Residential Wood Combustion $PM_{2.5}$ Sampling Project Whitehorse, Yukon – Winter 2009

Final Report

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Summary

Residential wood combustion (RWC) in wood stoves, fireplaces and fireplace inserts, is a commonly used method for heating homes in Canada and is a significant source of fine particulate ($PM_{2.5}$) air emissions, which can negatively impact human health. The impact of RWC emissions in the City of Whitehorse has been a concern for several decades. Previous studies by Environment Canada in the 1980s documented high levels of total suspended particulate (TSP) in the subdivision of Riverdale, particularly under stagnant conditions. Despite lower levels of particulate matter measured in more recent years, local government agencies often field complaints from residents regarding wood smoke, and there is anecdotal evidence that levels may be higher in certain parts of the city, such as Riverdale. An air quality project working group, including representatives from the Pacific and Yukon Region of Environment Canada, the City of Whitehorse, Yukon Environment and Health and Social Services Yukon in Whitehorse undertook this study with the objective to assess current $PM_{2.5}$ levels in Whitehorse during the winter months and to quantify the contribution of wood smoke. This would allow the establishment of a baseline for wood smoke contributions for this community against which the effectiveness of any future intervention could be assessed, such an appliance change-out program.

The $PM_{2.5}$ sampling campaign in Whitehorse took place from January to March 2009. Filter based sampling was employed at two sites in downtown Whitehorse and the subdivision of Riverdale. From the filter samples, the commonly used wood smoke markers, levoglucosan and a carbon isotope, ^{14}C, were measured to assess the contribution of RWC to $PM_{2.5.}$ An aethalometer was employed at the Riverdale site to measure black carbon.

Average / median concentrations were 7.7 / 6.4 $\mu g/m^3$ (n=18) and 10.2 / 7.1 $\mu g/m^3$ (n=12) at the Downtown and Riverdale sites, respectively. Overall, concentrations ranged from 1.6 $\mu g/m^3$ to a maximum of 31.3 $\mu g/m^3$ (Riverdale on February 11), exceeding the value of the Canada Wide Standard of 30 $\mu g/m^3$. Note that this does not represent a formal exceedance as it is not based on the annual 98^{th} percentile value. On average, fine particulate at Riverdale was composed primarily of organic carbon (55%), while elemental carbon made up 7%. Winter time PM concentrations measured during this study were significantly lower than those found in previous studies in the early 1980s and comparable to current levels in several communities in the interior of B.C. However, results from this study were higher than typically measured at the Whitehorse NAPS site for the January to March period. Causative factors here were likely a combination of a different sampling location and, to a lesser extent, different measurement methodology.

To estimate the 24 hour average concentrations of $PM_{2.5}$ throughout the sampling period, a simple linear regression was used to relate 24 hour average black carbon data, measured by aethalometer at Riverdale, to daily average $PM_{2.5}$ concentrations at the two sites. Assuming a consistent linear relationship between black carbon at Riverdale and $PM_{2.5}$ at both sites throughout the study period and within the range of black carbon measured, a

simple linear regression model predicted that the value of the Canada Wide Standard was likely exceeded on five days at Riverdale (all during a 9 day period in February) and none at the Downtown site.

Calculations based on the analysis of ^{14}C data indicate that the average wood smoke contribution to $PM_{2.5}$ ranged from 70-84% (average minimum-maximum %) at the Riverdale site. These results were supported by levoglucosan data, which also indicated a strong wood smoke influence in Whitehorse. Ratios (% w/w) of levoglucosan to $PM_{2.5}$ were 4.7 ± 1.6 and 6.0 ± 2.4 (avg. ± s.d.) at Downtown and Riverdale, respectively, indicating a slightly lower wood smoke contribution at Downtown, which is expected to have more contribution from traffic and heating from commercial buildings. Results from the aethalometer were also indicative of a strong wood smoke presence at Riverdale. Hourly concentrations of BC ranged from 0 to 8.6 $\mu g/m^3$ with an average of 0.9 $\mu g/m^3$ and a median of 0.2 $\mu g/m^3$. The wood smoke signal was observed to be highest in the early morning and late evening. Source apportionment results for wood smoke contribution from this study are in relatively close agreement to earlier studies in Riverdale, the most recent emission inventory for Whitehorse and a previous study in B.C.

The highest concentrations of $PM_{2.5}$ in Whitehorse were associated with calm winds, which limit dispersion and low temperatures, which are associated with increased wood burning. These conditions were found to be present on days with a strong surface level inversion caused by a stable ridge of cold arctic air or suspected subsidence of southwesterly or westerly air masses.

Results from this study confirm that any efforts to reduce winter time $PM_{2.5}$ in Whitehorse, particularly in the residential subdivision Riverdale, should consider RWC reduction strategies. If RWC emission reduction strategies are introduced, future work in Whitehorse could include follow-up monitoring to assess their effectiveness. Future studies should ideally include monitoring over a longer period to more fully capture the impact of RWC on cold season air quality in Whitehorse.

Résumé

La combustion résidentielle du bois dans les poêles à bois, foyers et poêles encastrables constitue une méthode couramment utilisée pour chauffer les maisons au Canada et représente une source importante d'émissions atmosphériques de matières particulaires fines ($MP_{2,5}$) qui peut avoir des répercussions néfastes sur la santé humaine. Les répercussions des émissions provenant de la combustion résidentielle du bois dans la Ville de Whitehorse sont depuis plusieurs décennies une source d'inquiétude. Menées par Environnement Canada dans les années 1980, les études précédentes ont permis de documenter des niveaux élevés de matières particulaires totales en suspension dans le lotissement de Riverdale, en particulier lorsque l'air est stagnant. Malgré des niveaux plus faibles de matières particulaires mesurés au cours des dernières années, les agences gouvernementales locales reçoivent souvent des plaintes des résidents en ce qui concerne la fumée de bois, et il existe des témoignages anecdotiques indiquant que les niveaux peuvent être plus élevés dans certaines parties de la ville, comme Riverdale. Le groupe de travail sur la qualité de l'air, composé de représentants de la région du Pacifique et du Yukon d'Environnement Canada, de la Ville de Whitehorse, du ministère de l'Environnement du Yukon, du ministère de la Santé et des Services sociaux du Yukon à Whitehorse, a entrepris cette étude dans le but d'évaluer les niveaux actuels de $MP_{2,5}$ à Whitehorse pendant les mois d'hiver et afin de pouvoir quantifier la contribution de la fumée de bois à ces émissions. Cela permettrait la mise en place d'une base de référence pour la contribution de la fumée de bois dans cette collectivité en fonction de laquelle l'efficacité de toute intervention à venir pourrait être évaluée, comme un programme de remplacement des appareils.

La campagne d'échantillonnage des $MP_{2,5}$ à Whitehorse a eu lieu de janvier à mars 2009. Des échantillons filtrés ont été utilisés sur deux sites dans le centre-ville de Whitehorse et dans le lotissement de Riverdale. À partir des échantillons filtrés, les marqueurs couramment utilisés pour la fumée de bois, soit le lévoglucosane et un isotope de carbone, le ^{14}C, ont été mesurés afin d'évaluer la contribution de la combustion résidentielle du bois aux $MP_{2,5.}$ Un aethalomètre a servi à mesurer le carbone noir à Riverdale.

Les concentrations moyennes et médianes étaient de 7,7 µg/m^3 et 6,4 µg/m^3 (n = 18), ainsi que de 10,2 µg/m^3 et 7,1 µg/m^3 (n = 12) dans les sites du centre-ville et de Riverdale, respectivement. Dans l'ensemble, les concentrations variaient de 1,6 µg/m^3 à un maximum de 31,3 µg/m^3 (Riverdale le 11 février), dépassant ainsi la valeur de la norme pancanadienne qui est de 30 µg/m^3. En moyenne, les matières particulaires fines à Riverdale étaient principalement composées de carbone organique (55 %), tandis que le carbone élémentaire représentait 7 %. Les concentrations hivernales de matières particulaires mesurées au cours de cette étude étaient bien plus faibles que celles trouvées lors d'études précédentes au début des années 1980 et étaient comparables aux niveaux actuels de plusieurs collectivités de l'intérieur de la Colombie-Britannique. Toutefois, les résultats de cette étude étaient supérieurs à ceux que l'on retrouve habituellement sur le site du Réseau national de surveillance de la pollution atmosphérique de Whitehorse au

cours de la période allant de janvier à mars. Dans ce cas, les facteurs de causalité résultaient probablement d'une combinaison d'un site d'échantillonnage différent et, dans une moindre mesure, de différentes méthodes de mesure.

Pour estimer la moyenne sur 24 heures des concentrations de $MP_{2,5}$ tout au long de la période d'échantillonnage, une régression linéaire simple a été utilisée afin d'établir un lien entre les données moyennes sur le carbone noir sur 24 heures (mesurées avec l'aethalomètre à Riverdale) et les concentrations de $MP_{2,5}$ moyennes quotidiennes dans les deux sites. En supposant une relation linéaire cohérente entre le carbone noir à Riverdale et les $MP_{2,5}$ dans les deux sites tout au long de la période d'étude et selon le nombre d'atomes de carbone noir mesurés, une régression linéaire simple a prédit que la valeur de la norme pancanadienne avait probablement été dépassée à cinq reprises à Riverdale (sur une période de neuf jours en février), mais pas au site du centre-ville.

Les calculs fondés sur l'analyse des données sur le ^{14}C indiquent que la contribution moyenne de la fumée de bois aux $MP_{2,5}$ varie de 70 % à 84 % (moyenne du pourcentage maximum et minimum) sur le site de Riverside. Ces résultats ont été corroborés par les données sur le lévoglucosane, qui a également indiqué une forte influence de la fumée de bois à Whitehorse. Les rapports (% p/p) entre le lévoglucosane et les $MP_{2,5}$ étaient de 4,7 ± 1,6 et de 6,0 ± 2,4 (écart-type moyen) dans le centre-ville et à Riverdale, respectivement, indiquant ainsi une contribution de la fumée de bois légèrement plus faible dans le centre-ville, qui devrait être plus élevée en raison de la circulation et du chauffage des bâtiments commerciaux. Les résultats de l'aethalomètre indiquaient également une forte présence de fumée de bois à Riverdale. Les concentrations horaires de carbone noir variaient de 0 $\mu g/m^3$ à 8,6 $\mu g/m^3$, avec une moyenne de 0,9 $\mu g/m^3$ et une médiane de 0,2 $\mu g/m^3$. D'après les observations, le signal de la fumée de bois était plus élevé tôt le matin et tard le soir. Les résultats de répartition par source obtenus dans cette étude en ce qui concerne la contribution de la fumée de bois sont relativement proches des résultats des études précédentes menées à Riverdale, de l'inventaire des émissions le plus récent fait à Whitehorse et d'une précédente étude menée en Colombie-Britannique.

