Prince George Air Quality Emissions and Modelling (2014-2016)

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1 Executive Summary

This study builds on previous work to update the City of Prince George, British Columbia's, air pollutant micro-emission inventory and modelling system from the years 2003 - 2005 to the years 2014 - 2016. This period was selected over a more-recent period to avoid complications due to high wildfire smoke impacts on the local air quality during the Summers of 2017 and 2018, which are difficult to model accurately. A 40 km by 40 km area centered over Prince George's urban center was modelled. Respirable particulate matter, $PM_{2.5}$ and PM_{10}, were the pollutants of primary focus. These pollutants have known negative health effects and are the only pollutants that have regularly exceeded provincial ambient air quality objectives in the city. Sulphur dioxide (SO_2) and oxides of nitrogen (NO_x) were also inventoried and modelled as these pollutants can react with ammonia in the atmosphere to form fine particles (called secondary formation particulate matter). Results from these secondary formation particulates are included here, instead of those for SO_2 and NO_x.

The modelling system consists of four main components: the micro-emission inventory (MEI), a meteorological model (CALMET), a dispersion model (CALPUFF) and a custom web-based scenario simulation tool (AirQuest). The updates to the MEI focused primarily on industrial emissions due to the large changes in this sector since the 2005 MEI. Many of the other emission sources were not updated since the 2005 MEI due to the relatively low magnitude of changes assumed to occur in these sources over the period. CALMET was updated using 2014-2016 meteorological data and underwent a thorough review resulting in changes to the input settings leading to improved performance. CALPUFF was then ran with the updated inputs from the 2016 MEI and CALMET model. These results are accessible in the AirQuest web-based tool for visualisations and simulating source specific emission reductions.

1.1 Micro-Emission Inventory (MEI) Summary

The MEI is a set of files detailing the amount, location, time and method which emissions are released by different source categories in the Prince George airshed. The MEI was updated from the previous 2005 inventory to represent emissions in 2016. Updates were focused on the industrial emissions, as this source category was expected to have changed the most over the 11-year period. All facilities with active air discharge authorizations during the modelling period were included. Emissions data were collected or calculated from stack tests, site operator data, and various allocations produced from tests on similar equipment. Approximately 60% of the emission sources in this category were updated. Industrial emissions in 2016 were lower than in 2005; for example, $PM_{2.5}$ emissions decreased by 40% and SO_2 emissions decreased by 24%.

Between the 2005 and 2016 MEI, an improved method was implemented for particulate matter (PM) emissions from dust. In the 2005 MEI dust emissions entering the atmosphere were unrealistically high, so a "transportable fraction" based on near-source vegetative capture of dust was implemented. Precipitation based reductions were also implemented; with the combined reductions (due to improvements in inventory methodology, not actual source reductions) resulting in a large decrease in dust in the 2016 MEI. Additionally, fugitive dust, added since the 2005 MEI, was updated for 2016.

Background PM was also updated for the 2014-2016 period by using monitoring data from low-pollution wind sectors and following methods outlined in Veira et al (2013). Background PM

represents emissions that are transported into the airshed from distant sources, both natural and anthropogenic – essentially the PM levels one would measure without the contributions from sources within the airshed. The background PM estimates do not take into consideration wildfire smoke, which significantly impacts the local air quality for short durations in some years.

Open burning sources were omitted because the activity became prohibited under the City of Prince George Clean Air Bylaw in 2010. This source had a relatively small contribution to $PM_{2.5}$ and PM_{10} at Plaza 400 in the 2005 model results so its removal made little difference. Rail emissions were not updated as we did not get a response to our requests for information from this sector. Given the expansion in rail activities since 2007, emissions from this source category are likely underrepresented in the MEI. Lesser affected sources that were also not updated include commercial, restaurant (updated since Stantec, 2010, during Phase 2 of the project), and various miscellaneous sources.

1.2 CALPUFF Model Results Summary

The CALPUFF model simulates the concentrations of air pollutants in the Prince George airshed using the emissions defined in the MEI and atmospheric conditions simulated by CALMET. The modelled air pollution concentrations matched the observations at the available monitoring stations reasonably well especially for particulate matter, the pollutants of interest. The contribution of each source to the mean monthly and annual concentrations were determined for neighbourhoods in the airshed.

***PM_{10}*:** Background concentrations were important in all seasons and neighborhoods. Road dust and commercial dust were large contributors to modelled PM_{10} with the largest contributions occurring during the spring and summer in the urban center ('Bowl' region) and the BCR industrial site. Other source contributions include industry, heating (mostly residential wood burning during the fall and winter), and vehicle tailpipe emissions.

***$PM_{2.5}$*:** Background concentrations were important in all seasons and neighborhoods. In addition to background levels, emissions from heating (mostly residential wood burning in winter and fall), road dust, commercial dust, and industry were the primary contributors to $PM_{2.5}$ concentrations in most neighborhoods. Other source contributions include vehicle tailpipe emissions, miscellaneous sources, and rail. Modelled averages in the 'BCR Industrial Site', 'Bowl', and several 'Hart' neighbourhoods tended to exceed the provincial 1-year annual average $PM_{2.5}$ objective of 8 $\mu g\ m^{-3}$ and approach or exceed the Canadian Ambient Air Quality Standard of 10 $\mu g\ m^{-3}$. The BCR industrial site was impacted primarily by industry, road dust, and commercial dust while the 'Bowl' and 'Hart' regions were primarily impacted by heating and road dust.

Heating emissions (mainly residential wood burning) dominate ambient concentrations in most neighbourhoods in winter, exceeded only by contributions from industry in the BCR industrial site. Road dust and commercial dust dominate the Spring and Summer contributions.

1.3 Conclusion Summary

$PM_{2.5}$ is the main air pollutant of concern in Prince George. While different areas of the city are affected by different sources, in most neighborhoods $PM_{2.5}$ comes from: background levels,

followed by dust, and then emissions from wood heating, and industry. Wood heating emissions dominate in winter, dust dominates in summer, and industrial emissions are an important contributor to ambient concentrations throughout the year..

Modelled $PM_{2.5}$ and PM_{10} concentrations were lower than observed when winds were coming from the north to east at Plaza 400. It is believed that this is a result of underestimated emissions from sources in the 'heavy industrial' areas located to the east and north of Plaza 400. A portion of the underpredictions are likely the result of the underestimation of the rail sources. Modelled $PM_{2.5}$ levels were higher than observed at Plaza when winds were from the southwest. It is believed that this is a result of overestimated emissions from wood heating.

1.4 Follow up and Future Work

AirQuest was updated to incorporate the new model data in May 2020. Future work on the modelling system should focus on continued refinement of the MEI, particularly rail and industry sources and on-road mobile sources contributing to the overestimation of NO_x emissions. Other sources not updated in the current MEI should also be considered for review, however contributions from these sources are less likely to change significantly over time. Further refinement of the meteorological model (CALMET) is also warranted. Early testing suggests there may be benefits to implementing surface interpolation barriers which separate observations in the valley from the surrounding plateau.

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3 Acknowledgements

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4 Introduction

The City of Prince George, located in central British Columbia, Canada, has a population of nearly 80,000 and lies at the junction of two major highways (Highway 16 and 97), two large rivers (the Fraser and the Nechako), and rail lines extending north-south and east-west. Its varied meteorology and 'bowl' shaped topography has a strong influence on the local air quality.

Respirable particulate matter (PM) is of concern primarily because of its effects on human health. PM is measured as a mass concentration by size: PM_{10} is PM less than 10 micrometers in diameter and $PM_{2.5}$ is the subset of PM_{10} with particle diameters less than 2.5 micrometers. The smaller particles are of greater health concern as they penetrate deeper into lungs. Particulate matter would exist in Prince George, even if there were no anthropogenic emissions within the city. This is due to the import of natural and anthropogenic PM from outside the airshed and is called *background* PM. These background levels make up a significant portion of the contributions to monthly and annual mean particulate concentrations in the airshed. Typical background concentrations of respirable particulate matter (PM_{10} and $PM_{2.5}$) were calculated based on monitoring data from low-pollution wind sectors following methods outlined in Veira et al, 2013 (Appendix A). These background levels do not include the impacts of wildfires as wildfire smoke has a relatively large impact on PM levels with high interannual variability. Particulate matter can be directly emitted into the atmosphere – this is called *primary formation* PM; it can also form in the atmosphere from the conversion of gases (mainly oxides of sulphur and nitrogen reacting with ammonia) – this is called *secondary formation* PM.

