

The MAML was moved to monitor approximately two locations per day, with the goal of assessing multiple air quality parameters where emergency response personnel and the public might be exposed. However, air quality during the measurement period varied quickly in time (~minutes to hours) and therefore the MAML data could not be used to assess differences in air quality between the monitoring locations; instead the data reflected the variation in air quality in time across the wider Fort McMurray area (Appendix C) The Fort McMurray Reentry Preliminary Air Quality Data Report (Government of Alberta, 2017a) similarly found that the MAML data was of limited use due to the short measurement periods and the close proximity to permanent air monitoring stations. Therefore, it would have been more useful to locate the MAML at a single site throughout the wildfire to characterize changes in supporting parameters, such as CO and NH_3 or to report on the AQHI. For most wildfires, the most suitable location for MAML monitoring would where the smoke is the thickest and there is human traffic; at this “hot spot”, the MAML data would be best positioned for health risk assessments. However, for the Horse River Wildfire, it is possible that the permanent air monitoring stations adequately sampled the hot spot. Therefore, the MAML may have best been positioned to evaluate the spatial variation of supporting parameters. For example, the MAML could have been deployed to select locations which are further apart (e.g., Anzac or Saprae Creek).

Therefore, it is proposed that during an emergency air monitoring response, a quick evaluation of the expected spatial and temporal variation of the air quality episodes should be performed before the deployment of monitoring equipment using available information. This evaluation could consider information such as the following, depending on what type of the data is available in the area:

- Nearby existing continuous air monitoring stations;
- EBAM data, if EBAM units were deployed earlier in the emergency response;
- Satellite and smoke plume model maps of fire hot spots and smoke plumes; and/or
- Best knowledge or estimates of on-site field staff.

If there is large temporal variability and less spatial variability, the MAML should be deployed at a minimum number of locations which are expected to have significantly different air quality and are not near permanent air monitoring stations that measure similar parameters. This would reduce the number of times the MAML is moved, allowing for more hours of collected data. Furthermore, the resulting data could be used to evaluate changes in air quality over time. Once the monitoring is deployed, the spatial and temporal variation should be re-evaluated using the data collected to ensure that the objectives of the monitoring plan are met.

Additional key considerations for EBAM and MAML deployment are included in Table 5 and Table 6.

Table 5: Additional Considerations for EBAM Monitoring Design during Wildfire Emergency Response

Additional Considerations for EBAM	Comments
1. Specific monitoring goal(s) • measure $PM_{2.5}$, a parameter that has direct effects on human health to assess health risks • determine the spatial and temporal variation of the smoke plume	Clearly identify the monitoring goal and monitoring duration for each monitoring phase.
2. Site requirements: ground power and security	Consider how site security and ground power may change over monitoring period to minimize relocation of instruments. Whenever possible, deploy within a fenced area to increase security during unmanned monitoring hours.
3. Human resources: after deployment, operates unmanned	Locate where 24-hour continuous data is most useful.

Table 6: Additional Considerations for MAML Monitoring Design during Wildfire Emergency Response

Additional Considerations for MAML	Comments
1. Specific monitoring goal(s) • measure $PM_{2.5}$ and complementary parameters (e.g., CO), which have direct effects on human health to assess health risk • determine the composition of the smoke plume	Prior to deployment, consider the expected spatial and temporal variation of wildfire smoke. Consider deployment to a single location where monitoring of additional parameters is most needed based on human traffic, smoke plume, and proximity to existing monitoring.
2. Site requirements: does not require ground power or security	Could be located where EBAM deployment is not possible to complement EBAM sites.

Recommendation #3: Document and assess the ability of Alberta's Monitoring Network to monitor, evaluate, and report on wildfire smoke.

Due to the logistical issues of deploying monitoring equipment during an emergency, the EBAMs did not collect data until five days after the evacuation of Fort McMurray, and the MAML started to take measurements several days after that. Therefore, the MAML and EBAM did not take measurements during a period that was strongly impacted by the wildfire. The Horse River Wildfire occurred in an area of the province with many permanent air monitoring stations due to the large population centre of Fort McMurray and oil sands industry. Therefore, the lag between the evacuation of Fort McMurray and the deployment of monitoring equipment was not critical. However, many parts of the province do not have existing air monitoring instruments in place.

