FINAL REPORT

Understanding how Wood-burning's Contributions to Particulate Matter Concentrations have Changed over Time

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This project estimated the contributions from wood burning to total $PM_{2.5}$ concentrations, using Particulate Matter ($PM_{2.5}$) chemical composition measurements from the Bountiful, Lindon and Salt Lake City stations and using EPA's Positive Matrix Factorization (PMF) model. Additional measurements, such as temperature, heat deficit, solid-fuel burning restrictions and snow cover, together with the PMF wood burning factors provided insight into the changes in wood-burning's contributions during the winter seasons for a 10-year period, 2007-2017.

Background

Several counties along Utah's Wasatch Front experience elevated $PM_{2.5}$ levels associated with winter-time persistent cold air pools (PCAPs) caused by topographical features, weather patterns, primary aerosol emissions, and secondary aerosol formation. The strength of PCAPs can be measured using heat deficit, which can also serve as an indication of whether a PCAP is building, being maintained, or being destroyed [1]. Meteorological factors limiting dispersion of the pollutants in the Salt Lake Valley include temperature, atmospheric stability (Heat Deficit), relative humidity and snow cover. These factors are closely related to the atmospheric chemistry of the secondary particulate formation [4]. For example, the reflection from the snow cover produces higher levels of solar radiation for photochemical reactions and the high humidity and low temperatures are important in the formation and conservation of secondary particulates [5].

The contribution of residential wood combustion to $PM_{2.5}$ has been the focus of several recent studies in Utah valleys. Previous studies, based on PMF analysis of 24-h filter samples collected at Utah Division of Air Quality (UDAQ) sampling sites, reported that on a typical winter day, wood burning contributes approximately to 16% of the particulate pollution levels ($PM_{2.5}$) in the Salt Lake Valley and 21% in Utah County [2-3].

Policy makers have devoted significant effort and funds to reducing wood burning during poor air quality episodes. A solid-fuel burning program was designed to reduce the levels of particulate emissions by restricting or banning the use of wood-burning stoves and fireplaces during PCAPs between November 1 and March 1. The solid-fuel-burning restrictions were implemented in 1999 for Salt Lake County and portions of Davis and Utah counties. Those restrictions were later extended to Cache County and portions of Weber, Box Elder and Tooele counties. Moreover, programs to convert operating wood-burning fireplaces to cleaner-burning natural gas or electric have been also part of the effort to decrease the particulate contribution from wood combustion. However, it is difficult to determine whether these policy efforts are having the desired effect because meteorological conditions can confound the interpretation of the study results that rely on chemical markers.

Objective
The goal of this study is to understand how wood-burning's contribution to winter time $PM_{2.5}$ levels have changed over time and how effective efforts have been to curtail wood-burning during PCAP events. The wood-burning PMF factors along with meteorological parameters were used to understand the decrease in the contributions.

Methods

Chemically speciated $PM_{2.5}$ measurements
The $PM_{2.5}$ composition collected at Bountiful, Lindon and Salt Lake City Chemical Speciation Network (CSN) monitors (from winter 2007 to summer 2018) was a key input for this analysis. The composition information includes total $PM_{2.5}$ mass, elemental composition, organic carbon (OC), elemental carbon (EC) as well as anions and cations including ammonium, nitrate, potassium, sodium and sulfate. The sampling frequency at the Salt Lake City monitor was once every three days, whereas the frequency at the other two monitors was once every six days. Detailed information about the CSN and The EPA Air Quality System (AQS) database can be found on the EPA's web site (http://www.epa.gov/ttn/amtic/).