Prince George has relatively high levels of PM for the province due to emissions from a broad mixture of residential, commercial, and industrial sources in and around the urban center, background concentrations already present in the area, as well as local meteorology and topography. Understanding the emission of air pollutants and how they are dispersed within the airshed is necessary to make sound air quality management decisions. Air pollution models can link emissions from specific sources to ambient concentrations across the airshed and therefore identify sources making the largest contributions to pollutant levels. Consequently, in the present study, the CAMLET/CALPUFF modelling system (Scire et al, 2011) was used over a 40 km by 40 km area centered on the City of Prince George for the 2014 - 2016 period. This updated a previous modelling study that was done for the 2003 - 2005 period. Updates were primarily made to the inputs to the meteorological model as well as sections of the micro-emission inventory.

The modelling system consists of four main components: the micro-emission inventory (MEI), the meteorological model (CALMET), the dispersion model (CALPUFF), and the custom web-based scenario analysis tool (AirQuest). This document summarizes the main projects findings; technical details for each component are described in further detail in Appendices A through D.

The MEI is a set of data tables listing hourly emission rates and parameters for all identified sources within the Prince George airshed. These data tables are produced for each source category and provide essential emission inputs to the modelling system. CALMET, the meteorological model, uses a combination of geospatial parameters, surface meteorological observations, and upper air observations to simulate atmospheric conditions necessary for modelling the dispersion of air pollutants. Modelled hourly wind fields, as well as other useful

meteorological variables, were produced on the 40 km x 40 km grid at 12 vertical heights in the atmosphere, starting at 10 m for the surface level.

The meteorological fields produced by CALMET in combination with emissions of PM_{10}, $PM_{2.5}$, SO_2, and NO_x (converted to NO and NO_2) from the MEI, are used by CALPUFF to calculate ambient concentrations at all points in the airshed for each hour in 2014-2016. Hourly nitrate (NO_3) and sulphate (SO_4) concentrations were also simulated via conversions from modelled SO_2 and NO_x. Nitrate and sulphate concentrations are used to calculate secondary particulate matter, a result of chemical reactions between the two with ammonia. These concentrations were calculated at receptors located at 1.5 m above the surface at a spatial resolution of 0.5 km close to the urban center and at a spatial resolution of 1.0 km in the surrounding area. Additional receptors were included at the ambient observation stations at the height of each air quality monitoring station for evaluation purposes.

The dispersion model was run separately for each emission source category in the MEI making it possible to allocate source contributions to the hourly ambient concentrations at each receptor location. These were then totalled and compared directly with observations from ambient monitoring stations for evaluation or left separate and used to identify sources of greatest concern in each region.

Since the pollutant ambient concentration is linearly related to the emission rate, scenario simulations can be performed by scaling the concentrations from an emission source directly. In other words, reducing the contribution from a source, say road dust, at a location corresponds to an equal proportional reduction in ambient concentration resulting from that source. Such scenario simulations can be performed using the AirQuest custom web-simulation tool and are useful for estimating and comparing the impacts that management strategies may have on ambient concentrations in the Prince George airshed.

4.1 Airshed Geography

The Prince George airshed was modelled as a rectangular zone, extending approximately 20 km outwards from the urban center that is located in the valley bottom (the ‘bowl’) approximately 150 m below the surrounding rolling plateau. Any emissions from sources outside of this region, while important, are too difficult to model accurately except for including them as background concentrations. The MEI developed for the Prince George airshed aims to capture all possible emissions within this imaginary boundary (Appendix A). An important external source that cannot be accounted for is wildfire smoke, which only significantly impacted the air quality for July and August of 2014. Consequently, respirable particulate matter observation data for these months were excluded from the model evaluation, due to wildfire smoke influence.

The ‘bowl’ air quality is influenced by a mixture of industrial, residential and commercial activity and has the densest road network of the airshed (Figure 1). The mostly residential ‘Hart’ region is north of the bowl and is mainly influenced by the surrounding residential homes as well as the industrial area to the east. This ‘heavy industrial area’, along the Fraser River northeast of the bowl, contains the majority of the large industry including two of the three pulp mills (the third is about 4 km north of the outlined area in Figure 1), two chemical plants and a small oil refinery. The second industrial area, the ‘BCR industrial’ area, is located south of the bowl along

the Fraser River and is influenced by several sawmills and nearby rail activity. Directly south of the 'bowl' is 'College Heights', a mostly residential area.

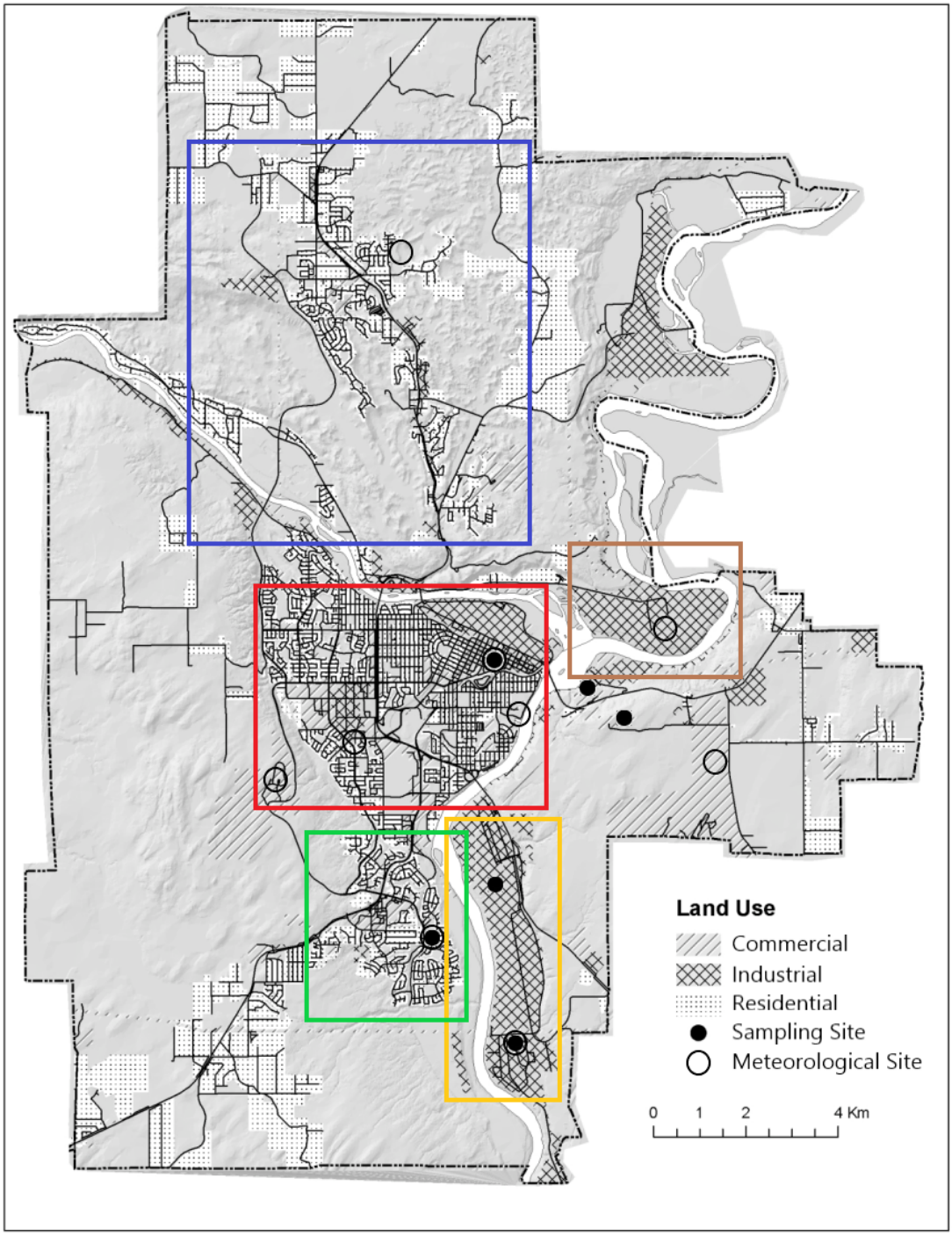


Figure 1. Place map for Prince George, BC with primary road network and main commercial, industrial, and residential areas marked. Air pollutant observation sites (6 total) are marked with a black point and meteorological observation sites (9 total) are marked with a ring (3 sites overlap). The blue box at the top outlines the approximate boundaries of the 'Hart' region. The red box below it outlines the 'Bowl' region. The brown and yellow boxes (middle right and bottom right boxes) indicate the approximate locations of the 'Heavy Industrial Area' and the 'BCR Industrial Site'. The 'College Heights' residential area is located just south of the 'Bowl' and west of the 'BCR Industrial Site', approximately marked with a green box. The Fraser River runs north to south along the east side of the 'Bowl'. The Nechako River runs east to west, joining the Fraser between the Bowl and the Heavy Industrial Area.