Therefore, it is proposed that the air monitoring network should be assessed for its ability to detect and characterize wildfire smoke, with a focus on identification of gaps in wildfire smoke monitoring. The current air monitoring network may provide sufficient data in dense urban areas (i.e. population centres (≥ 50,000 people) for major air pollutants present in wildfire smoke. However, smaller communities impacted by wildfires often have inadequate or no existing air quality monitoring. In addition, potential gaps in regional monitoring in a provincial scale also needed to be determined. Appropriate monitoring is needed to improve wildfire smoke forecasting, monitoring and evaluation. Various monitoring methods will be considered to fill these gaps, including portable $PM_{2.5}$ monitors, CO monitors at select locations, and satellite remote sensing data. The data collected by the air monitoring network should support work done in other areas of the Government of Alberta and externally, such as health assessments and wildfire smoke forecasting.

Recommendation #4: Evaluate consistency between EBAM units and Federal Reference Method (FRM) PM2.5 monitors.

The EBAM units are used for emergency monitoring because they can be transported and deployed relatively quickly and provide continuous real-time $PM_{2.5}$ data. One limitation is that the EBAM units are not designated as an FEM and therefore the data are not directly comparable with data collected by FEM analyzers at the permanent air monitoring stations. Under enhanced levels of $PM_{2.5}$, such as during wildfire smoke episodes, the EBAM units provide useful information. However, more quantitative information on comparability would be valuable. AEP has initiated a $PM_{2.5}$ collocation study, which includes an EBAM unit as well as other $PM_{2.5}$ monitoring equipment with FEM and FRM designation. Upon completion of the collocation period, it is recommended that the differences between the EBAM and other units be quantified and used to interpret the EBAM data during future emergency response monitoring campaigns.

5.0 Conclusions

During the Horse River Wildfire, AEP, in partnership with WBEA, assessed air quality data from permanent continuous air monitoring stations and deployed additional portable air monitoring platforms. In this report, the air monitoring data was used to characterize air quality during the fire and to develop recommendations for future monitoring during wildfires.

Due to logistical reasons, the portable monitoring platforms were not deployed until the most intense period of wildfire smoke (i.e., early May) had passed. Therefore, the report recommends that Alberta's Monitoring Network be evaluated for its ability to forecast, monitor, and report on wildfire smoke, with a focus on identification of monitoring gaps and possible monitoring methods to fill these monitoring gaps.

During the wildfire, all permanent continuous air monitoring stations observed AAAQO and AAAQG exceedances of $PM_{2.5}$ concentrations. At the Athabasca Valley station and Patricia McInnes station, the maximum 24-hour average $PM_{2.5}$ concentration were 1035 $\mu g/m^3$ and 1131 $\mu g/m^3$, respectively, which is well above the health-based AAAQO of 30 $\mu g/m^3$. Elevated levels of $PM_{2.5}$, including AAAQG and AAAQO exceedances, were also observed by the EBAM and MAML at various locations in Fort McMurray and surrounding areas. This demonstrates that $PM_{2.5}$ is a useful indicator of wildfire smoke and that $PM_{2.5}$ data is useful to support decisions to protect human health during emergency response. Therefore, EBAM units, which are relatively easy to transport and deploy, are an appropriate platform to assess the spatial and temporal variability of wildfire smoke during emergency response. One limitation noted in the report is that the EBAM units are not designated FEM. AEP is currently leading a colocation study including EBAM and other $PM_{2.5}$ analyzers, and this report recommends that evaluation of the colocation data include clear results for the EBAM that can be used to quantitatively interpret EBAM data collected alongside other platforms.