Data preparation and treatment
The raw data was pre-processed to determine which species to include in the PMF model. This pre-processing step included correcting for field blanks, identifying and addressing missing data, handling data below method detection limits, and data with poor or unknown data quality. The uncertainty of each reported measurement was also estimated. A detailed discussion of CSN data preparation and treatment is provided in [2, 6]

Source apportionment
Source apportionment modeling was performed using EPA PMF 5.0 model which is a statistical factor analysis technique used to differentiate the main sources that contribute to measured $PM_{2.5}$. The model looks for systematic patterns in the day-to-day chemical variations and quantifies a smaller set of groups named "factors or sources' which can explain the overall data variability. Data from each monitoring site was modeled independently but a similar pre-processing method and model procedure was used making possible the comparison across sites. The chemically-speciated measurements for the whole year were used in the model, but the analysis for this report focuses on winter months (Nov- Feb) and on the two factors interpreted as Fresh and Aged wood burning emissions. Dr. Robert Kotchenruther from the EPA Region 10 executed the PMF source attribution analysis.

Heat Deficit (HD)

The heat deficits values were obtained from the University of Utah's Aethalometer Dashboard available at https://kelly-1.chemeng.utah.edu/. This value is calculated from twice-daily rawinsonde data collected at the Salt Lake City airport and is available through the University of Wyoming. The expression used to calculate the HD is:

$$H_h = C_p \int_{1288\,m}^{h} \rho_z \,[\theta_h - \theta_z]\, dZ \qquad (\mathrm{J/m^2}) \qquad (1)$$

where C_p is the specific heat of air at constant temperature (1005 J kg−1 K −1), θ_h is the potential temperature (K) at height h, ρ_z is the air density from sounding (kg/ m^3) and θ_z is the potential temperature (K) from the rawinsonde sounding.

The density (ρ) was calculated using the Ideal Gas Law (equation 2) and the following values:

$$\rho = \frac{m}{V} = \frac{P}{R_{air}T} \qquad (2)$$

R_{air} (the specific gas constant of dry air) = 287.06 J /kg K ; P is pressure (millibars), V is volume (m^3) , m is mass (kg), and T is temperature (K).

The heat deficit was calculated from the Salt Lake Valley floor (1288 m) to h = 2200 m mean sea level (MSL) as this is the approximate elevation of the Oquirrh Mountain ridgelines, which form the western boundary of the valley [5]. The potential temperature at height h (θ(h)) is defined as the temperature a parcel of air would attain if it were adiabatically brought to a standard reference pressure (P0) of 1000 millibars, and can be calculated by Poisson's Equation (3):

$$\theta_{h=}T_h \left(\frac{P0}{P_h}\right)^{\frac{R_{air}}{Cp}} \qquad (3)$$

where T_h and P_h are the temperature (K) and pressure (millibar) at height h. In the event that the rawinsonde soundings did not have measurements at exactly 2200 m, the pressure and temperature values were calculated by linearly interpolating rawinsonde data to obtain approximate values. More information on heat deficit can be found in [1].

Conditional Probability Function (CPF)

The CPF is frequently used to show which wind directions and wind speed intervals are associated with a (specified) high concentration of a pollutant and provide the probability of that occurrence [7]. The bivariate polar plots created using openair CPF function were used to examine the direction of the highest emissions from wood burning to the monitoring stations.

Snow cover and wood-burning restrictions dates

The snow accumulation data were collected from the National Center for Environmental Information for the Salt Lake International airport. The monthly average-snow cover data over Dec-Feb was used to generate the plots. The summary of the wood-burning restrictions dates for the winter seasons 2007 to 2018 was provided by UDAQ.

Results

PMF analysis

The PMF model was able to differentiate the contributions of fresh (or primary) and aged wood burning to the $PM_{2.5}$ concentrations measured at the Salt Lake City and Bountiful monitoring stations. However, only the combination of both, fresh and aged wood burning, was identified for Lindon station. Figure 1 provides the time series fresh (primary) and aged wood smoke contributions at the Salt Lake City station. The plot shows the impact of fresh wood-burning emissions during wintertime and the importance of aged wood combustion contributions to the $PM_{2.5}$ levels during winter season and during summer time when wildfire activity is present.