4.2 Meteorology

Dispersion of air pollutants within the airshed is strongly influenced by the regional meteorology. Precipitation events can scavenge pollutants from the atmosphere and deposit them on surfaces, improving the local air quality. The wind is the main driver for dispersing pollutants, moving them from source to receptor and diluting them along the way. Lower winds speeds reduce the spread and dilution of pollutants, and in combination with temperature inversions and stagnation allow for fumigation events to occur where pollutants become 'trapped' in the bowl-shaped urban center. Nine meteorological stations and one upper air station monitored wind, temperature and humidity conditions during the 2014 - 2016 period and were used to develop the meteorological fields necessary for dispersion modelling (Appendix B). Four of the stations were located in the 'Bowl', three stations were located just south of the 'Heavy Industrial Area' only one station observed each of the southern 'College Heights' and northern 'Hart' regions. There were six stations regularly observing ambient concentrations within the airshed from 2014 - 2016, three of which recorded meteorological fields as well.

4.3 Project History

The initial modelling project (Phase 1) began in 2006 and consisted of the production of the original MEI and modelling system valid for the years 2003 - 2005. Phase 1 ended in 2010 with the most recent report (Stantec, 2010). In 2012, AirQuest, a web-based simulation tool for air quality and emission reduction scenarios, was developed for the project. Phase 2 began in 2013 and concerned the revision of the previous work to remove discrepancies, automate workflow, and refine several sources, while still being valid for the years 2003 - 2005. This also involved the addition of the secondary particulate matter modelling section. Phase 2 was completed in 2016 following a two-year break in the project. The current project, Phase 3, was initiated in 2018 and involved updating the MEI and modelling platform to be valid for 2014 - 2016.

5 Micro-emission Inventory Summary

The micro-emission inventory (MEI) is split into multiple source categories to allow attribution of modelled ambient concentrations to specific emission sources. Technical details regarding the emission modelling for each source can be found in Appendix A. Each source in the MEI is modelled individually with varying methods of calculating the temporal and geographical distributions of hourly emission rates. Total and average emission rates by emission source category are displayed in Table 1.

Table 1. Total and average annual emission rates by modelled emission source category. Totals are averaged for the three model years; there was little to no interannual variation. Average emission rates do not take into consideration temporal variability in emissions.

Emission Source	Total Emission Rates (t/y)		Average Emission Rates (g/s)	
	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$
Industry	1259.5	956.7	39.93	30.33
Residential Heat	193.7	190.8	6.14	6.05
Commercial Heat	5.5	5.5	0.17	0.17
On-Road Mobile	31.6	22.1	1.00	0.70
Rail Yards/Lines	13.2	12.6	0.42	0.40
Road Dust	378.8	60.6	12.01	1.92
Commercial Dust	758.0	148.7	24.04	4.71
Fugitive Dust	33.6	4.0	1.06	0.13
Restaurants	25.6	23.9	0.81	0.76
Miscellaneous	31.3	30.6	0.99	0.97
Total	**2698.6**	**1423.0**	**85.6**	**45.1**

The industrial source considers the emissions from air emitting units at 22 sites. Each site has one or more emitting units with individual emission parameters and operational data. Average emission rates are calculated, and each unit emits their average emission rate during the hours, weekdays, and months prescribed in their operational data. Industrial emissions in 2016 were lower than in 2005; for example, $PM_{2.5}$ emissions decreased by 40% and SO_2 emissions decreased by 24% (Appendix A). Reductions in emissions from the heavy industrial area northeast of the Plaza 400 monitoring site have also been verified by an analysis of ambient monitoring data (Jackson et al. 2017).

The Residential Heat category includes emissions from the use of natural gas and wood burning for heating residences, while the Commercial Heat category includes natural gas emissions for heating commercial buildings. The majority of the heating emissions are the result of residential wood burning as respirable particulate matter emissions from natural gas burning are small. Wood burning emissions are allocated to residential neighbourhoods based on population size and the approximate distribution of wood stoves from survey results. Emissions from vehicle tailpipes are handled by the on-road mobile source and are allocated to arterial and residential roads using traffic activity weighting factors. The rail source includes emissions from locomotives travelling on rail lines and within rail yards. Average emission rates are assigned to each line/yard based on the typical locomotive 'notch' level and emit constantly at most locations.

Traffic-induced dust emissions from paved and unpaved roads are considered in the road dust source. Peak emission rates are calculated for the arterial and residential roads and then distributed temporally based on traffic activity weighting factors; these are then subject to reduction from precipitation and vegetative capture. The reduction in emissions by considering vegetative capture was implemented subsequent to the 2005 MEI and results in a large reduction in dust emissions in the 2016 MEI - consequently the dust emissions are not comparable between the two inventories. The commercial dust source considers dust emissions resulting from construction, gravel pits, farm vehicles, and parking lot activity. Similar to road dust, peak

emission rates are determined for each commercial dust source and subsequently reduced by weighting factors. The last dust source, fugitive dust, considers vehicle traffic, material handling, and wind-induced stockpile dust emissions at specific sites. Fugitive dust emissions are subject to the same reduction methods as commercial dust and road dust.

Emissions from Restaurants are modelled at individual restaurant locations with emission rates based on which meals (breakfast, lunch, and/or dinner) are served there. These emissions are constant during the prescribed meal times. Many of the remaining sources in the Prince George airshed are captured in the Miscellaneous source category. This includes estimates of emissions from cigarette smoking, lawn equipment use, backyard barbequing, aircraft landing/take-off, Pacific Western Brewing, welding and autobody shops, non-road mobile emissions (mostly construction equipment), and farm mobile emissions.

Some emissions sources are not captured by the MEI. Modelling of open burning within the airshed, a relatively small source in the previous MEI, was not considered due to data limitations. Other sources can be too difficult to model reliably due to data limitations or intrinsic features of the source itself. For example, wildfire smoke can have a significant impact on the short-term air quality in Prince George however the source itself is difficult to quantify. Background concentrations were estimated in an attempt to capture the particulate matter levels that would be present if the city and its emissions were not there (excluding impacts from wildfire smoke). Biogenic sources, pollen for example, as well as long-range transport from other airsheds or countries (Asian dust) are difficult to quantify but are included within the background concentrations. These background concentrations make up a significant portion of the respirable particulate matter concentrations in the Prince George airshed. In addition, the secondary formation of particulate matter was modelled and these concentrations were included in the modelled particulate matter results.

6 CALPUFF Model Results

CALPUFF outputs hourly gridded concentrations for two separate grids in the model domain; the first matches the CALMET grid (40 x 40, 1 km resolution), while the second is a smaller, higher resolution grid covering the majority of receptors (26 x 36, 0.5 km resolution). The residential neighbourhood delineations produced during Phase 2 separate out ~48% of the model domain into 23 rectangular neighbourhoods of varying sizes (Figure 2). These neighbourhoods are used to assign residential heating and miscellaneous emissions. Nearly all neighbourhoods are mostly or entirely inside the inner domain except for Chief Lake, Cranbrook Hill, North Nechako, and Southwest. Hart North, Northwood, and Airport have portions outside of the inner domain.