Other parameters, such as NO_2, NH_3, SO_2, and CO were also monitored by the permanent continuous air monitoring stations and the MAML during the Horse River Wildfire. Median hourly NH_3 concentrations were 3 times and 22 times larger during the wildfire than during the non-wildfire impacted period at the Bertha Ganter station and Patricia McInnes station respectively. Furthermore, 13 episodes of 1-hour CO concentrations exceeding the health-based AAAQO were recorded at the Athabasca Valley station, and the median hourly concentrations were 2 times higher than the non-wildfire impacted period. This demonstrates that measurements of additional parameters provides valuable information about the composition of the smoke plume, and risk to human health. The MAML was deployed to multiple locations during the study, with the goal of measuring the spatial variation of additional air quality parameters in various neighborhoods. The smoke plume varied rapidly in time and therefore the MAML measurements were not representative of spatial variability and were difficult to interpret. Therefore, it is recommended that fewer MAML monitoring sites be selected in the future, so that monitoring can focus areas most heavily impacted by smoke and human traffic, and that are located far enough from permanent monitoring stations to provide useful data.

The primary goal of the portable air monitoring was to support decisions to protect the health of emergency response personnel and the public. During the wildfire, air monitoring data were shared internally with other agencies responsible for human health. Furthermore, daily summaries of EBAM and MAML data were posted publicly online, but due to rapid changes in air quality, this data was often out of date by the time it appeared. Therefore, a recommendation was made to automatically present the portable air quality monitoring data in an accessible near real-time system. This platform would distribute time sensitive information quickly and reduce the required human resources to process the data.

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Appendix A: Supplementary Information for Air Quality Monitoring

Appendix A1: Permanent Continuous Air Monitoring Stations

Table A-1: Permanent Continuous Air Monitoring Locations and Monitored Parameters Considered in this Report

Stations	Latitude	Longitude	Parameters Considered in this Report				
			$PM_{2.5}$	NO_2	NH_3	CO	SO_2
Anzac[8]	56.44928	-111.03722	✓	✓	×	×	✓
Horizon	57.30372	-111.73962	✓	✓	×	×	✓
Bertha Ganter	57.18945	-111.64045	✓	✓	✓	×	✓
Fort McKay South	57.14908	-111.64262	✓	✓	×	×	✓
Athabasca Valley	56.73268	-111.39020	✓	✓	×	✓	✓
Patricia McInnes	56.75135	-111.47637	✓	✓	✓	×	✓

[8] Monitoring was interrupted from May 6th - 13rd, 2016 due to power outage caused by the wildfire

Table A-2: Summary of Analyzers Used at the Permanent Continuous Air Monitoring Stations

Stations	$PM_{2.5}$	NO_2	NH_3	CO	SO_2
Anzac[8]	SHARP[9]	Thermo 42i	×	×	API T100[10]
Horizon	SHARP	Thermo 42i	×	×	Thermo 43i
Bertha Ganter	SHARP	Thermo 42i	API 201	×	Thermo 43i
Fort McKay South	SHARP	Thermo 42i	×	×	API T100
Athabasca Valley	SHARP	Thermo 42c	×	Thermo 48i (trace level)	Thermo 45c
Patricia McInnes	SHARP	Thermo 42i	API 201	×	Thermo 43i

[9] Synchronized Hybrid Ambient Real-time Particulate

[10] API T100 was used for SO_2 measurement until August 2nd, 2016, when it was replaced with a Thermo 43i

Appendix A2: Beta-attenuation Particulate Monitors (EBAM)

Figure A-1: EBAM Unit 3 at YMM Airport Location on May 7th 2016 (Photo Credit: Marty Collins)

Table A-3: EBAM Measurement Locations and Dates Appendix A3: Mobile Air Monitoring Laboratory (MAML)

Unit #	Site Name	Latitude	Longitude	Dates	Description
1	Clearwater Hotel	56.72375	-111.38032	May 7 - May 20	Fort McMurray Downtown
	Provincial Courthouse	56.72594	-111.37702	May 20 - Jun 10	Fort McMurray Downtown
	Keyano Main Campus	56.714362	-111.34826	Jun 10 - Jun 21	Fort McMurray Downtown
	Waterways	56.69973	-111.34239	Jun 21 - Aug 25	Fort McMurray South
	Abasand	56.72026	-111.3878	Aug 25 - Nov 30	Fort McMurray South
2	First Nation Health Centre	56.44121	-111.17358	May 10 - Aug 17	Gregoire Lake Estate
	Beacon Hill	56.72369	-111.35815	Aug 25 - Nov 29	Fort McMurray South
3	Forestry Warehouse	56.65583	-111.20526	May 7 - Jun 21	YMM Airport
	Ecole Boreal Elementary School	56.71168	-111.37759	Jun 21 - Nov 30	Fort McMurray South-Abasand
4	Regional Emergency Operations Centre	56.65776	-111.32434	May 7 - Jun 10	Keyano Industrial Campus
	Frank Lacroix Arena	56.69367	-111.35932	Jun 21 - Nov 5	Fort McMurray South-Beacon Hill