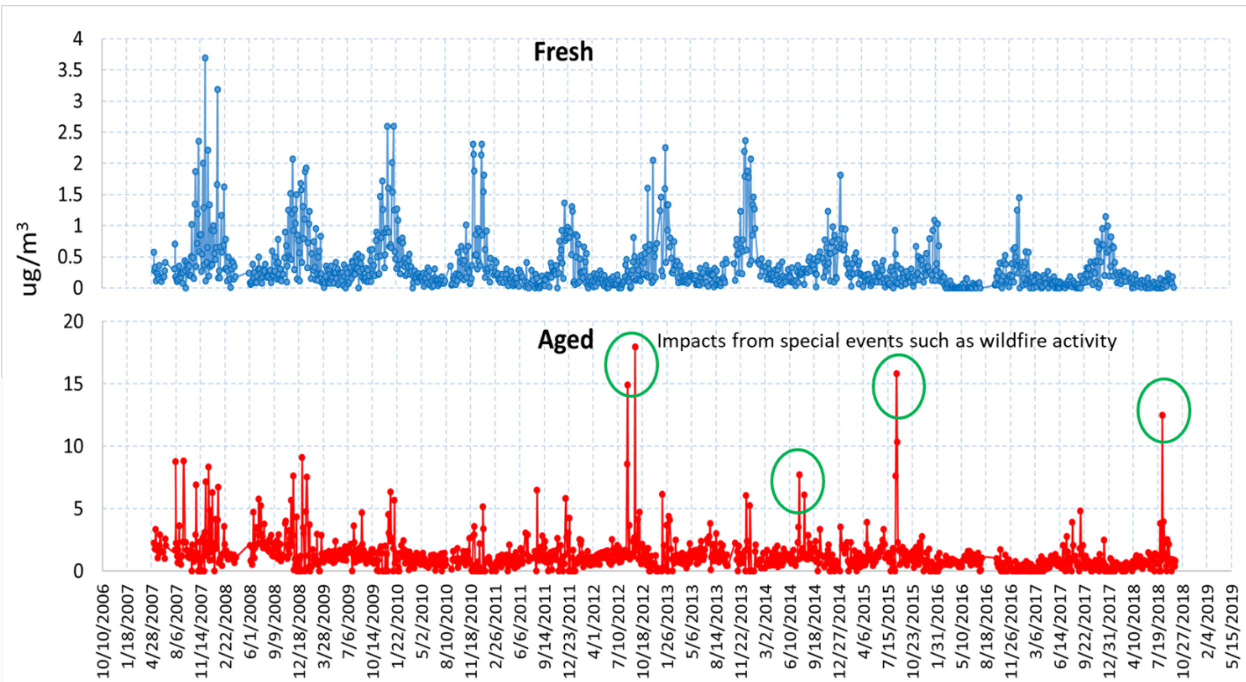

Figure1. PMF factors associated with fresh (primary) and aged wood-burning emissions at the Salt Lake City station.

Based on this analysis, the average total primary and aged wood burning contribution to $PM_{2.5}$ varied across all three monitoring sites and was estimated to be 2.03 μg/ m^3 and ranged between 10 and 20% of total winter $PM_{2.5}$ during the winter seasons 2007 to 2014 at the Salt Lake City station. For the same period, the contribution at Lindon and Bountiful stations were 1.96 and 1.56 μg/ m^3, respectively, with percentages of total winter $PM_{2.5}$ between 10 and 23% for both stations. These contributions of wood burning to the total $PM_{2.5}$ align with previous studies that have analyzed source contributions to $PM_{2.5}$ along the Wasatch Front.

For the last two winter seasons included in the analysis, 2016 and 2017, the estimated contribution values were significantly lower than those estimated for the previous seasons at the three stations. The estimated contribution was 0.28 μg/ m^3 at Lindon, 0.46 μg/ m^3 at Salt Lake City and 0.41 μg/ m^3 at Bountiful. The percent contribution to the total $PM_{2.5}$ ranged between 3 and 9 % for the three stations. These results are presented in Figure 2.