Les plus fortes concentrations de $MP_{2,5}$ à Whitehorse étaient associées à des vents calmes, qui limitent la dispersion, et à de basses températures, qui sont associées à l'augmentation de la combustion du bois. Ces conditions étaient présentes les jours de forte inversion de température au niveau de la surface causée par une crête stable d'air arctique froid ou par l'affaissement soupçonné de masses d'air en provenance du sud-ouest ou de l’ouest.

Les résultats de cette étude confirment que les efforts visant à réduire les $MP_{2,5}$ en hiver à Whitehorse, surtout dans le lotissement de Riverdale, devraient prendre en compte des stratégies de réduction de la contribution de la combustion résidentielle du bois. Si des stratégies de réduction des émissions de la combustion résidentielle du bois sont mises en place, le travail à venir à Whitehorse pourrait comprendre une surveillance afin d'évaluer l'efficacité de ces stratégies. Les recherches à venir devraient idéalement comprendre une surveillance sur une période plus longue afin de mieux comprendre les répercussions de la combustion résidentielle du bois sur la qualité de l'air en saison froide à Whitehorse.

1. Introduction

1.1 Background

Residential wood combustion (RWC) in wood stoves, fireplaces and fireplace inserts, is a commonly used method for heating homes in Canada and is a significant source of fine particulate ($PM_{2.5}$) emissions. RWC accounts for 8% of all $PM_{2.5}$ emissions in Canada, or 36% when open sources are excluded (Environment Canada, 2009). In communities where RWC is used as a major heating source, this fraction can be much higher. $PM_{2.5}$ is an air pollutant of concern for human health due to its ability to penetrate deeply into the lungs, and exposure has been linked to reduced cardiovascular and lung function, increased hospitalization and increased mortality. Many studies have investigated potential health effects associated specifically with wood smoke particles and a number of comprehensive review papers on this topic have been well summarized recently (E Risk Sciences, 2009).

Whitehorse is the largest city in the Yukon Territory, having a population of 22,898 in the census metropolitan area (Statistics Canada, 2006). Like in many communities in Canada, due to the abundance of wood as an inexpensive fuel source for heating, RWC is common in Whitehorse. A 2006 emission inventory for Whitehorse (Senes, 2008), estimated that, on an annual basis, heating contributes 84% to $PM_{2.5}$ emissions, followed by fugitive dust (~9%), mobile (both on and off road sources) (~4%) and industrial point sources (~3%). Commercial buildings primarily rely on fuel oil or propane for heating while residences utilize a combination of fuels. No information on the detailed breakdown of emissions from residential heating in Whitehorse is currently available, however, the 2007 National Pollutant Release Inventory attributes 97% of $PM_{2.5}$ emissions from commercial and residential fuel burning in the *Yukon* to residential wood combustion (Environment Canada, 2009). Similarly the 2006 Whitehorse emission inventory attributes more than 98% of $PM_{2.5}$ emissions from heating to wood fuel, although the estimate is based on a study of communities in Northern BC. (Senes, 2008).

In addition to the abundance of RWC in Whitehorse, meteorology and topography also affect ambient concentrations of PM in the winter. Ambient concentrations of $PM_{2.5}$ on any given day are a function of emission levels and the degree of atmospheric dispersion present. Atmospheric dispersion is a function of both the wind speed and mixing height, with higher wind speeds and mixing heights allowing for more efficient dispersion and dilution of pollutants. In the case of RWC in Whitehorse, emission levels are expected to be inversely correlated to ambient temperature over a certain range, as more wood fuel is burned as temperatures decrease. Whitehorse, which is situated in the Yukon River Valley, has a continental arctic climate, leading to episodes of cold temperatures and surface level inversions, which inhibit the dispersion of pollutants. The subdivision of Riverdale is particularly susceptible to stagnation due to it being located in a bowl, partially encircled by an escarpment. Due to the proximity of Whitehorse to the Gulf of Alaska, however, cold stagnation episodes can be tempered by inflow of warmer maritime air masses.

The impact of RWC emissions in Whitehorse has been a concern for several decades. Poor air quality in Whitehorse in the early 1980s, particularly in the subdivision of Riverdale, prompted Environment Canada's Environmental Protection Service to commission several studies. These included a wood burning survey (Orecklin and McCandless, 1983), monitoring studies and associated data analysis over four heating seasons from 1981 to 1984 at several sites in Riverdale (Senes, 1983; McCandeless, 1984) and a legislative review and recommendations paper (Hatfield, 1984). Monitoring studies included the measurement of total suspended particulate (TSP), carbon monoxide (CO), nitrogen oxides (NOx), polycyclic aromatic hydrocarbons (PAHs) and meteorology. High concentrations of TSP (max. = 553 $\mu g/m^3$) were observed during the study with average concentrations above the Canadian 24 hour average objective of 120 $\mu g/m^3$ at one site in Riverdale for two of the heating seasons. An inverse correlation was found between TSP concentrations and wind speeds at the airport. Analysis of a subset of samples showed that 95% of the TSP was comprised of $PM_{2.5}$ and that RWC constituted the bulk of the particulate mass (McCandeless, 1984).

Recent data from the National Air Pollution Surveillance (NAPS) station in Whitehorse are shown in Figure 1. Hourly $PM_{2.5}$ data from 2001 to 2008 measured using a Tapered Element Oscillating Microbalance (TEOM), averaged over 24 hours and segregated by month show that median values are < 3 $\mu g/m^3$ throughout the year, with the large peaks in the summer months attributable to forest fires in 2003 and 2004. Despite the relatively low values measured in the winter months in recent years, local government agencies often field complaints from residents regarding wood smoke, and there is anecdotal evidence that levels may be higher in certain parts of the city, such as Riverdale, particularly during stagnation events.

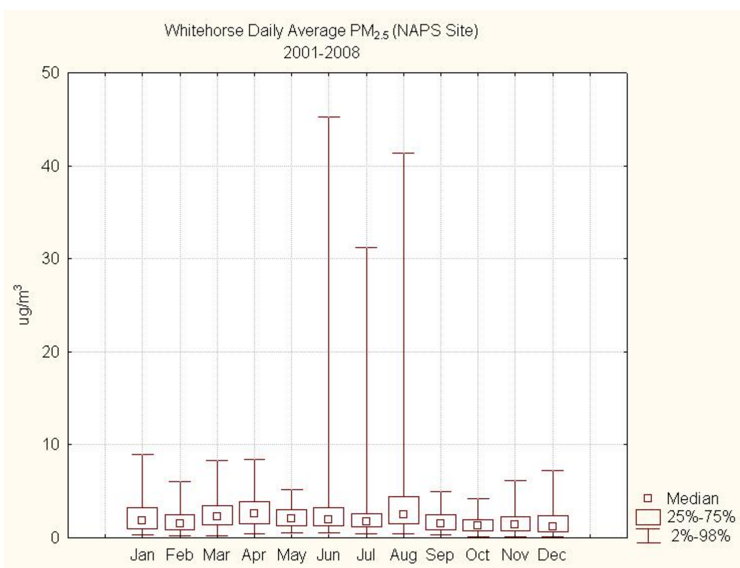


Figure 1: NAPS Daily Average $PM_{2.5}$ Data Segregated by Month (2001-2008)

1.2 Current Study

An air quality project working group, including representatives from the Pacific and Yukon Region of Environment Canada, the City of Whitehorse, Yukon Environment and Health and Social Services Yukon was convened in 2008 to discuss options for determining current impacts of RWC emissions in Whitehorse, including the subdivision of Riverdale. The objective was the development of a baseline from which to better understand the contribution of wood smoke to $PM_{2.5}$ levels in the city. Such a baseline would also help assess the effectiveness of any future intervention that may be considered for this community, such an appliance change-out program. The purpose of this study is to assess $PM_{2.5}$ levels in Whitehorse during the winter months and to quantify the contribution of wood smoke. To assess the contribution of wood smoke to $PM_{2.5}$ using a limited number of samples obtained during this short term study, three markers for wood smoke were employed: levoglucosan, ^{14}C (carbon 14) isotope and an Aethalometer, which measures black carbon.

Levoglucosan is a compound that is emitted in large concentrations during the burning of cellulose. It has no other significant sources and is relatively stable in the atmosphere after emission, making it a useful marker of a biomass burning contribution in particulate matter (Simoneit *et al.*, 1999). Several studies have made use of ambient levoglucosan concentration ratios with PM or organic carbon (OC) to identify biomass burning plumes (e.g. Leithead *et al.*, 2006; Jordan *et al*, 2006a; Puxbaum *et al.*, 2007); however, emission profiles can vary due to different burning conditions and fuel types, therefore reliance on ambient levoglucosan concentration ratios alone to estimate biomass burning contribution to PM can be subject to uncertainty (Hedberg *et al.*, 2006). However, levoglucosan data when used in combination with other methods of source apportionment can provide an estimate of relative levels of wood smoke contribution.

The measurement of the radioactive isotope ^{14}C has become an increasingly common technique used to apportion particulate matter to biomass combustion (e.g. Lewis *et al.*, 2004; Jordan *et al.,* 2006b; Szidat *et al.*, 2006; Ward *et al.*, 2006). ^{14}C decays over time (half life = 5730 yrs), therefore determining its concentration in ambient particulate matter can be used to calculate the contribution of "contemporary' or "modern" carbon versus "fossil carbon". Fossil fuels contain no ^{14}C and thus are termed "fossil carbon" sources, while biomass has a much higher content due to recent incorporation of ^{14}C from the atmosphere and are thus termed "modern" sources. The ^{14}C content of the particulate matter, which can be expressed as a fraction of modern carbon (f_m), can therefore be used to determine the extent to which the particulate matter carbon originated from fossil fuel combustion versus biomass burning combustion.

The third method used to distinguish particulate emitted by RWC was a dual wavelength aethalometer. The aethalometer measures the attenuation of light at two different wavelengths by particulate that have been collected on a filter tape. Absorption at 880nm is calibrated to give a concentration of Black Carbon (BC), while increased absorption at the wavelength of 370nm (UV) relative to 800nm, due to certain aerosol components of wood smoke, has been shown to provide a qualitative indicator of the presence of wood smoke (Allen, 2004; Jeong *et al.*, 2004; Park *et al.*, 2006)

2. Methodology

2.1 Sampling sites

Sampling for this study was conducted at two sites in the city of Whitehorse – one in the downtown core and one in the neighbourhood of Riverdale. The city is located along the Yukon River, approximately 150km northeast of the waters of the Gulf of Alaska. The Yukon River runs from SSE to NNW to the east of the downtown core as seen in Figure 2, and is approximately 620m above sea level. To the west of downtown area an escarpment rises to a height of approximately 700m above sea level upon which Whitehorse Airport is located. The subdivision of Riverdale is on the eastern bank of the Yukon River southeast of the downtown area. Riverdale is situated in a bowl with an escarpment partially encircling the subdivision to the south and east.