Appendix A3: Mobile Air Monitoring Laboratory (MAML)

Figure A-2: MAML Deployed at Gregoire on May 16th 2016 (Photo Credit: Marty Collins)

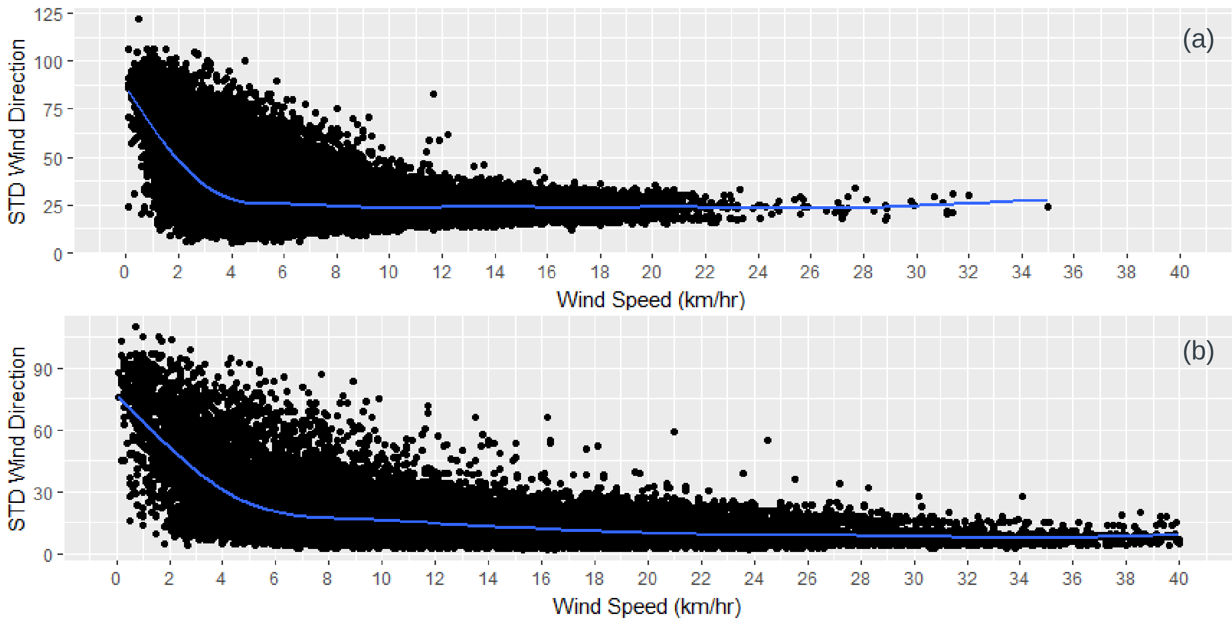
Table A-4: MAML Measurement Locations and Dates

Site Name	Latitude	Longitude	Date	Time (MST)
Phase I: Heavily impacted locations (May 16th - May 22nd, 2016)				
Gregoire	56.6747	-111.3429	May 16	13:50-17:50
Beacon Hill	56.6943	-111.3627	May 17	07:10-11:10
Urgent Care Centre	56.7124	-111.3475	May 17	12:30-16:30
Abasand	56.7103	-111.3753	May 18	08:20-12:20
Ecole McTavish High School	56.7616	-111.4520	May 18	13:25-15:25
Grayling Terrace	56.7081	-111.3610	May 19	09:30-13:30
Wood Buffalo	56.7210	-111.4641	May 19	13:49-17:49
Waterways	56.6985	-111.3385	May 20	09:00-13:00
Downtown Hospital	56.7175	-111.3596	May 20	13:30-17:30
REOC	56.6573	-111.3300	May 21	08:02-11:02
Saprae Creek	56.6507	-111.1494	May 21	12:08-16:08
Thickwood	56.7315	-111.4193	May 22	07:50-10:50
Provincial Building	56.7279	-111.3831	May 22	11:07-13:07
Phase II: Re-entry communities (May 31st - Jun 4th, 2016)				
Hardin Street	56.7293	-111.3751	May 31	11:55-13:55
Urgent Care Centre	56.7124	-111.3475	May 31	14:55-16:55
Karl A Clark Elementary School	56.7174	-111.3578	Jun 1	08:27-12:27