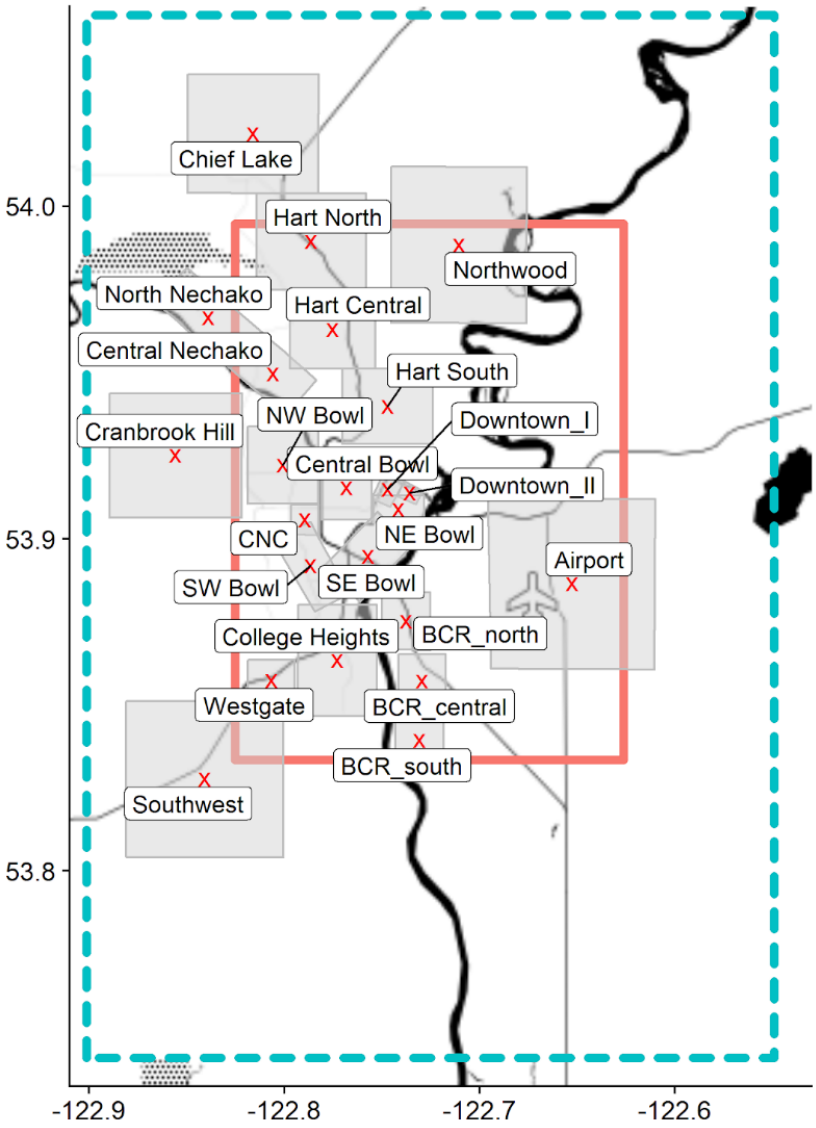


Figure 2. Residential neighbourhood definitions for Prince George, BC. Neighbourhood midpoint are marked with an 'x', with a line connecting the label to the midpoint if necessary. The blue dashed line indicates the outer bounds of the 40 x 40, 1 km resolution grid, while the red solid line indicates that of the 26 x 36, 0.5 km resolution grid.

6.1 PM_{10} Concentrations

There is a large range in the spatial distribution of 3-year average annual total modelled PM_{10} concentration (Figure 4). PM_{10} tends to be highest at the 'BCR Industrial Site' and the airport, with elevated values in and around the 'Bowl' and 'Hart' regions. These latter regions have a modelled annual average typically near 25 µg m^{-3}. The outskirts of the airshed are not as strongly impacted by PM_{10}, especially in the northeastern and southern regions.

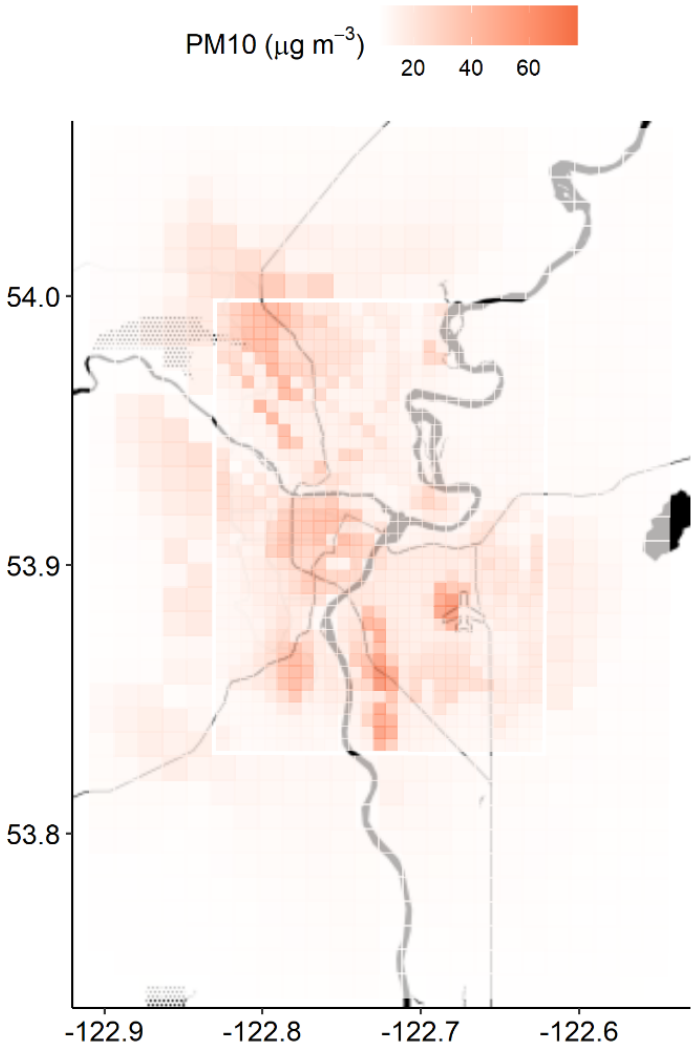


Figure 3. 3-year annual average modelled PM_{10} concentration (µg m^{-3}) for the Prince George airshed. There is a fine, 0.5 km resolution, grid over the urban center and a coarser, 1 km resolution, grid surrounding that.

The gridded 3-year annual averages can be summarised by region and allocated to emissions sources (Figure 4). Background concentrations make up almost half of the 3-year annual average modelled neighbourhood PM_{10} concentrations. The remainder of contributions are primarily from road dust and commercial dust, with secondary contributions from industry, heating, and on-road mobile. Contributions to annual average neighbourhood PM_{10} concentrations from rail and miscellaneous sources are insignificant for most neighbourhoods. Annual average road dust contributions are highest in the 'Bowl' and 'BCR' regions, while commercial dust contributions are less variable between neighbourhoods and are greatest in the 'Hart' and the 'BCR' regions. BCR north and Downtown I have the highest contributions from rail, and miscellaneous contributions are primarily in the 'Bowl' regions.