Figure 2: Whitehorse Sampling Sites (Image from Google Earth)

The locations of the sampling sites are shown in Figure 2. The sampling site in downtown Whitehorse (DT) was located at the Wood Street Annex School, at Wood Street and 4th Avenue (60° 43' 12.1" 135° 03' 31.4"). Sampling took place on the rooftop, approximately 8m above ground level. The area surrounding the sampling site in downtown Whitehorse is mix of residential and commercial development. The Riverdale site (RD) was located on the rooftop of Vanier Senior Secondary School at 16 Duke Street (60° 42' 9.0" 135° 01' 46.0"), approximately 2.5km southeast of the downtown sampling site, with sampling taking place approximately 4m above ground level. The surrounding area is residential consisting primarily of detached homes and some apartment buildings. Both buildings upon which the samplers were located are heated by diesel boiler, with exhaust chimneys on the roof. Impact to the samplers was expected to be minimal however, as the chimneys were approximately 50m away, above the level of the sampling inlets and not located in the predominant upwind direction.

2.2 Sampling and Analysis

2.2.1 $PM_{2.5}$ Filter Based Sampling

Integrated 24-hour ambient $PM_{2.5}$ samples were collected using Partisol 2000H samplers (Thermo Scientific, Waltham, MA), following a 1 day in 3 schedule (midnight to midnight) for two months from January 24 to March 22, 2009 for a total of 20 sampling events. One Partisol sampler (Sampler A) was located at the Downtown site, sampling a single Teflon filter for each sampling event, which was subsequently analysed for $PM_{2.5}$ mass and levoglucosan. Two Partisol samplers were located at the Riverdale site. One sampler (Sampler B) was modified to house a dual stage filter pack. A Teflon front filter was analysed for $PM_{2.5}$ mass and levoglucosan, while the back-up quartz filter was analysed for organic and elemental Carbon (OC/EC). A second Partisol sampler (Sampler C) at the Riverdale site employed a single quartz filter which was subsequently analysed for OC/EC and ^{14}C. OC results from this sampler were corrected for positive artifacts by subtracting the value from the back-up quartz filter on Sampler B.

All filters were prepared at Chester Labnet (Tigard, Oregon) and sent to Whitehorse in coolers on ice. Filters were stored in a freezer at the Environment Canada office until the day prior to sampling. After sampling, all filters were wrapped in aluminum foil and stored in a freezer, prior to shipping to the laboratory on ice.

All Teflon filters were analysed for $PM_{2.5}$ mass by gravimetry at Chester Labnet and subsequently sent to the University of British Columbia School of Environment Health Laboratory (Vancouver, BC) for analysis of levoglucosan by gas chromatography mass spectrometry (GC/MS) following a modified version of a method developed by Simpson *et al.,* (2004).

A 1.5 cm^2 punch from all quartz filters were analysed for OC/EC at Chester Labnet by thermal optical transmittance (TOT) using the NIOSH Method 5040 temperature program. The remainder of the quartz filters from Sampler C were sent to the University of Arizona Accelerator Mass Spectrometry Laboratory Facility for analysis of ^{14}C by a method described by Ward *et al*., (2006).

2.2.2 Continuous Measurements

In addition to filter based sampling at the Riverdale site, a Magee Scientific AE-21 Dual Wavelength aethalometer (Magee Scientific Company, Berkeley, CA) with a $PM_{2.5}$ sharp cut cyclone was installed to continuously measure black carbon (BC) at 880nm and 370nm (UV channel). The aethalometer was set up in a ground floor room with the inlet line running outside to a height of ~4m through a ventilation duct. Sampling took place from January 27 to March 31, 2009.

Meteorological sensors were installed adjacent to the Partisol samplers at both sites to measure hourly temperature and wind speed/direction from January 26 to March 31, 2009. Sensors were mounted on 2 metre poles, therefore winds were measured at approximately 10m and 6m above ground level at the Downtown and Riverdale sites, respectively. In addition, temperature, 10m winds and twice-daily sounding data from the Environment Canada climate station at Whitehorse Airport were used in this study.

2.2.3 Quality Control

Two field blank samples were taken for each sampler. $PM_{2.5}$ mass, levoglucosan and OC/EC results were corrected for these blank values, while ^{14}C results were corrected based on laboratory blank filters. One duplicate sample was taken to assess any differences in comparing results from a standard Partisol 2000 set-up to that to with the filter pack set-up. Results for the duplicate sample were 7.1/8.1 $\mu g/m^3$ and 552/590 ng/m^3 for $PM_{2.5}$ and levoglucosan, respectively. Average laboratory surrogate recoveries for levoglucosan were 105%; results were not recovery corrected.

3. Results and Discussion

3.1 Meteorology

Meteorological data from the study period is show in Figures 3 and 4(a, b, c). Temperatures remained below freezing for most of the sampling campaign, with an average of -12 °C at the two sites. Average temperatures at the airport were -18.2, -16.0 and -9.9 for January, February and March, respectively, making it a slightly colder winter than the 30 year period from 1971 to 2000, (-17.7° C, -13.7° C and -6.6° C for January, February and March, respectively).

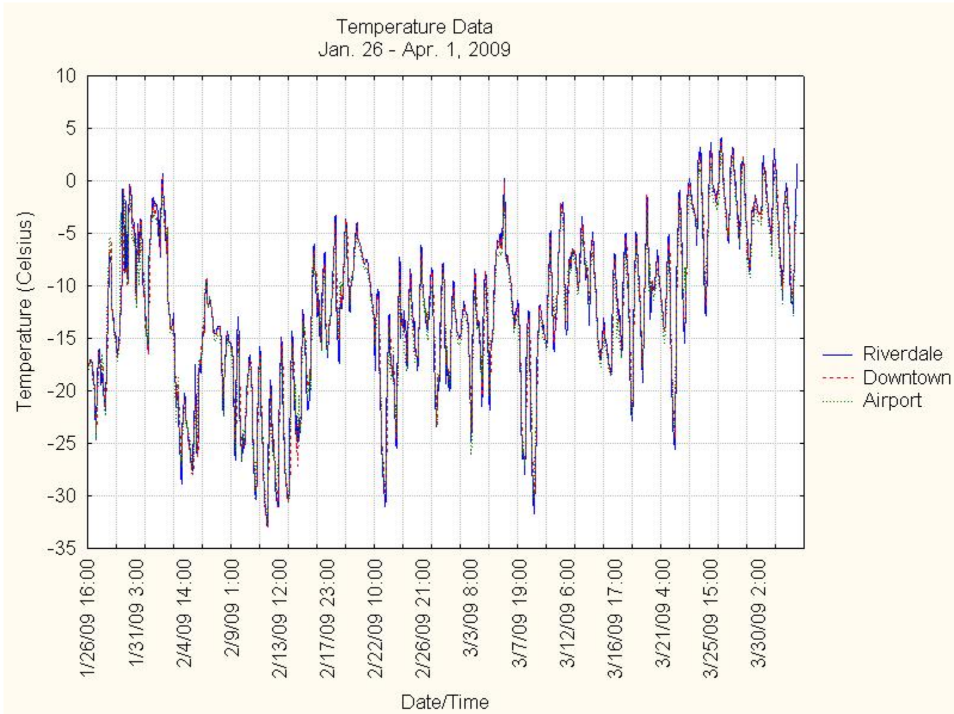
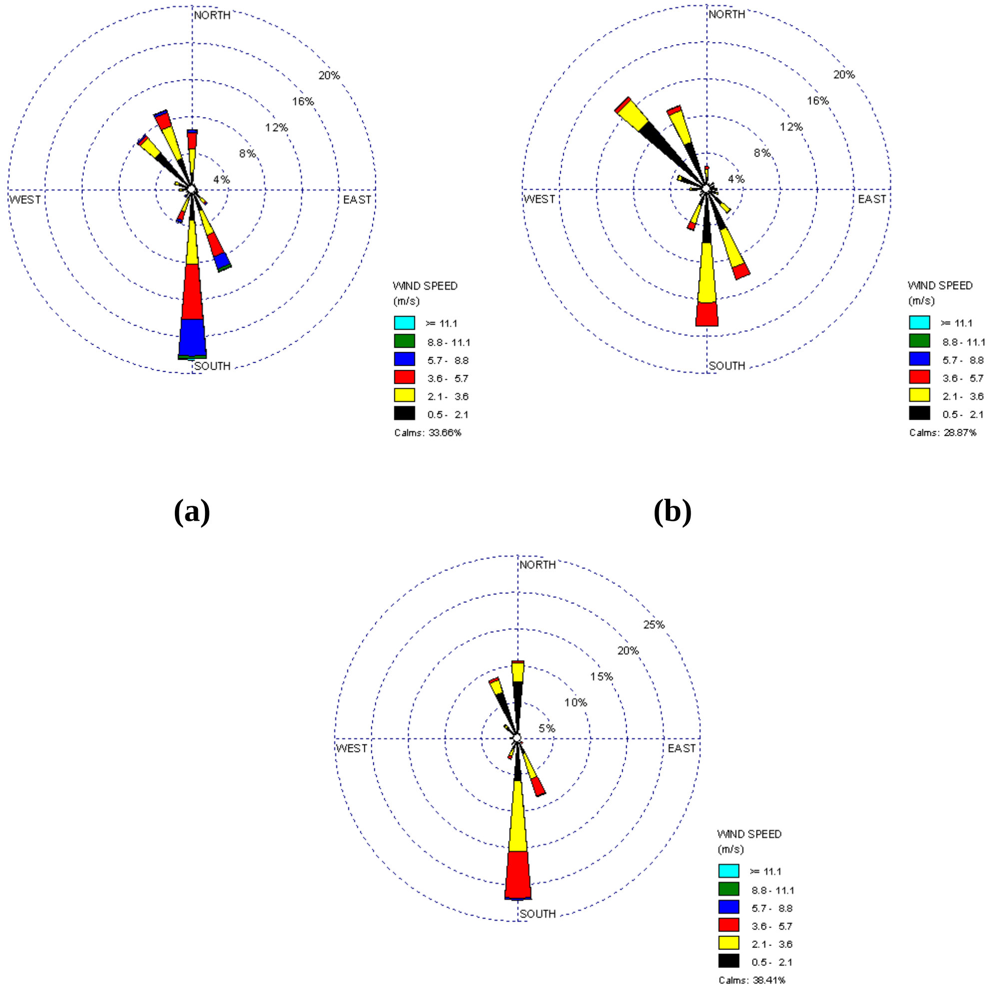


Figure 3: Hourly Temperature Data During the Sampling Period

Winds roses show similar distribution of wind directions at the two sampling sites, with the winds generally following the topography of the Yukon River Valley. The Downtown site had a higher frequency of stronger winds than Riverdale, which is more sheltered by the escarpment. Downtown, having a primarily south, and to lesser extent south-southeast wind contribution, could be impacted by emissions in Riverdale. Similarly, Riverdale, having a significant NW and NNW wind contribution could be impacted by emissions from the downtown core. Whitehorse Airport shows a similar wind vector distribution to the Downtown site but with a higher predominance of winds from the south. This site, being atop the escarpment, is not as affected by the local topography.