Site Name	Latitude	Longitude	Date	Time (MST)
Ecole McTavish High School	56.7616	-111.4520	Jun 1	13:02-16:02
Parsons Creek Access	56.7772	-111.4500	Jun 2	08:40-12:41
Thickwood	56.7315	-111.4193	Jun 2	13:13-16:13
Wood Buffalo	56.7210	-111.4641	Jun 3	08:35-11:35
Gregoire	56.6747	-111.3429	Jun 3	12:21-16:21
Beacon Hill	56.6943	-111.3627	Jun 4	08:54-11:20
Phase III: Restricted destroyed areas by the wildfire (Jun 7th - Jun 9th, 2016)				
Abasand	56.7103	-111.3753	Jun 7	10:38-13:38
Waterways	56.6985	-111.3385	Jun 7	14:10-17:10
Beacon Hill	56.6943	-111.3627	Jun 8	07:19-15:19
First Nations Health Centre	56.4416	-111.1728	Jun 9	07:32-11:32
YMM Airport	56.6562	-111.2331	Jun 9	12:20-14:20

Appendix B: Low Wind Speed-Wind Direction Biases

Cheristanidis, Batsos, & Chaloulakou (2014) and DeGaetano (1998) both identified large uncertainties in wind directions when low wind speeds (<1 m/s) are reported. Therefore, data collected at low wind speeds are often excluded from pollution rose and wind rose figures. To verify the wind speed threshold, the standard deviations of wind direction are plotted as a function of wind speed for various permanent continuous monitoring stations, as shown in Figure B-1. Large standard deviations in wind directions occurred for low wind speeds (<5 km/hr or <1.4 m/s). Therefore, for this report, data are included in pollution roses only if the wind speed is >1 m/s.