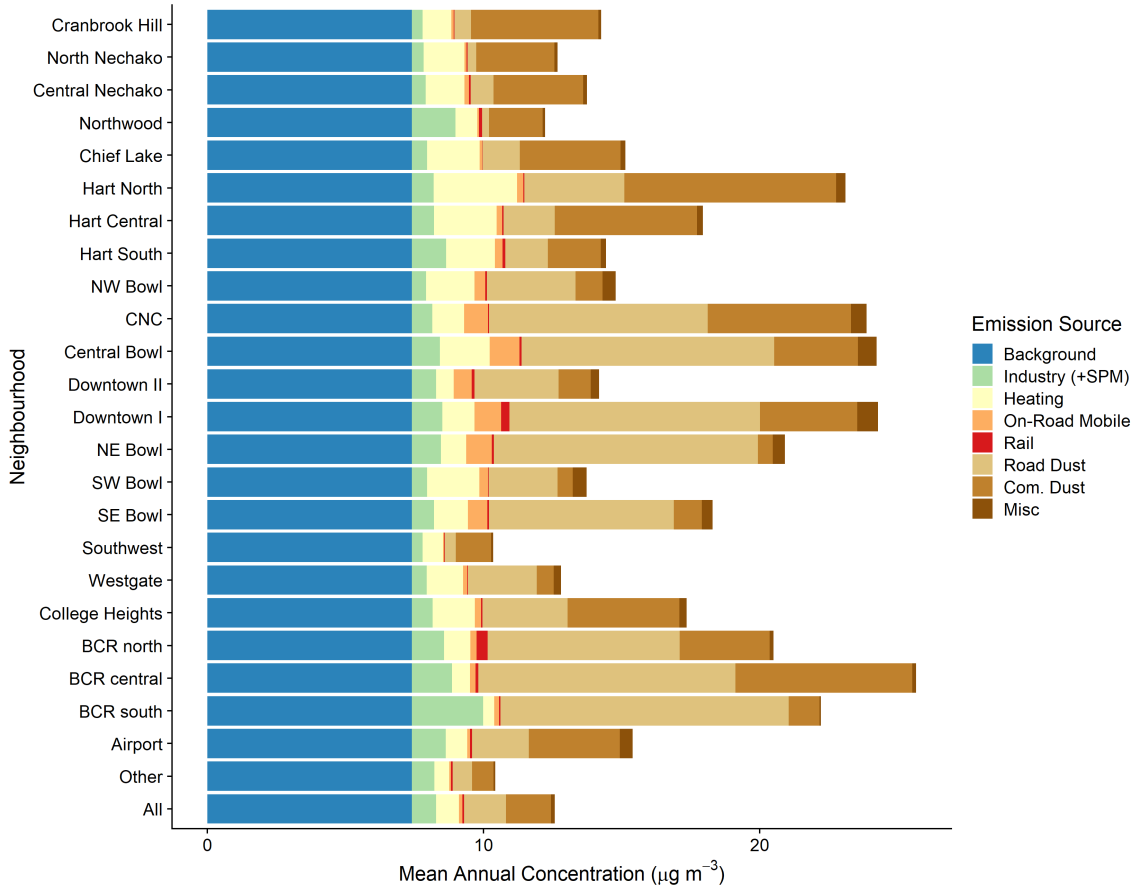


Figure 4. 3-year average of mean annual modelled PM_{10} concentrations (μg m^{-3}) for residential neighbourhoods in Prince George, BC, by emission source for 2014 to 2016. Industry and secondary particulate matter (SPM) are combined as industry is the primary contributor to SPM. 'Heating' includes emissions from residential and commercial heating, the majority of which is from residential wood burning. Commercial dust includes contributions from fugitive dust, which are relatively small. The 'Misc' source covers restaurants as well as several smaller residential and commercial sources (such as emissions from cigarette smoking or plane takeoffs/landings at the airport). Neighbourhoods are sorted approximately by latitude from north to south, grouping nearby neighbourhoods together. The 'Other' neighbourhood is all the areas not covered by any neighbourhood, while the 'All' neighbourhood considers every location in the 40x40 km airshed. Neighbourhood locations are defined in Figure 2.

The modelled monthly average PM_{10} concentrations were lowest overall in Winter months (Figure 5). The remaining seasons had similar total concentrations; however, neighbourhood source contributions vary. The greatest contribution to the monthly average PM_{10} concentrations for many neighbourhoods is from background levels. Background levels do not vary within the model domain but do vary by season. The remaining major sources contributing to monthly average neighbourhood PM_{10} in the model were road dust, commercial dust, industry (including secondary particulate matter), and heating. On-road mobile, miscellaneous, and rail emissions have smaller contributions. Road dust and commercial dust contributed the most in non-Winter months. Road dust dominates the contributions in the 'BCR' and 'Bowl' regions, especially during the Spring months. Commercial dust contributions are focused more in the 'Hart' and 'BCR' regions. Industrial contributions are relatively small. These contributions and consistent between seasons at the 'BCR' regions, but Winter/Fall contributions are higher than in Spring/Summer for the other neighbourhoods. Contributions from heating emissions to monthly average PM_{10}, primarily from wood burning, are highest in the Winter and Fall months.

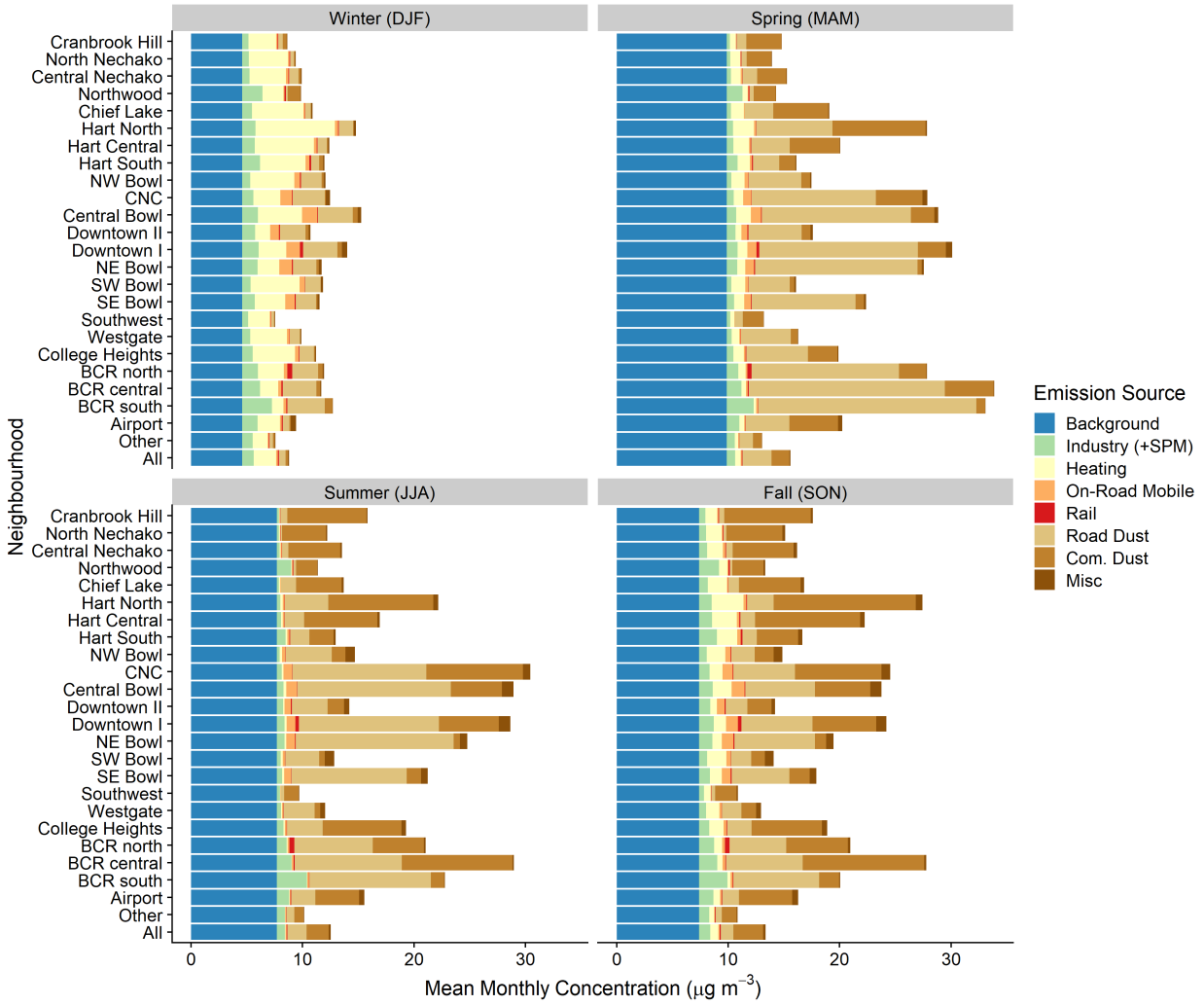


Figure 5. Seasonal means of monthly average modelled PM_{10} concentrations (µg m^{-3}) for residential neighbourhoods in Prince George, BC, by emission source for 2014 to 2016. Industry and secondary particulate matter (SPM) are combined as industry is the primary contributor to SPM. 'Heating' includes emissions from residential and commercial heating, the majority of which is from residential wood burning. Commercial dust includes contributions from fugitive dust, which are relatively small. The 'Misc' source covers restaurants as well as several smaller residential and commercial sources (such as emissions from cigarette smoking or plane takeoffs/landings at the airport). Neighbourhoods are sorted approximately by latitude from north to south, grouping nearby neighbourhoods together. The 'Other' neighbourhood is all the areas not covered by any neighbourhood, while the 'All' neighbourhood considers every location in the 40x40 km airshed. Neighbourhood locations are defined in Figure 2.

6.2 $PM_{2.5}$ Concentrations

The gridded 3-year annual averages of modelled $PM_{2.5}$ shows a similar pattern to that for PM_{10} (Figure 6). These concentrations are highest in and around the 'Hart', 'Bowl', and 'BCR Industrial Site' regions, as well as near the airport. Most of the higher resolution inner grid exceeds the BC annual ambient air quality objective of 8 µg m^{-3} for $PM_{2.5}$. The southwest and southeast corners of the airshed are least impacted by $PM_{2.5}$ and there tends to be a local minimum following the two rivers.