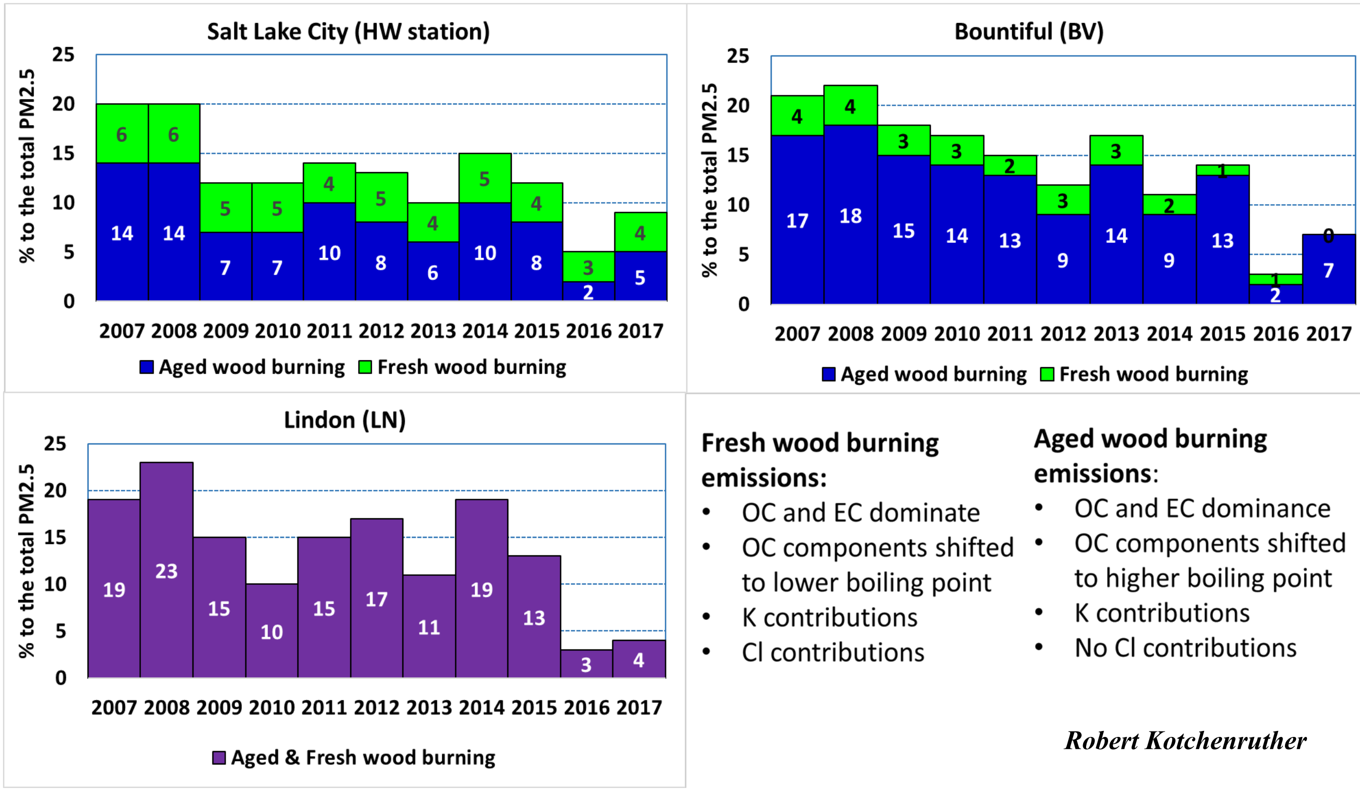

Figure 2. PMF wood burning factor contributions to the total $PM_{2.5}$ for each winter season and at the 3 monitoring stations included in this study.

The contributions of aged wood burning seems to be an important fraction of the wood burning's overall contributions to $PM_{2.5}$ levels. This points to the importance of oxidative processing of organic carbon (OC) emitted during the wood combustion process.