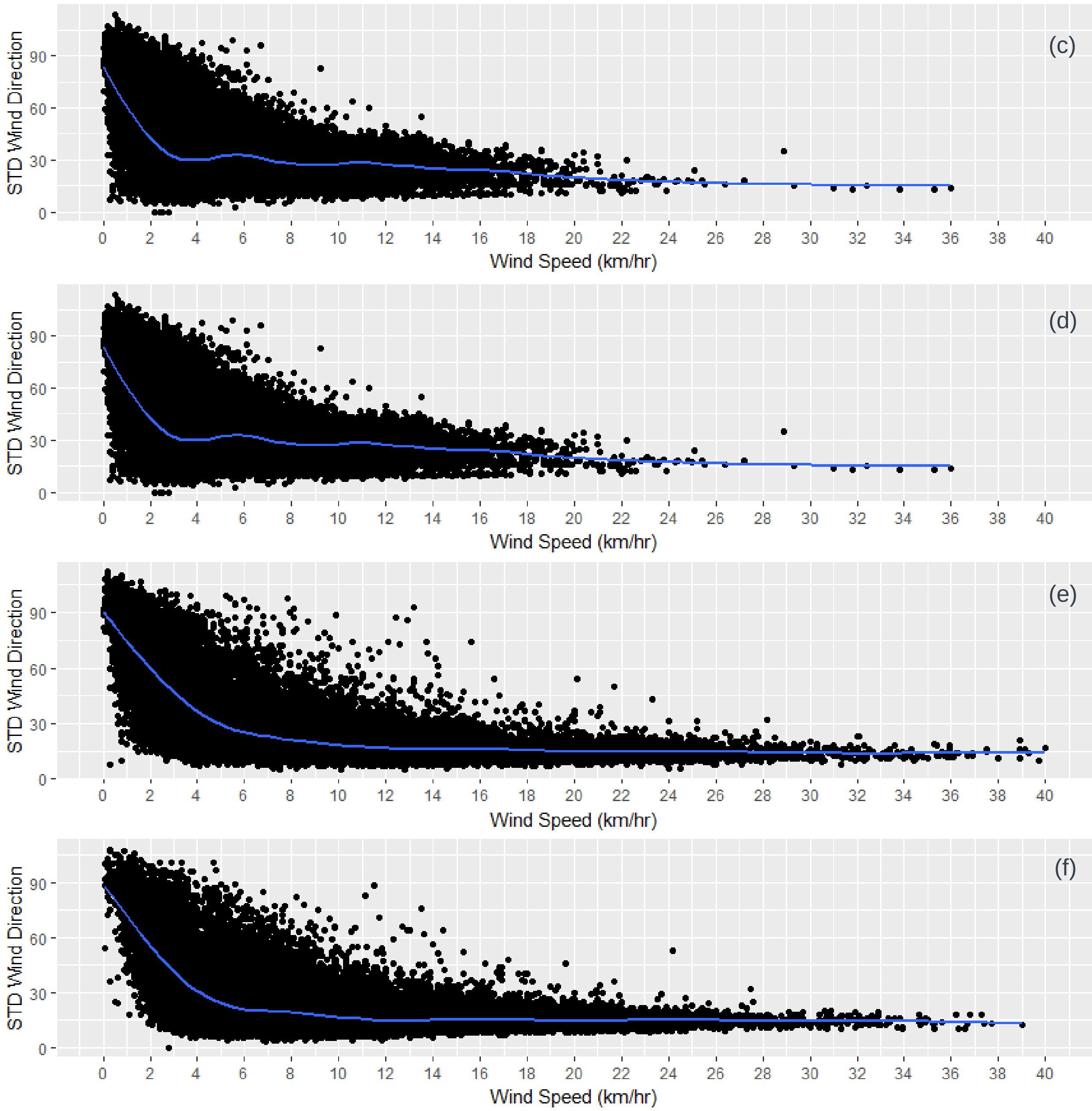


Figure B-1 Standard Deviation of Wind Direction as a Function of Wind Speed: (a) Anzac; (b) Horizon; (c) Bertha Ganter; (d) Fort McKay South; (e) Athabasca Valley; (f) Patricia McInnes; Blue line indicated as the data trend-line

Appendix C: Spatial and Temporal Variation of $PM_{2.5}$

During the Horse River Wildfire, the MAML took measurements at multiple locations, typically sampling half a day at each location. The goal of this sampling schedule was to measure air quality where emergency personnel were located and prior to public re-entry of Fort McMurray. In order to evaluate the MAML sampling schedule, the spatial and temporal variation of $PM_{2.5}$ was analyzed using data collected by the four EBAM units. The hourly average $PM_{2.5}$ measured from the four EBAM units located in downtown Fort McMurray (Unit 1: Clearwater Hotel), at Gregoire Estates (Unit 2: First Nation Health Centre), Fort McMurray REOC (Unit 3), and Fort McMurray Airport (Unit 4: Forestry Warehouse) were used for these tests. The data were analyzed for May 7th – 22nd, 2016, during Phase I of the MAML campaign, which was targeted to measure impacted areas where emergency response personnel were located.