(a) **(b)**

(c)

Figure 4: Wind Roses for the Sampling Period for: Downtown (a), Riverdale (b) and (c) Whitehorse Airport

3.2 $PM_{2.5}$ Results

3.2.1 Measured $PM_{2.5}$

All $PM_{2.5}$ and OC/EC concentration results are shown in Table 1. Several sampling events were missed or had to be discarded due to inclement weather and sampler problems. Average / median concentrations were 7.7 / 6.4 $\mu g/m^3$ (n=18) and 10.2 / 7.1 $\mu g/m^3$ (n=12) at the Downtown and Riverdale sites, respectively. Higher concentrations at Riverdale are likely the result of lower wind speeds and presumably closer proximity to wood smoke sources, although such a detailed emission inventory was not undertaken as part of this study. A partial $PM_{2.5}$ mass reconstruction at the Riverdale site shows that, on average (n=12), carbon made up the bulk of the $PM_{2.5}$ mass, with OC contributing

55% and EC contributing 7%. The remaining 38% would be made up of atoms associated with OC as well as inorganic species.

Overall, $PM_{2.5}$ concentrations ranged from 1.6 µg/m^3 to a maximum of 31.3 µg/m^3 (Riverdale on February 11). The City of Whitehorse or Yukon Territory do not have air quality standards or objectives in place for $PM_{2.5}$. The Canada Wide Standard for 24 hr average $PM_{2.5}$ is 30 µg/m^3, based on the 98th percentile, averaged over 3 consecutive years, while British Columbia has established a 24 hr average $PM_{2.5}$ objective of 25 µg/m^3 and an annual average objective of 8 µg/m^3. For comparison, average January to March $PM_{2.5}$ concentrations for a selection of interior B.C. cities and towns are shown in Table 2.

Table 1: $PM_{2.5}$ and OC/EC results

Date	$PM_{2.5}$ (µg/m^3)		OC (µg/m^3)	EC (µg/m^3)
2009	**Downtown**	**Riverdale**	**Riverdale**	**Riverdale**
1/24	2.4	1.6	0.5	0.1
1/27	6.3	7.1	5.8	0.9
1/30	2.2	1.6	0.6	0.1
2/2	1.7	nd	1.1	0.1
2/5	13.5	nd	12.1	1.5
2/8	6.9	nd	8.0	1.4
2/11	nd	31.3	18.5	2.4
2/14	nd	19.9	12.5	1.2
2/17	21.0	nd	18.8	2.3
2/20	11.3	nd	9.3	1.0
2/23	15.3	nd	15.3	2.2
2/26	1.9	nd	1.5	0.1
3/1	12.8	nd	nd	nd
3/4	12.0	12.5	7.2	0.8
3/7	5.4	9.8	5.5	0.5
3/10	6.3	7.2	4.1	0.4
3/13	6.5	7.0	4.2	0.7
3/16	2.0	2.0	0.7	0.1
3/19	5.0	6.0	4.2	0.4
3/22	6.9	21.9	11.6	1.0
Avg.	**7.7**	**10.2**	**7.4**	**0.9**
s.d.	**5.4**	**8.6**	**6.0**	**0.8**

nd = no data

Table 2: Average Jan – Mar $PM_{2.5}$ 2001-2008 at selected interior B.C. communities (Environment Canada, 2010)

Location	$PM_{2.5}$ (µg/m^3)
Golden[1]	10.2
Kelowna	5.7
Prince George	9.8
Quesnel	8.7
Williams Lake	8.2

[1] Data from 2003 – 2007 only

$PM_{2.5}$ results from this study are higher than typically found at the Whitehorse NAPS site for the January to March period (see Figure 1). A comparison between $PM_{2.5}$ measurements taken Downtown (filter-based) with the NAPS site (TEOM) was made for the 9 sampling days where there were concurrent data available (Figure 5). The correlation is poor, with the filter based sampler generally reading higher. It is difficult to make conclusions based on a small data set, however the different locations are likely a factor (see Figure 2). Although both sites are located in the downtown core, the NAPS station is adjacent to the river and may sample cleaner river-channeled winds relative to the Downtown site, which was located approximately 500m away. An additional causative factor could be that TEOMs read lower than filter-based samplers in cold winter locations due to the loss of volatile particulate matter (Allen *et al*., 1997; Dann *et al*., 2006). Coincidentally, the NAPS station will be moved to a new downtown site in 2011, one block from the Wood Street Annex.

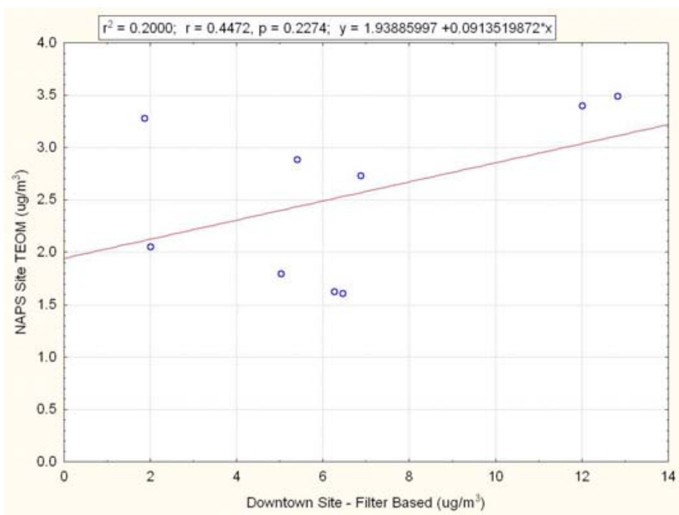
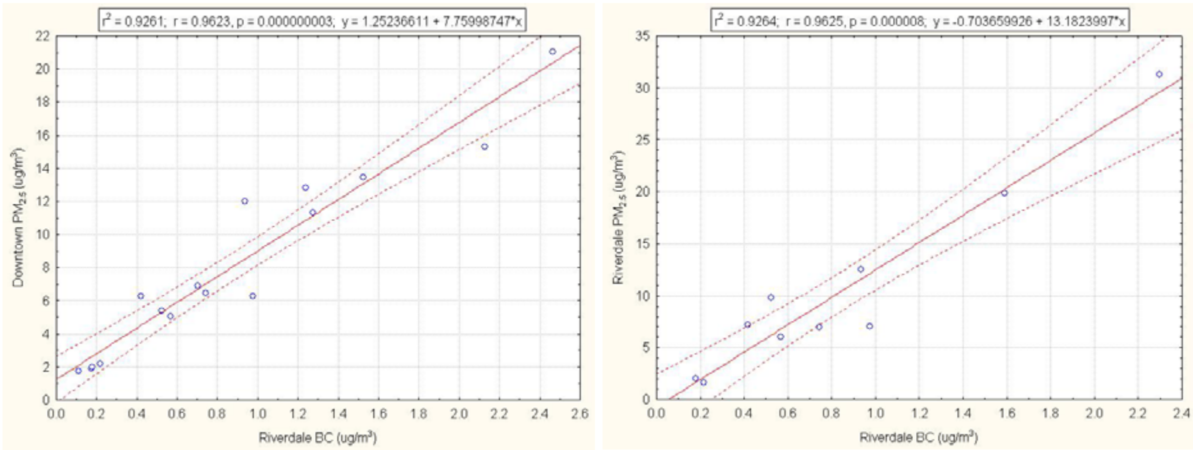


Figure 5: Correlation of $PM_{2.5}$ Results for Downtown site (filter based) and NAPS Site (TEOM)

3.2.2 Modelled $PM_{2.5}$

To estimate the 24 hour average concentrations of $PM_{2.5}$ throughout the sampling period, a simple linear regression model was used to relate 24 hour average black carbon data, measured by the aethalometer at Riverdale, to daily average $PM_{2.5}$ concentrations measured at the two sites (Figure 6 a and b). One outlier point (where the standard residual was greater than 2σ) was removed for each regression. The regressions show a good fit with r^2 values of 0.93 and very low statistically significant p values for both Downtown and Riverdale.



(a) **(b)**

Figure 6: Black Carbon-$PM_{2.5}$ Correlation at Downtown (a) and Riverdale (b)

Assuming a consistent linear relationship between Riverdale black carbon and $PM_{2.5}$ at both sites throughout the study period and within the range of black carbon measured, daily average $PM_{2.5}$ concentrations can be predicted from the linear regression, from January 27th to March 31st. Predicted values and associated 95% confidence intervals along with the observed values are shown in Figure 7. It can be seen that there are five days at Riverdale where $PM_{2.5}$ is predicted to have exceeded the value of the Canada Wide Standard, all occurring during a 9 day period in February, with a maximum predicted $PM_{2.5}$ concentration of 41.7 µg/m^3 (95% CI = 33.1 - 47.4) on February 13th. At the Downtown site the maximum was predicted to be 25.4 µg/m^3 (95% CI = 22.5 – 28.3), also on February 13th.