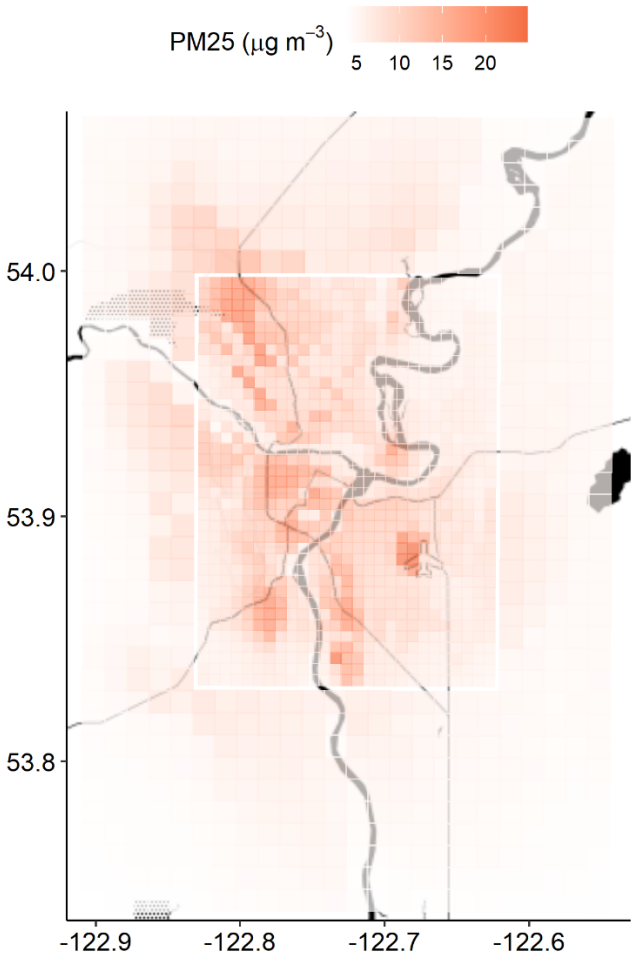


Figure 6. 3-year annual average modelled $PM_{2.5}$ concentration (µg m^{-3}) for the Prince George airshed. There is a fine, 0.5 km resolution, grid over the urban center and a coarser, 1 km resolution, grid surrounding that.

The 3-year annual average of modelled $PM_{2.5}$ contributions to mean neighbourhood concentrations consist primarily of contributions from background, road dust, heating, industry, and commercial dust (Figure 7). Lesser contributions from on-road mobile, miscellaneous sources and rail can be found in most neighbourhoods. Several neighbourhoods in the 'Hart' and 'Bowl' regions, as well as the 'BCR' region are modelled to exceed the BC annual ambient air quality objective of 8 µg m^{-3} for $PM_{2.5}$. Only the Central Bowl, Hart North and Downtown I neighbourhoods are modelled to exceed the 2015 Canadian Ambient Air Quality Standards (CAAQS) for annual $PM_{2.5}$ of 10 µg m^{-3}. In addition to these neighbourhoods, BCR Central, CNC and the NE Bowl areas exceeded the 2020 CAAQS for annual $PM_{2.5}$ of 8.8 µg m^{-3}. Background contributions can make up more than half of the annual average $PM_{2.5}$ concentrations and are assumed constant over the entire airshed. Industrial contributions include the contributions from secondary particulate matter and are largest in the 'BCR' regions. Heating emissions, most of which are from residential wood burning, contribute relatively high amounts to the annual average $PM_{2.5}$, especially in the 'Hart' regions. Contributions from road dust are more concentrated in the 'Bowl' and 'BCR' regions, while commercial dust is larger primarily in the 'Hart' and 'BCR' regions. On-road mobile and miscellaneous emission have relatively small contributions, mainly focused in the 'Bowl' region. Rail contributions are quite small, with greatest contributions to the BCR north and Downtown I neighbourhoods.

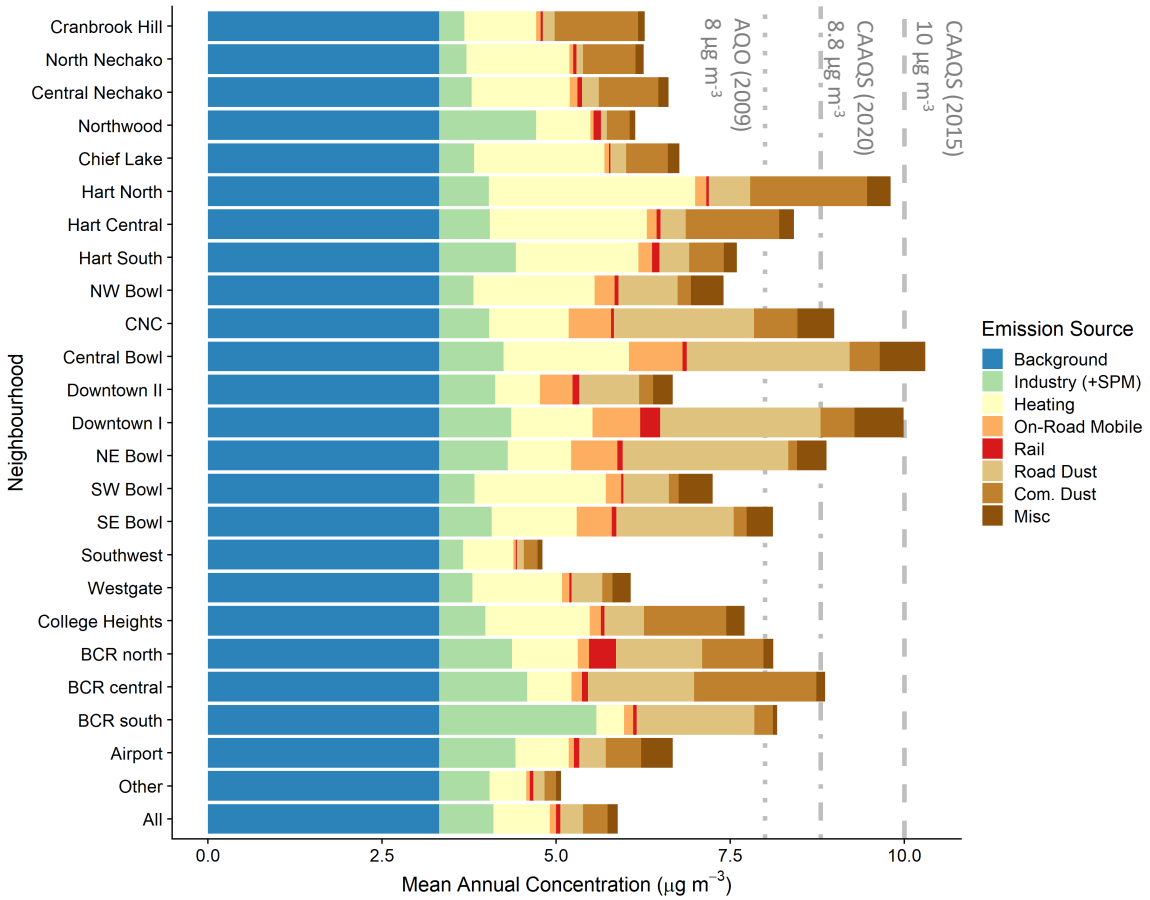


Figure 7. 3-year average of mean annual modelled $PM_{2.5}$ concentrations (µg m^{-3}) for residential neighbourhoods in Prince George, BC, by emission source for 2014 to 2016. Industry and secondary particulate matter (SPM) are combined as industry is the primary contributor to SPM. 'Heating' includes emissions from residential and commercial heating, the majority of which is from residential wood burning. Commercial dust includes contributions from fugitive dust, which are relatively small. The 'Misc' source covers restaurants as well as several smaller residential and commercial sources (such as emissions from cigarette smoking or plane takeoffs/landings at the airport). Neighbourhoods are sorted approximately by latitude from north to south, grouping nearby neighbourhoods together. The 'Other' neighbourhood is all the areas not covered by any neighbourhood, while the 'All' neighbourhood considers every location in the 40x40 km airshed. Neighbourhood locations are defined in Figure 2. The Air Quality Objective (AQO) and the 2015 & 2020 Canadian Ambient Air Quality Standards (CAAQS) for annual average $PM_{2.5}$ are marked with dotted, dot-dashed and dashed lines, respectively.