The time series plot of EBAM measurements is shown Figure C-1. There is a large temporal variation in $PM_{2.5}$ concentrations from each EBAM unit, with episodes of strong wildfire smoke influence and a diurnal variation. Lower values are typically observed overnight, when wildfire activity is reduced. $PM_{2.5}$ concentrations also varies spatially, with the units located in and near Fort McMurray (Units 1, 3, 4) experiencing higher levels of $PM_{2.5}$ than Unit 2, which is located in Gregoire Estates, 30 km southeast of Fort McMurray. The periods when the MAML took measurements are also indicated on the figure, with each grey rectangle indicating several hours of MAML measurements taken at a single location. The MAML sampled 13 locations in total were over 7 days during Phase I of the campaign. This figure demonstrates that the date and time of the sampling is as important or, possibly, more important than the sampling location for the MAML measurements. For example, on the morning of May 17th, all EBAM units in the vicinity of Fort McMurray (Units 1, 3, 4) measured enhanced levels of $PM_{2.5}$, suggesting that there was a strong influence from wildfire smoke across Fort McMurray, while on May 22st, all of the Fort McMurray EBAM units measured relatively low amounts of $PM_{2.5}$. On May 17th at Beacon Hill and the Urgent Care Centre, the MAML measured higher levels of smoke-related parameters ($PM_{2.5}$ 1000-1700 µg/m^3; NH_3 40-130 ppb; and CO 200-600 ppb) than on May 22st at the Downtown Provincial Building and Thickwood ($PM_{2.5}$ 5-15 µg/m^3; NH_3 5 ppb; and CO ~100-200 ppb). Based on the variability in the EBAM data, these differences are most likely due to differences in the sampling period and not the spatial variation in wildfire smoke.

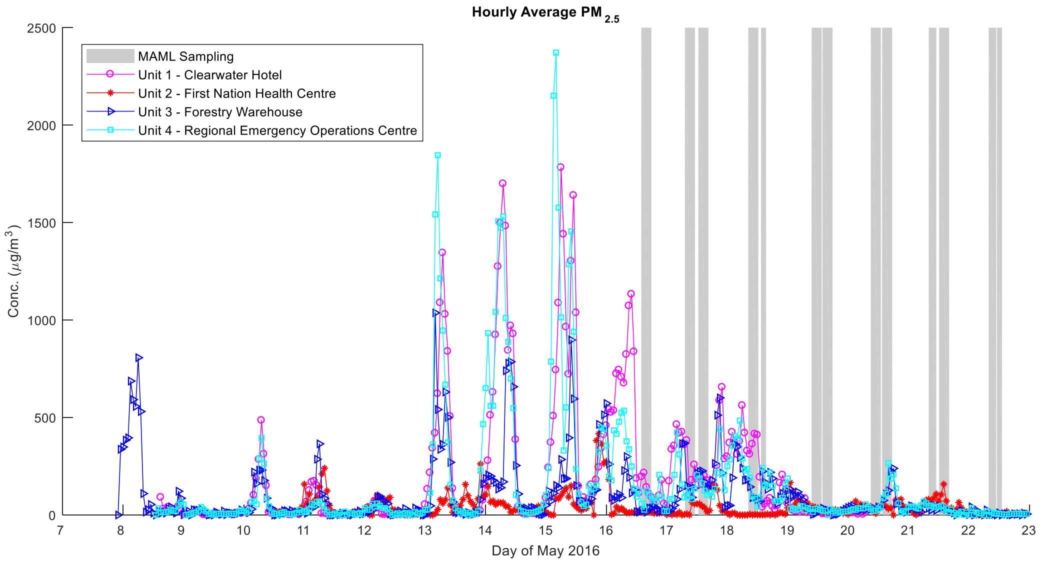


Figure C-1 Time Series Plot for of EBAM 1-hour Average $M_{2.5}$ Concentrations from May 8th – May 22nd 2016, with MAML Measurement Periods Indicated by the Grey Rectangles.

The correlation between the data collected by the EBAM units at different locations is shown in Figure C-2, and was calculated relative to data collected by Unit 1 (located in downtown Fort McMurray) in order to quantify spatial variation in terms $PM_{2.5}$ concentrations. The mean absolute difference in the hourly data for a EBAM Unit minus Unit 1, and the associated standard error (σ/√N), were also calculated. The data collected by Unit 4 (Fort McMurray REOC) is most similar to the data collected by Unit 1, with a mean absolute difference of -22±15 µg/m^3 and R = 0.74. This is consistent with the close proximity between these two units. The data collected by Unit 3 (located near Fort McMurray Airport) is also correlated with the data collected by Unit 1 (R = 0.62), but with a more negative mean absolute difference of –101±16 µg/m^3. The data collected by Unit 2 (Gregoire Estates) does not appear to be related to the data collected downtown (R = 0.13), and measures much lower levels of $PM_{2.5}$, with a mean absolute difference of -198±24 µg/m^3. Therefore, as would be expected, the spatial variation is more significant for larger distances between stations.