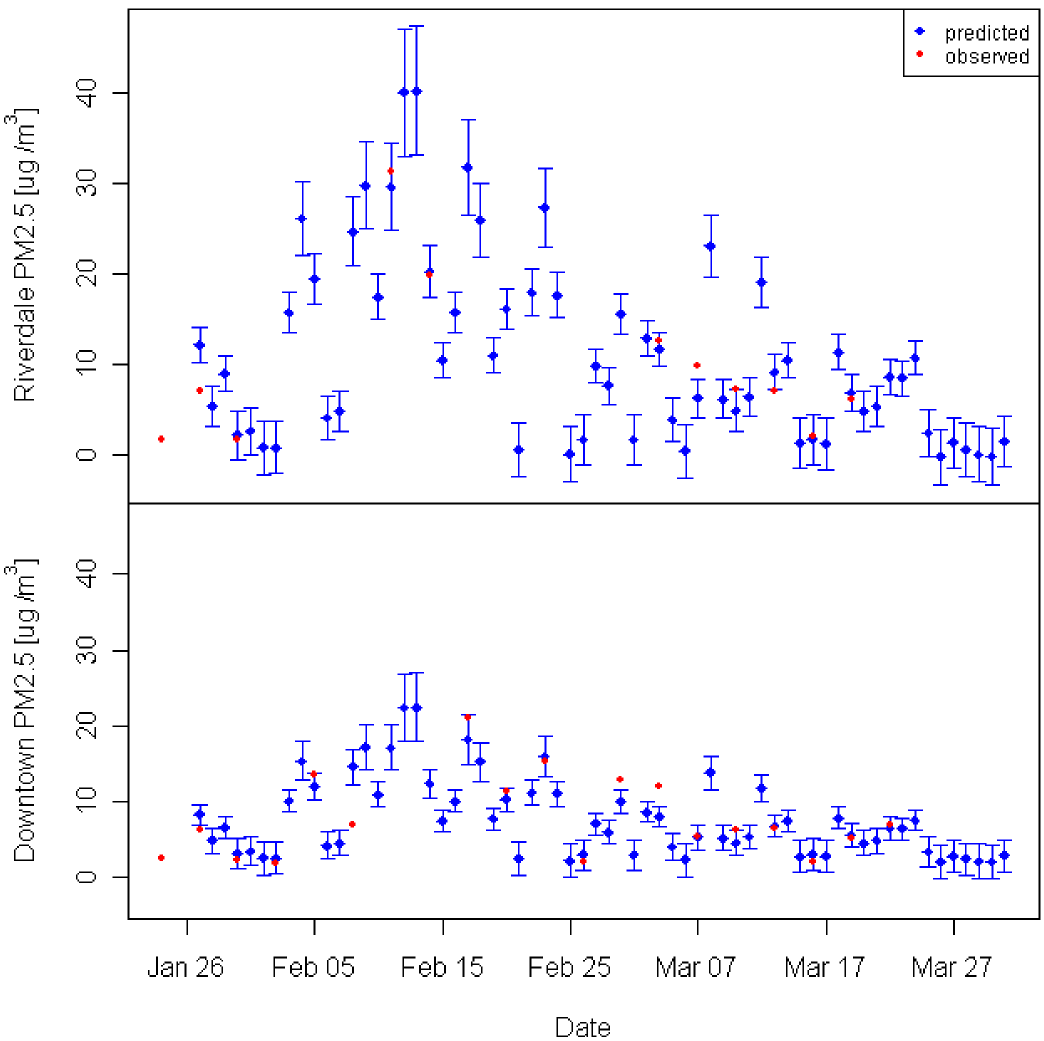


Figure 7: Predicted and Observed 24 Hour Average $PM_{2.5}$ Concentrations at Downtown and Riverdale (error bars on predicted values are 95% confidence intervals).

3.3 Source Apportionment of $PM_{2.5}$

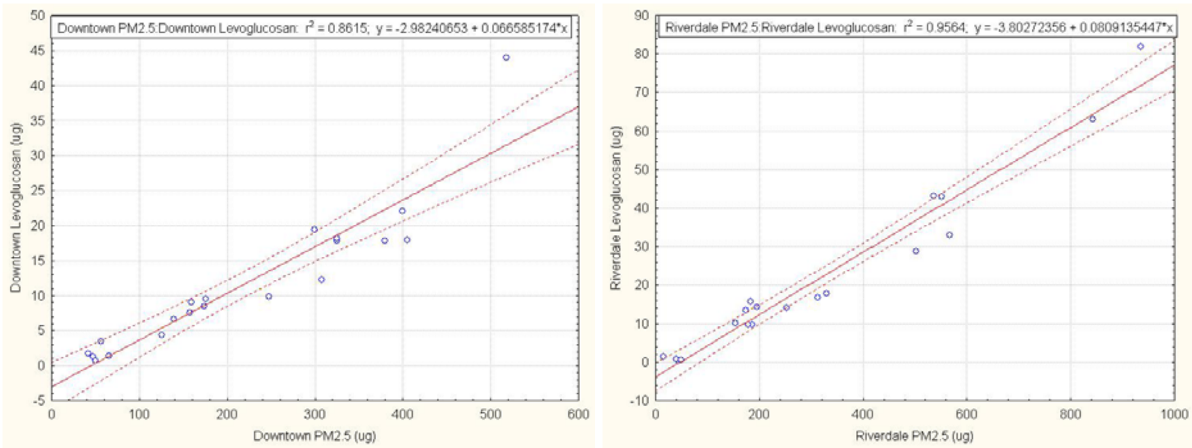
3.3.1 Wood Smoke Markers

All levoglucosan and ^{14}C results are shown in Table 3. Average concentrations of levoglucosan were 453 and 754 ng/m^3 at Downtown and Riverdale, respectively, but varied widely from sample to sample, as the concentration of $PM_{2.5}$ varied substantially over the course of the study. Ratios (% w/w) of levoglucosan to $PM_{2.5}$ were 4.7 ± 1.6 and 6.0 ± 2.4 (avg. ± s.d.) at Downtown and Riverdale, respectively, indicating a slightly higher wood smoke contribution at Riverdale. Note that to allow for more data points in calculating the ratios, damaged filters were included, as it was assumed that the ratio between $PM_{2.5}$ and levoglucosan mass would not be affected. Correlations of levoglucosan to $PM_{2.5}$ mass at both sites are shown in Figure 8. A stronger correlation for the Riverdale site ($r^2 = 0.96$) indicates that there is less variability in source contribution here compared to the Downtown site ($r^2 = 0.86$), which is expected to have more contribution from traffic and heating from commercial buildings.

Table 3: Levoglucosan and Carbon-14 Results

Date	Levoglucosan (ng/m^3)		Levo:$PM_{2.5}$ (% w/w)		Fraction of Modern Carbon (f_M)	Min. Wood Smoke (%)	Max. Wood Smoke (%)
2009	**DT**	**RD**	**DT**	**RD**	**RD**	**RD**	**RD**
1/24	50	16	2.1	1.0	nd	nd	nd
1/27	249	604	4.0	8.6	0.85	61	73
1/30	135	31	6.1	1.9	nd	nd	nd
2/2	74	nd	4.3	9.2	nd	nd	nd
2/5	741	nd	5.5	5.7	1.00	76	91
2/8	370	nd	5.4	5.4	0.91	67	81
2/11	nd	2344	4.7	7.5	1.01	77	93
2/14	nd	1599	5.5	8.0	1.01	76	92
2/17	1781	nd	8.5	8.8	1.01	77	93
2/20	731	nd	6.5	nd	0.98	73	88
2/23	678	1314	4.4	5.8	0.97	74	89
2/26	49	nd	2.6	nd	0.88	62	74
3/1	714	nd	5.6	nd	nd	nd	nd
3/4	480	672	4.0	5.4	0.92	67	81
3/7	258	544	4.8	5.6	0.95	69	83
3/10	357	373	5.7	5.2	0.93	65	79
3/13	312	382	4.8	5.5	0.87	61	73
3/16	26	22	1.3	1.1	nd	nd	nd
3/19	177	399	3.5	6.6	0.92	65	78
3/22	336	1701	4.9	7.8	1.01	76	92
Avg.	**453**	**724**	**4.7**	**6.0**		**69.7**	**84.0**
s.d.	**411**	**752**	**1.6**	**2.4**			

nd = no data



(a) **(b)**

Figure 8: Levoglucosan-$PM_{2.5}$ Correlation at Downtown (a) and Riverdale (b)

The fraction of modern carbon (f_m) results as determined by the University of Arizona Accelerator Mass Spectrometry Facility are shown in Table 3. Due to high uncertainties at low filter loadings, sample filters having less than 100µg of carbon were not included. While there can be several sources of modern carbon particulate in addition to wood smoke, such as cooking, cigarette smoke and secondary biogenic aerosols, it can be assumed that the former two are negligible compared to wood smoke in Whitehorse. The average OC:EC ratio was 8.9 in this study, indicating that secondary organics were present (Ward *et al*., 2006), however it is likely a reasonable assumption that at temperatures typical of the sampling period the biogenic contribution to secondary aerosol formation is low. One uncertainty associated with using the ^{14}C method for source apportionment is the need to determine the theoretical fraction of modern carbon that should be present in wood typically burned in Whitehorse. ^{14}C levels in the atmosphere have varied over time, peaking in 1965 due to nuclear testing and declining since then (Ward *et al*., 2006). The fraction of modern carbon found in trees, which incorporate ^{14}C through respiration of CO_2, therefore will be dependant on the age of the wood. In calculating the contribution of wood smoke shown (Table 3), the laboratory used annual atmospheric ^{14}C levels over the last 130 years. The minimum and maximum % wood smoke were determined from calculations using average atmospheric values of ^{14}C for the last 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120 and 130 years. Given that the range of age of the dead wood harvested in the southern lakes area for fuel wood in Whitehorse is 60 to 120 years (K. Price, pers. comm., 15 Jan. 2010), this calculation should provide a reasonable estimate of wood smoke contribution for this study. Wood smoke contribution ranged from 61% to 93% with an average range of 70-84%. It is expected that in the wintertime in Whitehorse, the dominant source of wood smoke is RWC. The only other source of wood combustion are industrial/commercial wood boilers, however, these units are relatively few in number and are not expected to be a significant source of wood smoke relative to RWC, particularly in Riverdale.

The results of this study are in relatively close agreement to earlier studies in Riverdale in which chemical mass balance modeling (CMB) showed RWC constituted 90% of particulate mass, results which were confirmed with ^{14}C analysis, showing that nearly all aerosol carbon was from modern sources (McCandless, 1984). Results are also in close agreement with the most recent emission inventory for Whitehorse, which estimated that 82% of $PM_{2.5}$ is attributable to wood combustion for heating (Senes, 2008), although this number is projected to be higher for the winter season.

Table 4 shows levoglucosan concentration and source apportionment results for some recent studies in western North America. Results from the current study are comparable to results from a study in Golden, BC, which determined the wood burning contribution to $PM_{2.5}$ using PMF modeling. It is expected that wood burning conditions in Golden would be similar to those in Whitehorse. In addition, both the Golden and Prince George studies used the same laboratory for levoglucosan analysis as the current study making results directly comparable.