Effect of meteorological parameters on the PM2.5 levels

$PM_{2.5}$ and HD

The total $PM_{2.5}$ levels were plotted against HD values for the same days included in the PMF analysis for each station, and are shown in Figure 3. The graph shows a good correlation between both variables and the increase in $PM_{2.5}$ levels with the valley HD, as previously reported [5, 8-9]

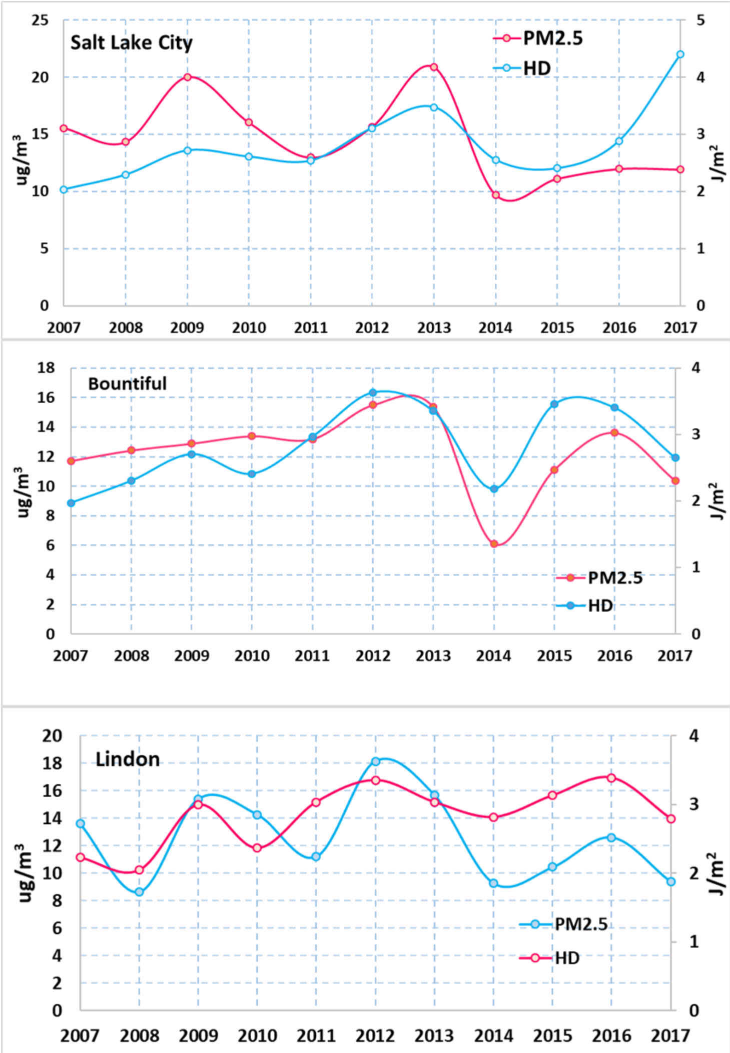

Figure 3. $PM_{2.5}$ and HD for Salt Lake City, Bountiful and Lindon stations.

Normalized PMF wood factors

The PMF factors associated with aged and fresh wood burning emissions were combined and plotted in Figure 4 as a total wood burning factor before and after being normalized by the HD value. In addition, meteorological parameters such as the average winter season temperature and snow accumulation were included in Figure 4.

Figure 4 illustrates the decrease in wood burning emissions during the 10-year period (2007-2017). This trend is the same for either the raw results or those results normalized by HD, with a significant reduction during 2016 and 2017 winter seasons. Nevertheless, when comparing the trends of the wood burning emissions before and after normalization, the reduction in the emissions is more noticeable for the seasons with higher HD values, which are associated to the PCAPs. For example, in winter seasons 2012 and 2013, which have a higher HD values, the decrease in wood burning emissions is better illustrated after the normalization is applied, which reinforces the importance of the inclusion of valley HD in this analysis. The PMF results suggested that the contribution of wood burning to $PM_{2.5}$ levels was between 5 to 13 times larger in 2007 than in 2017, depending on the station studied.