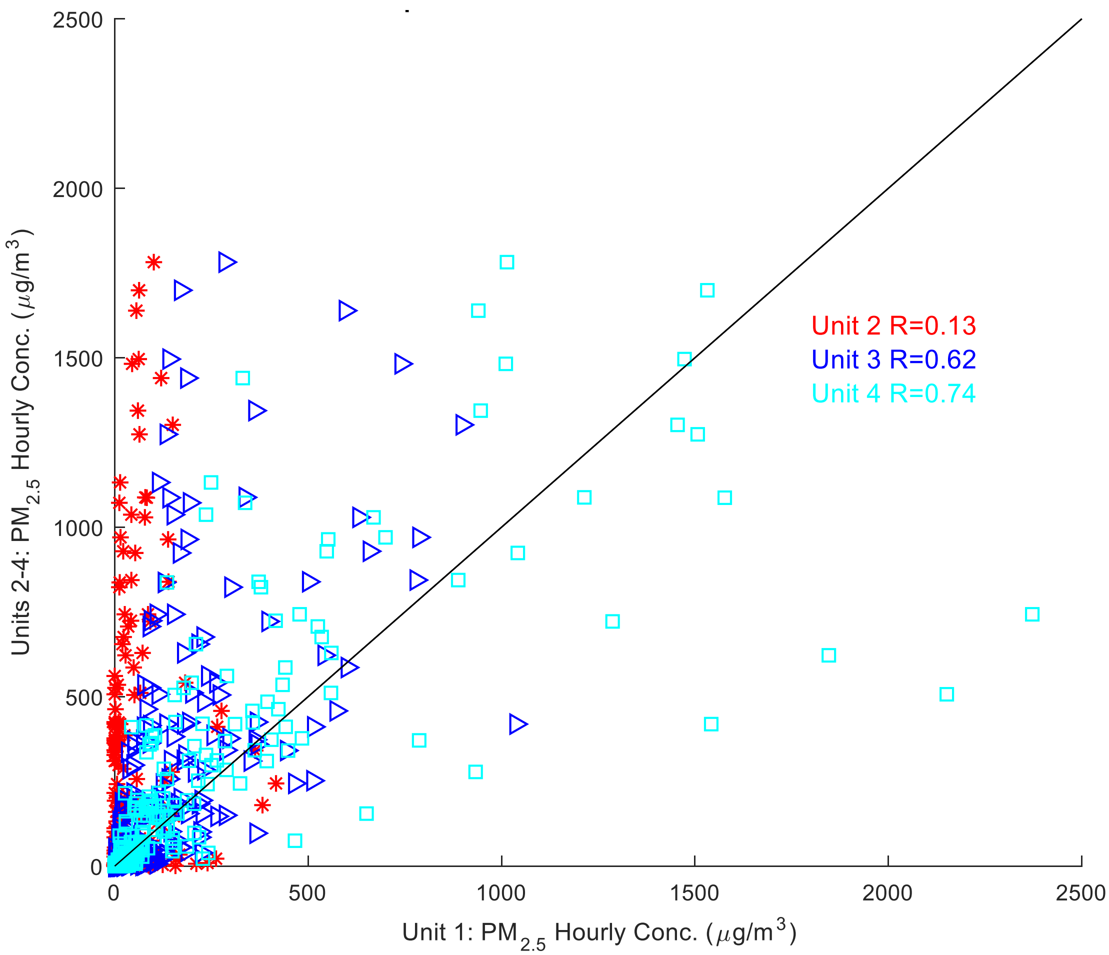


Figure C-2: Scatter Plot Showing Spatial Correlation Across EBAM Unit 1 (x-axis) Versus Unit 2 to 4 (y-axis) from May 8th - May 22nd, 2016

The EBAM $PM_{2.5}$ time series suggests that for locations within Fort McMurray, the spatial variation of air quality is not very significant compared with the temporal variation. Therefore, it is difficult to infer the spatial variation of air quality using the MAML data, given the close proximity of the measurements within Fort McMurray. Furthermore, since the MAML moved locations frequently, the data could not be used to assess changes in time in air quality parameters such as CO and NH_3 that are not measured by the EBAMs.