Table 4: Ambient wintertime levoglucosan concentrations and levo/$PM_{2.5}$ ratio

Study Location	[Levoglucosan] (ng/m^3) (avg ± sd)	[Levo]/[$PM_{2.5}$] (%) (avg ± sd)	Wood burning Contribution to $PM_{2.5}$	Reference
Golden, BC [1]	1020 ± 478	5.1 ± 1.1	74% [a]	Jeong *et al.*, 2008
Prince George, BC [2]	255 ± 249	1.6 ± 0.9	24% [b]	STI, 2008
Seattle, WA [3]	227 ± 155	2.2 ± 1.2	23% [c]	Onstad and Simpson, 2008
Libby, MT [4]	2840 ± 860	10	82% [d] 78-82% [e]	Ward *et al.*, 2006
Whitehorse, YK				
Downtown	453 ± 411	4.7 ± 1.6	-	This study.
Riverdale	724 ± 752	6.0 ± 2.4	70-84% [f]	

[1] December 2004 to February 2005 (n = 24)
[2] December to February 2004/2005 and 2005/2006 (n = 47)
[3] October to February 2004/2005 and 2005/2006 (n = 39)
[4] November to February 2003/2004 (n = 19)
[a] PMF December to February 2004/2005 and 2005/2006. Note: 74% includes both wood burning and winter heating factors (which may include some gas furnace heating)
[b] PMF December to February 2004/2005 and 2005/2006
[c] Results were scaled from subset of "high wood smoke days". The scaling factor was determined from PMF
[d] Chemical Mass Balance modeling
[e] ^{14}C dating to determine wood smoke contribution
[f] ^{14}C dating to determine wood smoke contribution

3.3.2 Aethalometer Black Carbon

Five minute average Aethalometer BC and UV minus BC data from Riverdale for the duration of the study are shown in Figure 9. Concentrations of BC ranged from 0 to 8.6 $\mu g/m^3$ with an average of 0.9 $\mu g/m^3$ and a median of 0.2 $\mu g/m^3$. BC results correlated well with the co-located filter based EC results ($r^2 = 0.94$). It can be seen that UV-BC is greater than 0 much of the time, particularly during BC peaks, indicating that the driving factor of high BC concentrations is wood smoke. Diurnal and weekly concentration patterns are also indicative of wood smoke source (Figure 10 and 11). Both the diurnal BC and UV-BC show a pattern that is typical of home heating with concentrations rising in the early morning as residents start up their wood stoves, falling off in the late morning through the afternoon and rising again in the early evening. The daily BC shows lower concentrations on Friday and Saturday, presumably due to residents being out of the house more on these evenings. If there was a significant traffic impact at this site one would expect Saturday and Sunday concentrations to be lower.

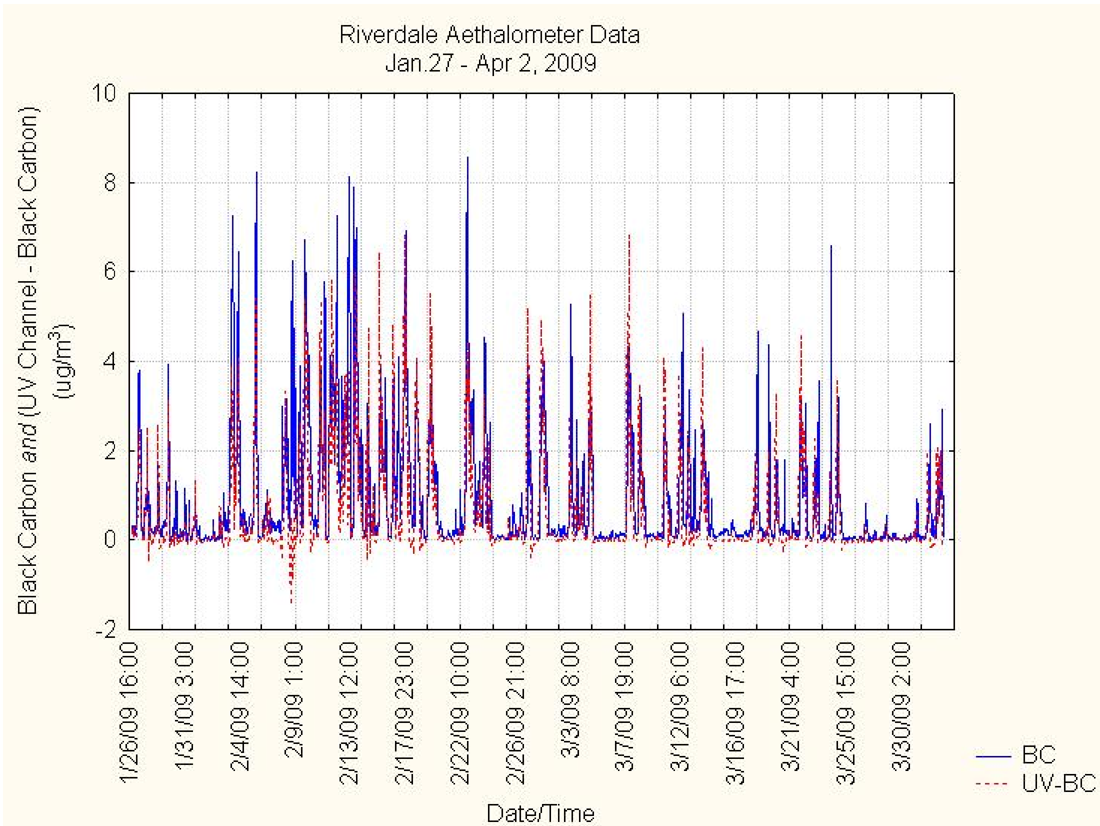
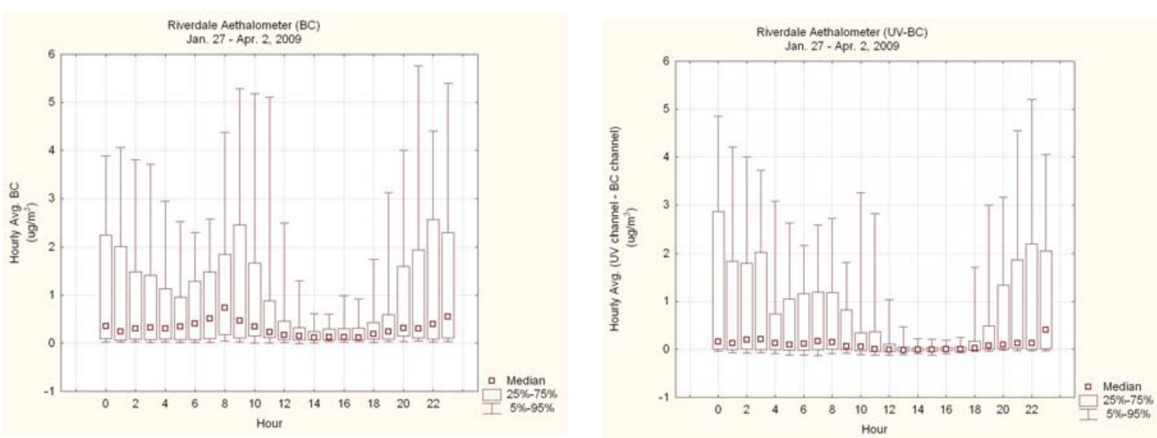


Figure 9: Aethalometer Data at Riverdale



(a) **(b)**

Figure 10: (a) Diurnal Aethalometer BC and (b) UV-BC data from Riverdale

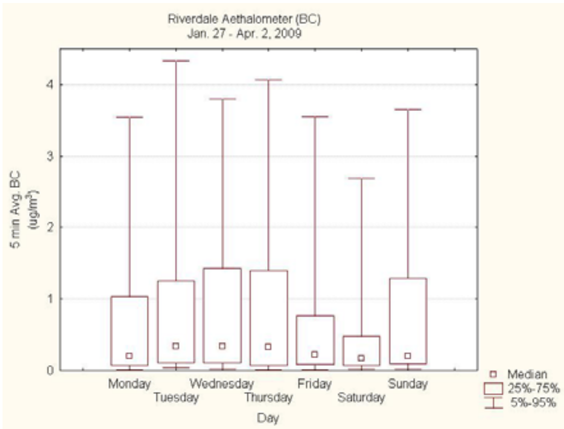


Figure 11: Weekly Aethalometer BC Data from Riverdale

3.4 Episode analysis

Meteorological data from the five days having the highest $PM_{2.5}$ as predicted by linear regression modeling with black carbon data (Sec. 3.2.2) at Riverdale are summarized in Table 5. These days are characterized by having average to well below average daily average temperatures and low daily average wind speeds. The mixing heights and ventilation index, calculated using data generated from Environment Canada's GEM-Regional forecast model at the time of daily maximum temperature, are also low on these five days, creating ideal conditions for accumulation of wood smoke in the Whitehorse area (note: Ventilation Index values from 0 to 33 are categorized as "Poor", 34 to 54 as "Fair" and 55 to 100 as "Good" ventilation). RWC contribution at Riverdale determined on two of the days is higher than average, indicating again that this source can be an important factor in causing higher $PM_{2.5}$ concentrations.

Table 5: Data from five days predicted to have the highest $PM_{2.5}$

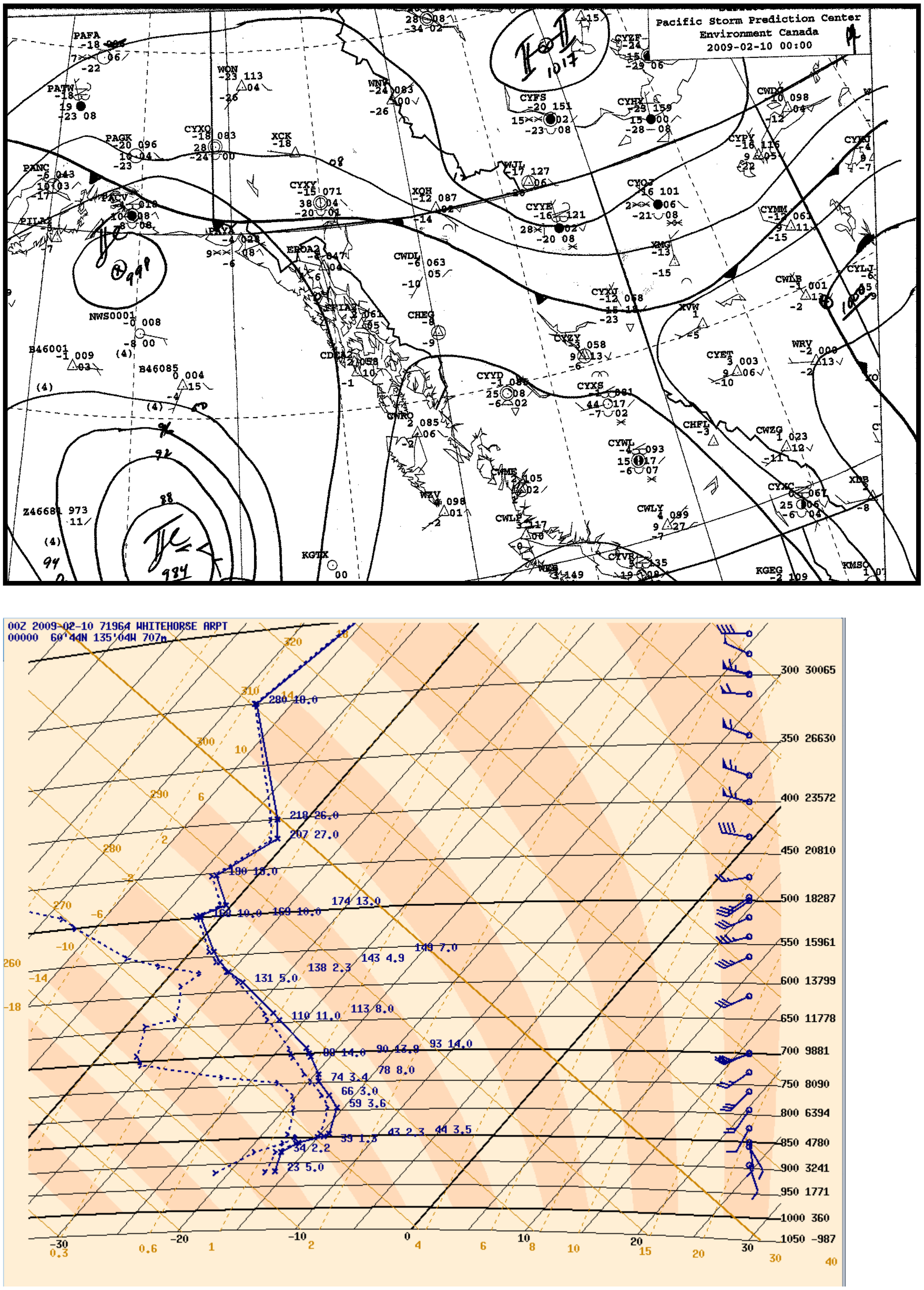
Date	$PM_{2.5}$ (µg/m³)		Temperature (°C)			Wind Speed (m/s)			Modeled Mixing Height (m)	Modeled Ventilation Index	Wood Smoke (%)
2009	**DT**	**RD**	**DT**	**RD**	**YXY**	**DT**	**RD**	**YXY**	**YXY**	**YXY**	**RD**
2/9	19	31	-19.8	-19.9	-20.5	0.5	<0.5	<0.5	182	14	Not determined
2/11	19	31	-24.1	-24.1	-23.8	0.7	0.5	1.0	184	21	77-93
2/12	25	41	-27.0	-26.6	-27.1	0.5	<0.5	0.0	174	14	Not determined
2/13	25	42	-24.1	-24.3	-23.6	0.8	0.7	1.4	138	20	Not determined
2/17	20	33	-12.2	-12.2	-12.5	0.6	0.5	<0.5	127	12	77-93