The main contributors to modelled monthly average $PM_{2.5}$ concentrations in Prince George varied by season and neighborhood and were background, road dust, heating, industry, and commercial dust (Figure 8). On-road mobile, rail, and miscellaneous sources have much lesser contributions. Background $PM_{2.5}$ concentrations do not vary within the model domain but do vary by season. Source contributions tend to vary between seasons, except for industrial contributions (including secondary PM) which remained relatively stable. All neighbourhoods were impacted by industrial emissions, however, those located near the heavy industrial area northeast of the city or the BCR industrial area south of the city had the highest contributions from industry. Emissions from heating, most of which are from residential wood burning, had the highest contribution in the Winter and Fall months, but was almost zero in the Summer months. These contributions were highest in the 'Hart' and 'Nechako' regions northwest of the city, with Hart North having the highest overall concentrations of all neighbourhoods due mostly to heating emissions. Concentrations originating from heating (mainly wood burning) were also

high in the neighbourhoods southwest of the city. In contrast to heating, contributions from road dust were highest in the Spring and Summer months. During these months, road dust had the greatest impact on the monthly average $PM_{2.5}$ concentrations for neighbourhoods located in the 'Bowl' and 'BCR' regions. Commercial dust contributions are near zero in the Winter and are highest in Summer and Fall; these contributions are concentrated in the BCR, Hart, and Nechako neighbourhoods. On-road mobile and miscellaneous source contributions are concentrated in the 'Bowl' regions, while rail contribution mainly impact the BCR north and Downtown I neighbourhoods.

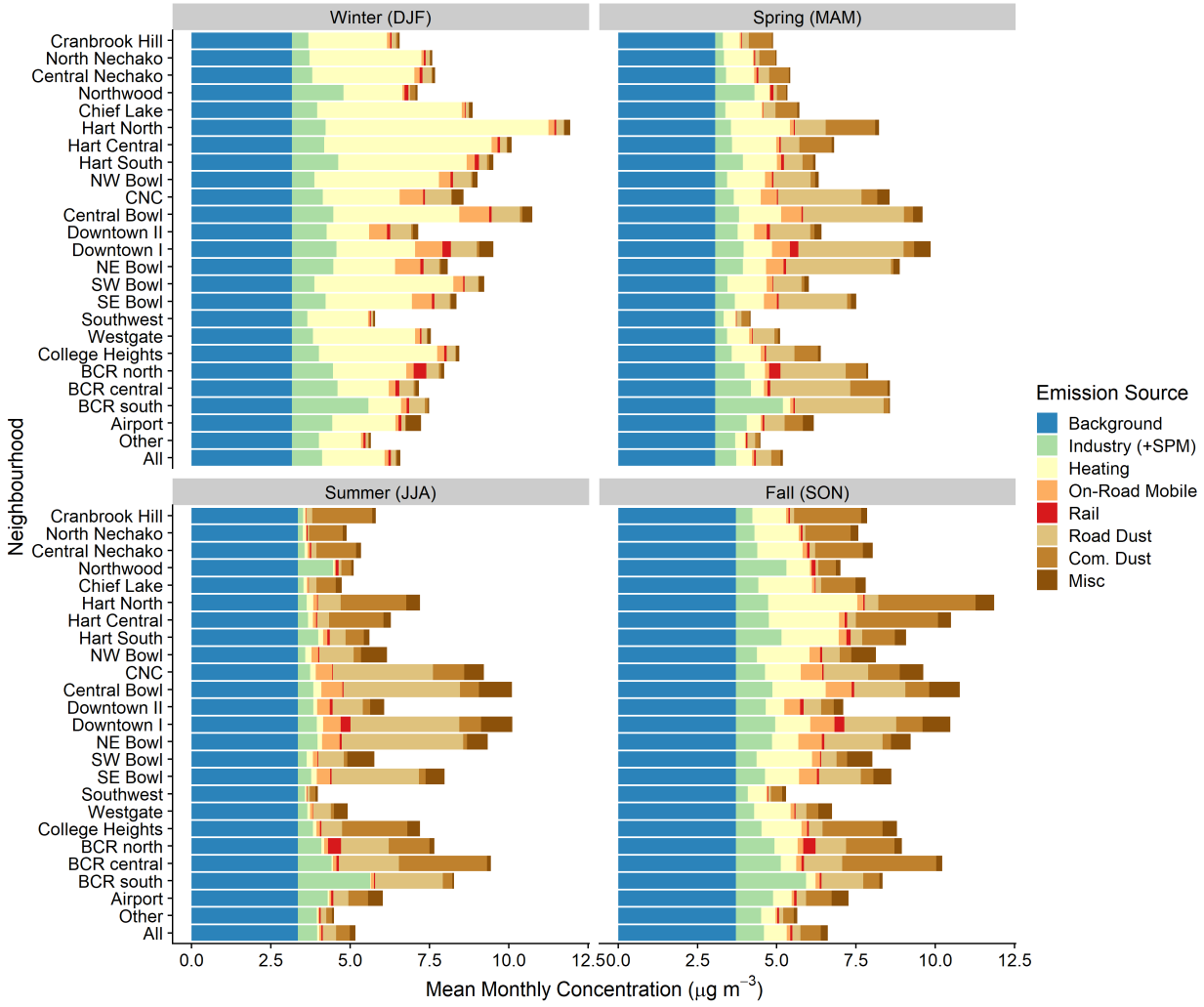


Figure 8. Seasonal means of monthly average modelled $PM_{2.5}$ concentrations (µg m^{-3}) for residential neighbourhoods in Prince George, BC, by emission source for 2014 to 2016. Industry and secondary particulate matter (SPM) are combined as industry is the primary contributor in the airshed to SPM. 'Heating' includes emissions from residential and commercial heating, the majority of which is from residential wood burning. Commercial dust includes contributions from fugitive dust, which are relatively small. The 'Misc' source covers restaurants as well as several smaller residential and commercial sources (such as emissions from cigarette smoking or plane takeoffs/landings at the airport). Neighbourhoods are sorted approximately by latitude from north to south, grouping nearby neighbourhoods together. The 'Other' neighbourhood is all the areas not covered by any neighbourhood, while the 'All' neighbourhood considers every location in the 40x40 km airshed. Neighbourhood locations are defined in Figure 2.

7 Conclusions: Limitations, Future Work and Recommendations

$PM_{2.5}$ is an important air pollutant of concern in Prince George, BC Columbia primarily due to its health impacts. While different areas of the city are affected by different sources, outside of background levels, in most neighborhoods $PM_{2.5}$ comes from: dust, and then emissions from wood heating, and industry. Wood heating emissions dominate in winter, dust dominates in summer, and ambient levels from industry are more consistent through the year.

7.1 Limitations

The accuracy of the CALPUFF dispersion model output is directly affected by limitations in the MEI, such as the presence of unknown sources, error in estimation of source emission rates, and incorrect specification of other source parameters. For example, if the emission amount for a source in the inventory is too low or high by say 30%, the modelled ambient concentrations from that source will also be too low or high by 30%. The accuracy is also influenced by the performance of the meteorological model, as it forms the basis for dispersing pollutants in the airshed. Eliminating all errors is not possible - there is no such thing as a 'perfect model' - so consideration of the limitations is needed to properly interpret model results.

The CALMET/CALPUFF modelling system was developed for use at larger spatial scales than our model domain and consequently may not be optimised for our application. CALMET output matches observations well at most stations, however, there are some discrepancies. CALMET inputs from meteorological stations that are close to each other influence the wind field produced by CALMET at each location, even with surface interpolation barriers in place (Appendix B). This influence tends to reduce the accuracy of the winds, and in turn the accuracy of the dispersion modelling, at observation stations when compared with model outputs at the same location.

Shortcomings in the ambient concentrations calculated by CALPUFF likely stem mostly from uncertainties in the MEI. However, there are also limitations in CALPUFF that can affect its estimation of ambient concentration. CALPUFF allocates area and line source emissions, such as those from road dust, to the midpoint of each area or line. As a result, larger regions are not represented as well as smaller regions and receptors located near the centre of an area or line may have incorrectly high concentrations.

Unlike previous renditions of the project, emissions from open burning were not included. In 2005, this source only made up 3% of the modelled annual average $PM_{2.5}$ concentration at the Plaza 400 site (Stantec 2010). Since the 2005 MEI, open burning has been eliminated within the city, which would further reduce the actual open burning emissions in 2014-2016. Based on data from the Open Fire Tracking System, there were on average forty open burns per year within the model domain from 2014 - 2016. Additional details on the date, size and duration of each fire were not available. Consequently, due to time constraints open burning emissions were not included, which would slightly reduce the total modelled PM_{10} and $PM_{2.5}$.