Over the course of this study there were 14 days having similar meteorological conditions, which appear to be conducive to elevated $PM_{2.5}$ (daily average temperature at YXY <10 °C, daily average wind speed at YXY <1.5 m/s and poor ventilation at YXY) Riverdale BC concentrations on these 14 days ranged from a minimum of 0.73 µg/m³ to a maximum of 3.11 µg/m³, corresponding to predicted $PM_{2.5}$ concentrations of 10.3 µg/m³ (95% CI = 7.0 - 10.8) to 41.7 µg/m³ (95% CI = 33.1 - 47.4) at Riverdale and 6.9 µg/m³

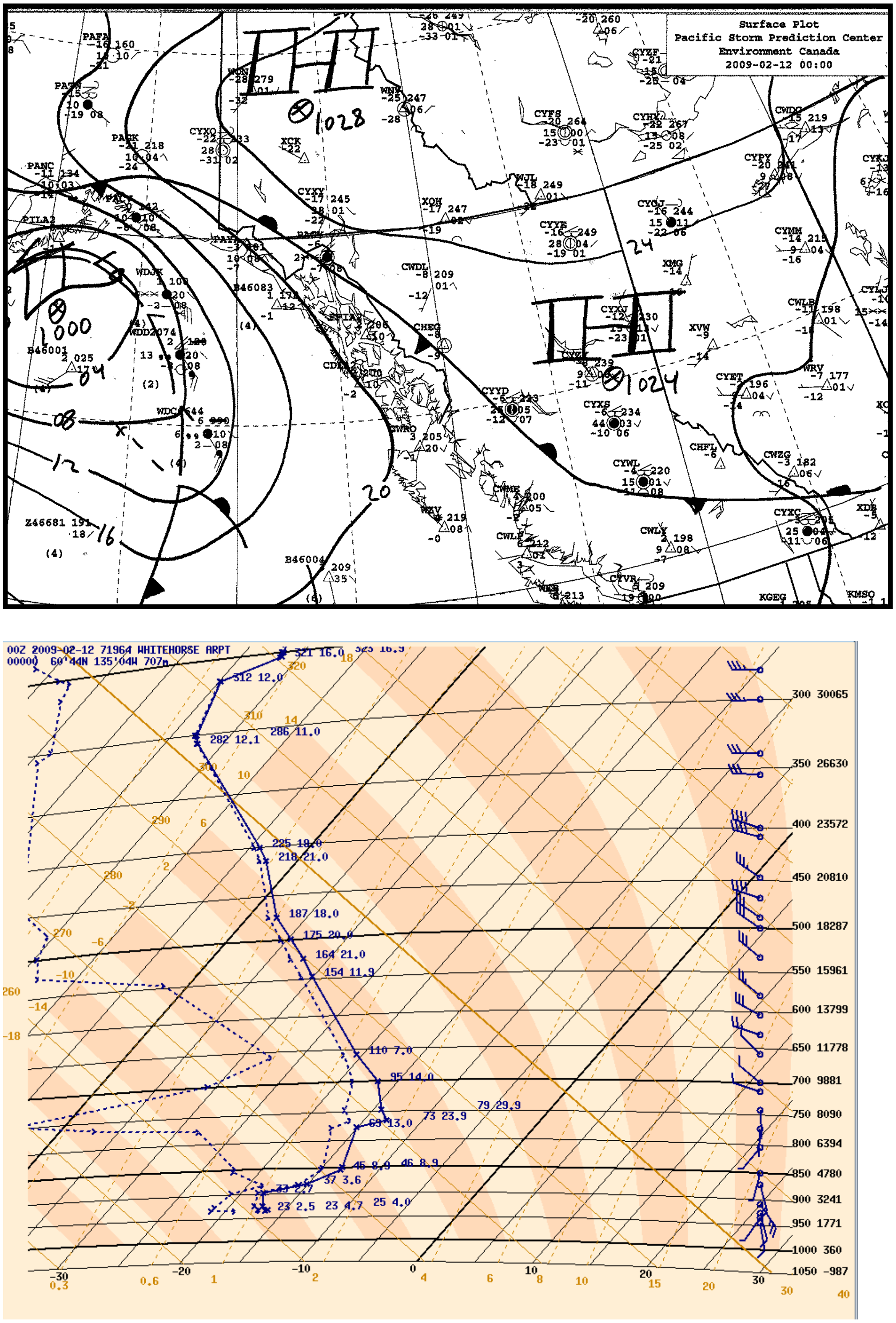
(95% CI = 6.0 - 7.8) to 25.4 μg/m^3 (95% CI = 22.5 – 28.3) at Downtown. For the months of January, February and March there were 24 days where these meteorological conditions were met, compared to 12 days over the same period in 2008 and 7 days over the same period in 2010.

Figures 12a, b, c, d and e show the surface weather maps over north western Canada and the temperature soundings from Whitehorse Airport (YXY) at 4pm local time for the five days listed in Table 5. Soundings show the existence of surface level temperature inversions on all five days, leading to the stable conditions observed which would further explain the high predicted $PM_{2.5}$ values. Observations from February 11th, 12th and 13th show the presence of a strong stable ridge of cold arctic air and a particularly strong surface level inversion. February 9th and 17th show a different synoptic pattern, however, strong winds from the southwest and west at 500mb height on these days could be causing subsidence as air flows over the coastal mountain range, which would lead the observed surface level inversions, and stable conditions.

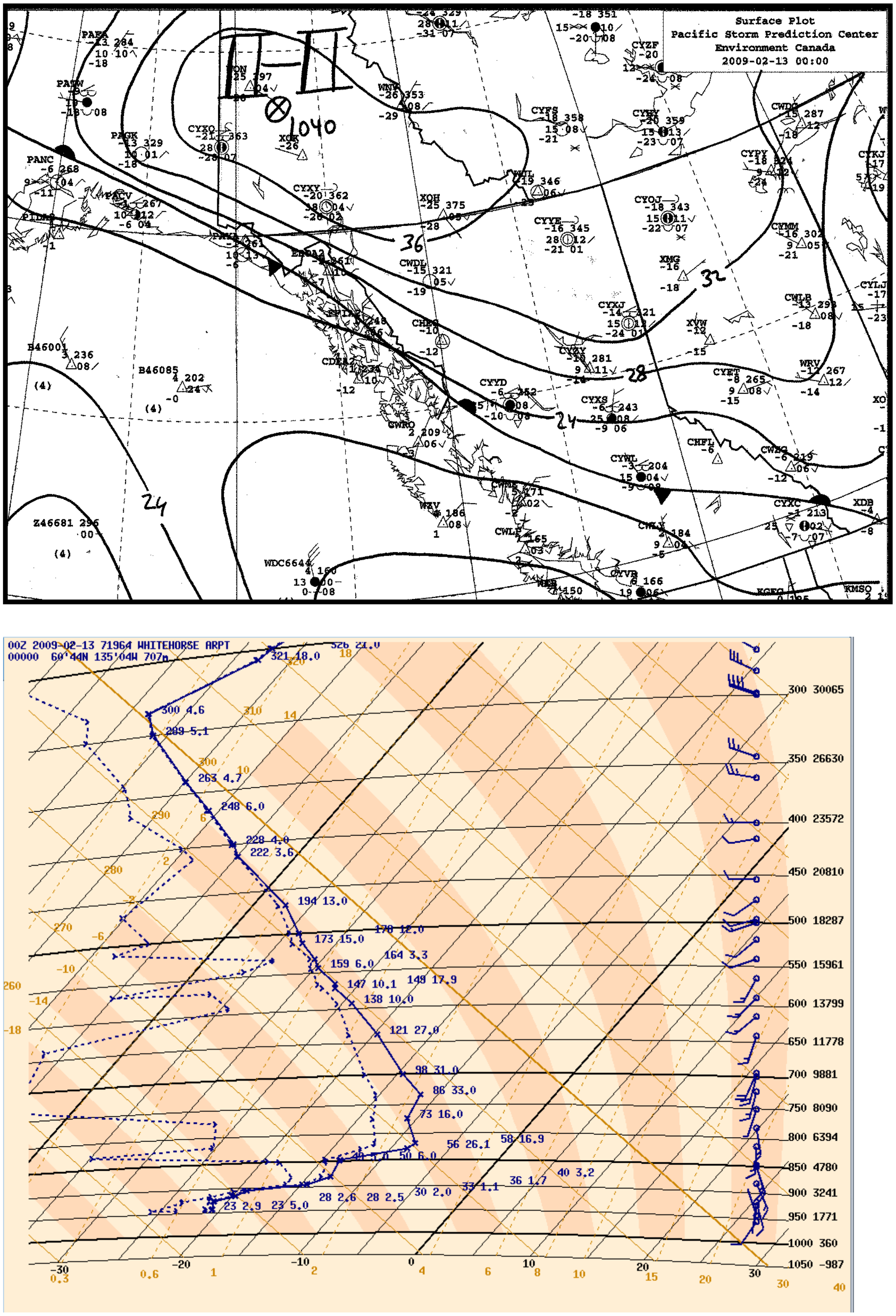
Figure 12(a, b, c, d and e): Environment Canada Surface Weather Maps and Temperature Sounding Data



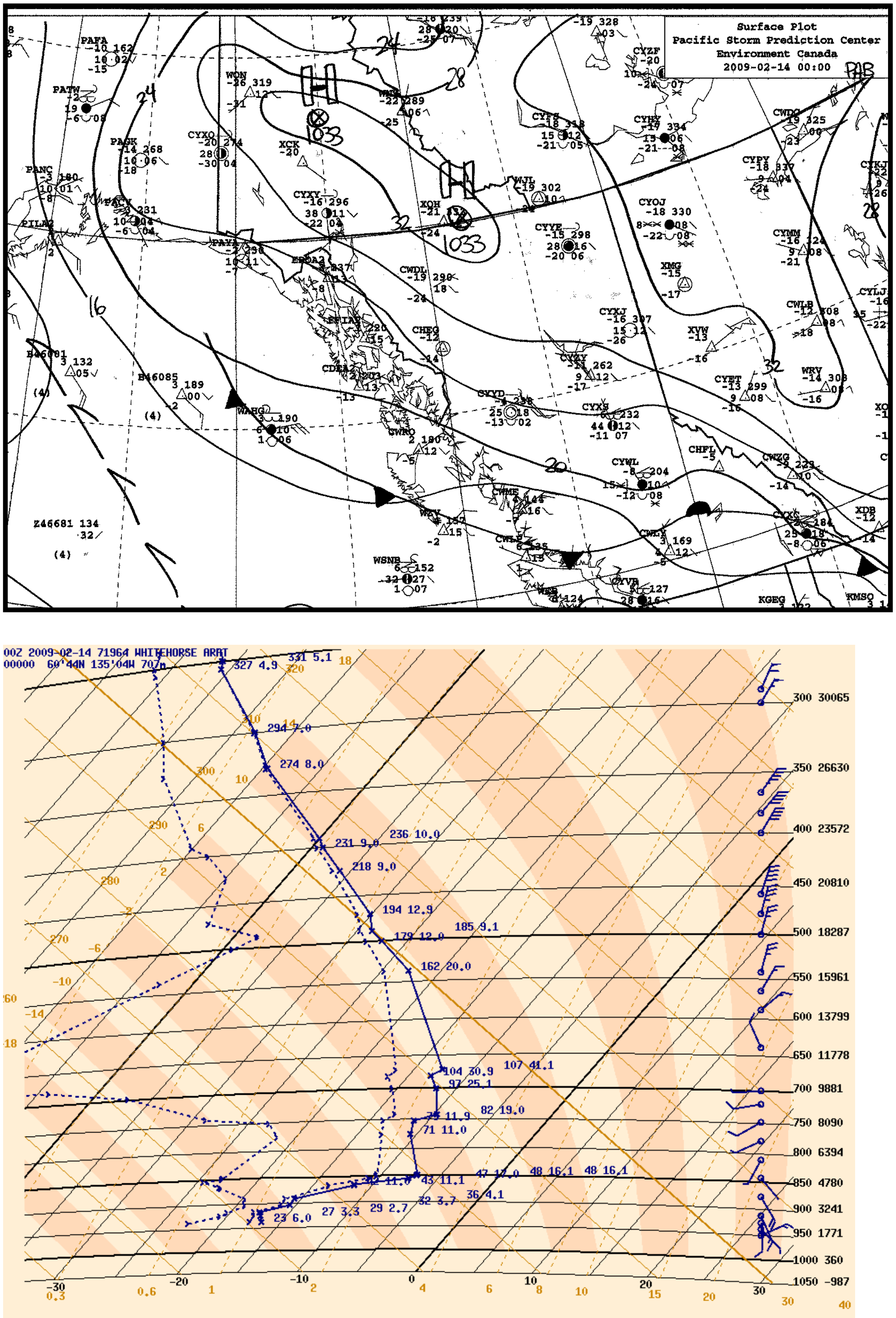
(a) February 9th at 4pm



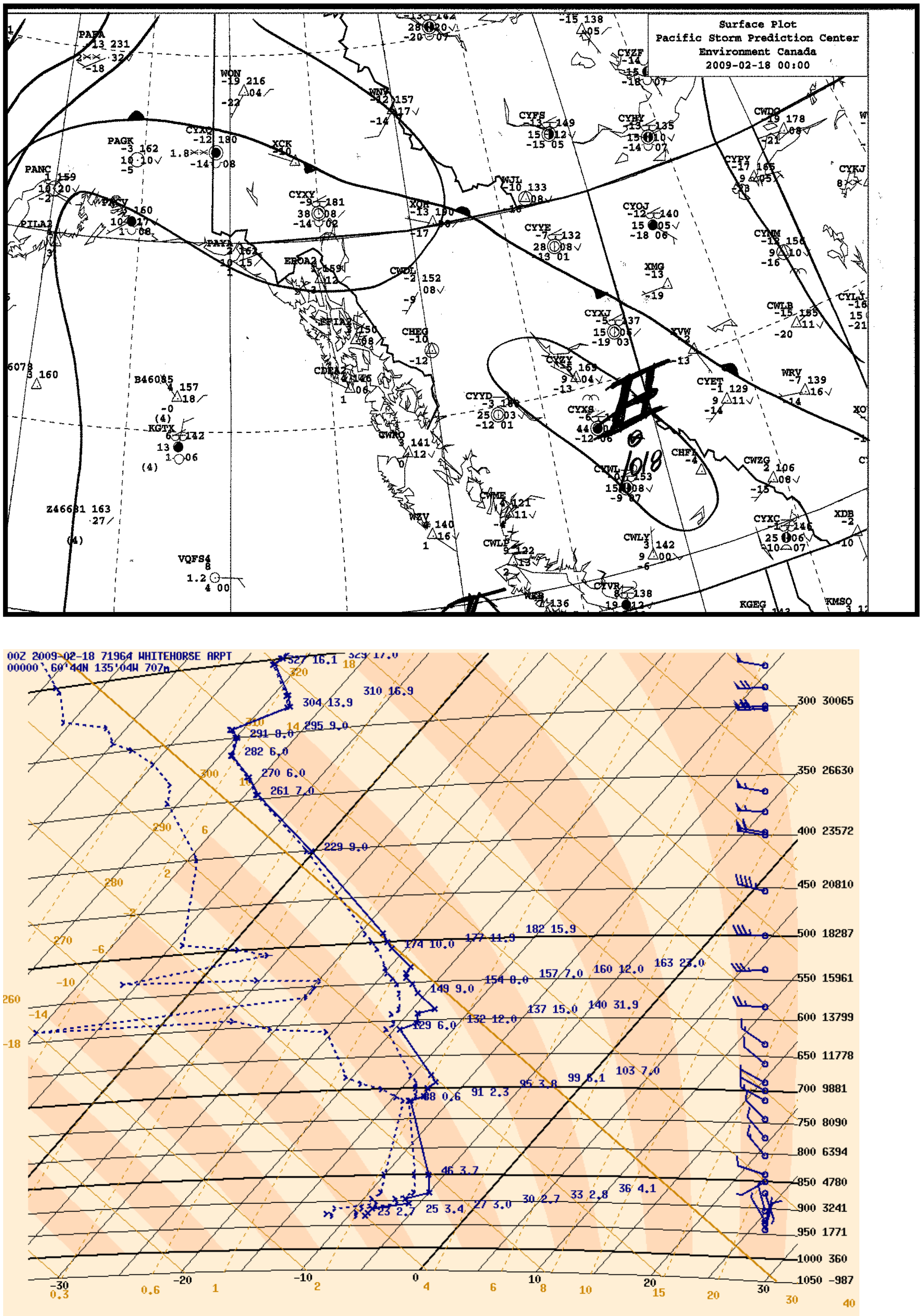
(b) February 11th at 4pm



(c) February 12th at 4pm



(d) February 13th at 4pm



(e) February 17th at 4pm

4. Conclusions

The use of levogucosan, ^{14}C and black carbon measurements as markers during the two month sampling campaign was successful in determining the presence and contribution of wood smoke to $PM_{2.5}$ in Whitehorse, thereby meeting the primary objective of this study. Average concentrations of $PM_{2.5}$ were 7.7 µg/m^3 and 10.2 µg/m^3 at the Downtown and Riverdale sites, respectively. Overall, concentrations ranged from 1.6 µg/m^3 to a maximum of 31.3 µg/m^3 on February 11th at Riverdale, which exceeded the value of the Canada Wide Standard of 30 µg/m^3. Note that this does not represent a formal exceedance as it is not based on the annual 98th percentile value.

On average, fine particulate at Riverdale was composed primarily of organic carbon (55%), while elemental carbon made up 7%. Assuming a consistent linear relationship between black carbon measured by the Aethalometer at Riverdale and $PM_{2.5}$ at both sites throughout the study period and within the range of black carbon measured, a simple linear regression model predicted that the value of the Canada Wide Standard was likely exceeded on five days at Riverdale (all during a 9 day period in February) and none at the Downtown site. Winter time PM concentrations measured during this study are significantly lower than those found in previous studies in the early 1980s and comparable to current levels in several communities in the interior of B.C. However, results from this study were higher than typically found at the Whitehorse NAPS site for the January to March period.

Calculations based on the analysis of ^{14}C data indicate that the average wood smoke contribution to $PM_{2.5}$ ranged from 70-84% at Riverdale. These results are supported by levoglucosan data, which also indicate a strong wood smoke influence. Ratios (% w/w) of levoglucosan to $PM_{2.5}$ were 4.7 ± 1.6 and 6.0 ± 2.4 (avg. ± s.d.) at Downtown and Riverdale, respectively, indicating a slightly higher wood smoke contribution at Riverdale. Black carbon results from the aethalometer also support the strong wood smoke presence at Riverdale, with the wood smoke signal being highest in the early morning and late evening. Source apportionment results for wood smoke contribution from this study are in relatively close agreement to earlier studies in Riverdale, the most recent emission inventory for Whitehorse and a previous study in B.C., lending credibility to the results.

The highest concentrations of $PM_{2.5}$ in Whitehorse were associated with calm winds and poor ventilation, which limit dispersion and low temperatures, which are associated with increased wood burning. These conditions were found to be present on days with a strong surface level inversion caused by a stable ridge of cold arctic air or suspected subsidence of south and southwesterly air masses.

Results from this study confirm that efforts to reduce winter time $PM_{2.5}$ in Whitehorse, particularly in the residential subdivision Riverdale, should consider RWC reduction strategies. If RWC emission reduction strategies are introduced, future work in

Whitehorse could include follow-up monitoring to assess their effectiveness. Future studies should ideally include monitoring over a longer period to more fully capture the impact of RWC on cold season air quality in Whitehorse.

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