Several other sources were also not updated with 2014 - 2016 data. Emissions from rail activity will have increased since 2005 due to the implementation of an inland port terminal in Prince George in 2007. Emission and rail activity data were requested, but not provided. Modelled concentrations from rail emissions using 2005 data are relatively low in most neighbourhoods

however these values are almost certainly underestimated, given the increase in rail activity in 2014 – 2016 compared with in 2005.

CALFUFF results suggest that emissions from Residential Heating, 96% of which is from wood burning, contribute to a higher than expected proportion of the ambient $PM_{2.5}$ levels in many neighborhoods in the Winter. This suggests the possibility that the emissions from residential wood burning in the MEI could be too high. When winds are from the south to west at Plaza 400, placing the monitoring site downwind from several of the residential areas, the model overpredicts $PM_{2.5}$ by approximately 17% on average (up to 28% overprediction in the Winter). This overprediction of concentrations by the model could be a result of overestimation of residential wood emissions and should be investigated further.

$PM_{2.5}$ is underpredicted by the model at Plaza 400 when winds are from the east to northeast (winds coming from the heavy industrial area). PM_{10} is underpredicted at Plaza from this wind sector by ~42%, similarly for $PM_{2.5}$ (~41%). These underpredictions are much less when winds are from other directions for PM_{10} and $PM_{2.5}$ (5% and 8%, respectively). Industrial emissions are modelled using an average value which is either on or off, depending on whether the site is operating at that time. Average values are determined from stack test results for the major sources - these stack tests are performed under normal operating conditions at facilities and may not represent emissions under sub-optimal conditions, so may under-represent true average emission rates. Also, in reality these emissions can vary by time of year and time of day. As many of these average values are based on a few single-point-in-time measurements, this variability is not captured. Several of these average values are from allocations produced from tests done on similar equipment which may be underestimating the $PM_{2.5}$ emission rates. Since the majority of PM in the heavy industrial area to the northeast of Plaza 400 is emitted from stacks, this underprediction suggests that either the average emission rates of these pollutants is underestimated in the MEI, or that the modelling system is diluting and dispersing the emissions too well.

7.2 Future Work and Recommendations

Due to technical and time limitations not every imagined improvement could be made. In addition, the AirQuest web simulation tool has only recently been updated to include these new Phase 3 model outputs.

Future work should test the implementation of seven surface interpolation barriers in the CALMET meteorological model to limit the influence of the observations located in the valley on the model winds over the surrounding plateau (and vice versa). Only one barrier is currently implemented, between the Plaza 400 and Exploration Place observation stations, due to CALMET's requirement for a full data record from at least one station in each region. Interpolating missing observation data and implementing the remaining barriers should improve the modelling of wind channelling in the valley.

Several sources were not updated from the Phase 2 work with data from 2014 - 2016. While most of these sources likely have not changed very much, a complete update to the 2014 - 2016 period is recommended. In 2007 an inland rail terminal became operational in Prince George, significantly increasing the rail activity in the city. It is recommended for future work to focus on gathering the necessary data requirements to update the rail emission inventory for Prince

George. The modelling of restaurants and commercial activity were not updated in Phase 3 to match the geographical and temporal distribution of each in 2014 - 2016. Restaurant emissions were updated during Phase 2, subsequent to the Stantec (2010) report, but prior to the current work. Relative contribution to concentrations from these sources are small, so these updates were not prioritized. Data regarding the location and approximate timings of open burning fires in the Prince George airshed were provided, however, hourly emission rates were not simulated due to time limitations. While ambient contributions from this source are relatively low; it is still recommended that this source be implemented in the model. Additional investigation into the on-road mobile source is recommended, as overpredictions of NO_x indicate emissions from this source are almost certainly too high.

Underpredictions of PM at Plaza 400 associated with specific wind directions were identified and are believed to be the result of underestimation of industrial emissions. The accuracy of the industrial emissions could be improved by including a measure of variability for sites with semi-annual stack results or through implementation of specified operation dates and times provided by site operators in the hourly emission calculations. In addition, allocations were somewhat arbitrarily created for industrial emissions for baghouses, cyclones, and several natural gas boilers. These allocations should be further investigated, as an underestimated allocation may explain the reduced contribution from industry. In addition, overpredictions of $PM_{2.5}$ at Plaza 400 when winds are from the south to west, especially during the winter, suggest that residential heating emissions from wood may be overestimated in the MEI.

8 References

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9 Glossary

Term	***Definition***
AirQuest	A web-based scenario simulation tool used for visualizing the model simulations. Emission scenarios (Say reducing several sources by 30%) can be run using this tool for visualizing the impact of the scenario on the modelled ambient concentrations.
Airshed	A geographic area where the atmosphere behaves coherently regarding dispersion of emissions, and where receptors within the region are potentially influenced by the pollutant concentrations resulting from the emissions within that area.
Background PM	Particulate matter (PM) would exist in Prince George, even if there were no anthropogenic emissions within the city. This is due to the import of natural and anthropogenic PM from outside the airshed and is called *background* PM. These background levels make up a significant portion of the contributions to monthly and annual mean particulate concentrations in the airshed.
CALMET	The meteorological model used to simulate the atmosphere for the dispersion modelling system. Uses observed weather data and land/terrain information to simulate hourly meteorological conditions.
CALPUFF	The dispersion model used to simulate the concentrations of pollutants based on CALMET's simulated atmosphere and the micro-emission inventory's prescribed emissions. CALPUFF keeps track of the emitted pollutants as they are dispersed by the simulated atmosphere.
Concentration	The mass of pollutant per volume of air at a location. This is what receptors are exposed to and result from emissions being dispersed within the airshed.

Dispersion	The movement of air pollutants both away from emission source and by diffusing outwards through wind and turbulence.
Emissions	Pollutants released directly from source stacks or diffuse areas (e.g. dust). These emissions are dispersed in the atmosphere and result in the concentrations at receptor locations.
Emissions Scenario Simulations	Since pollutant concentration scales linearly with emission rate, scenario simulations can be made by scaling the concentrations from an emission source by the amount that source changed. In other words, reducing a source at a location corresponds to a equal proportional reduction in concentration from that source. The AirQuest custom web-simulation tool can perform such scenarios to estimate and compare the impacts that management strategies may have on ambient concentrations.
Fumigation Events	Atmospheric phenomena where elevated pollutants become trapped below a thermal inversion but can efficiently mix downwards resulting in high surface concentrations, usually for a short time period. Can occur sometimes in mid-mornings under calm, clear conditions and is exacerbated in valleys.
Low-pollution wind sector	Wind directions and speeds where emissions from major sources are not anticipated to impact an observation station. Used for calculating background concentration level estimations.
Micro-Emission Inventory *abbr: MEI*	A set of files detailing where, when, and how emissions are released by individual emission source categories. This MEI is used along with the simulated atmosphere from CALMET to model the dispersion of pollutants in CALPUFF.
Particulate Matter, Respirable *abbr: PM* *incl: PM_{10}, $PM_{2.5}$*	Solid particles suspended in the atmosphere. PM is measured as a mass concentration by size: PM_{10} is PM less than 10 micrometers in diameter and $PM_{2.5}$ is the subset of PM_{10} with particle diameters less than 2.5 micrometers. The smaller particles are of greater health concern as they penetrate deeper into lungs.
Primary Formation PM	Respirable particulate matter (PM) directly emitted by anthropogenic and natural sources (dust, exhaust, etc)
Receptors	Those potentially impacted by atmospheric pollution (i.e. people).
Secondary Formation PM *also: Secondary PM* *abbr: SPM*	Respirable particulate matter (PM) formed through the interaction of pollutants in the atmosphere. NO_x and SO_2 emissions are inventoried and modelled as they can react with ammonia in the atmosphere to form these fine particles
Surface Interpolation Barriers	Programmatic boundaries used to divide geographic areas in the meteorological model so that observations on one side of the barrier will not be interpolated to the other side of the barrier. Useful for nearby stations influenced differently by local topographic configuration such as for separating valley and plateau observations.
Transportable Fraction	A percentage value describing the amount of dust remaining locally after being reduced by impacting vegetation.

Appendix A: Updated Prince George Micro-Emission Inventory (2016)

[This is a stand-alone document that details the MEI.]

Appendix B: CALMET Setup and Evaluation

[This is a stand-alone document that details the CALMET set up, evaluation, and results.]

Appendix C: CALPUFF Setup and Evaluation

[This is a stand-alone document that details, the CALPUFF set up, evaluation and results.]

Appendix D: AirQuest Documentation

[This contains instructions and documentation on the AirQuest visualization and scenario tool, once the new model results are implemented in the AirQuest platform.]