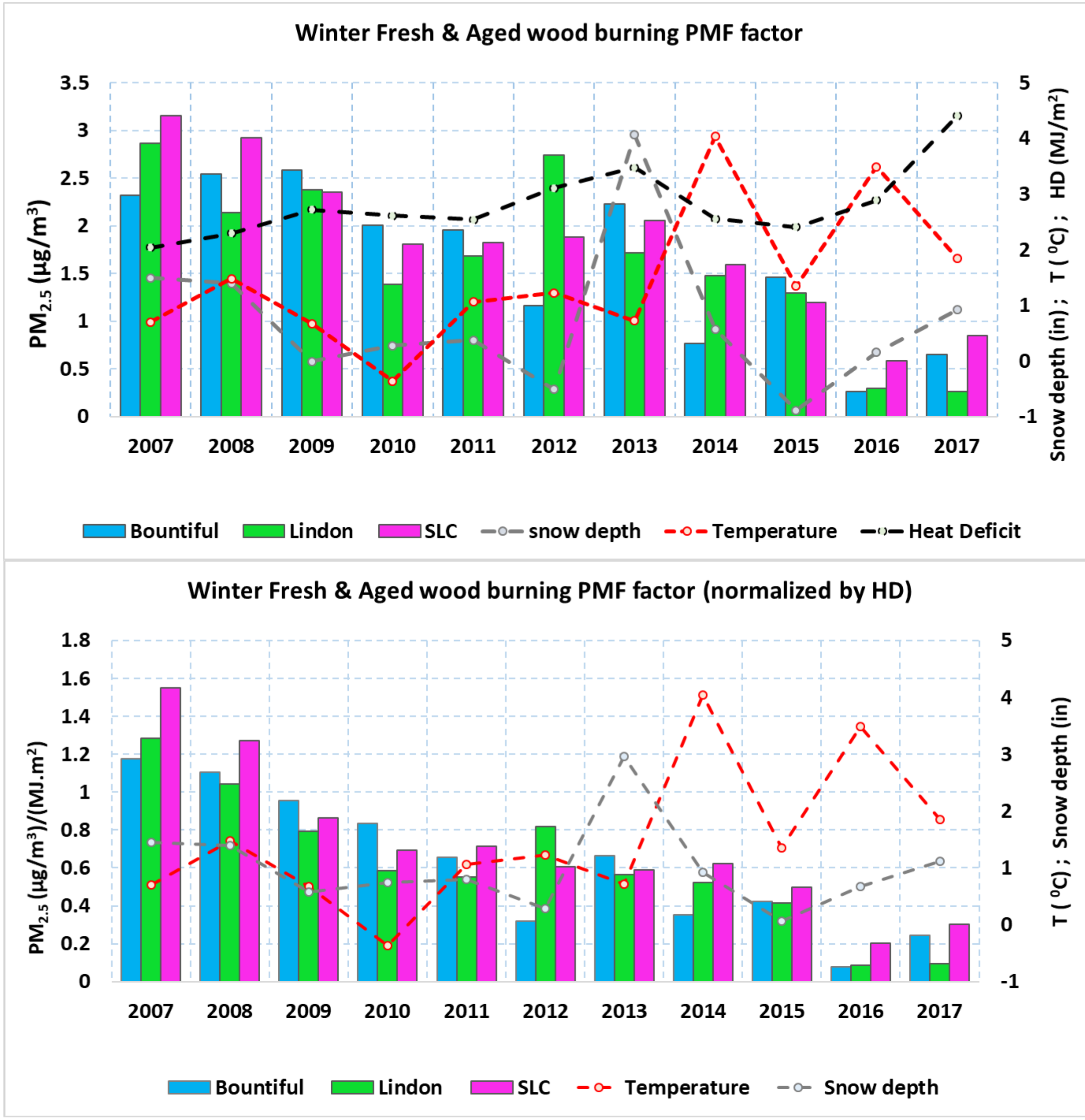

Figure 4. PMF wood burning factor before and after normalization by HD for Salt Lake City, Bountiful and Lindon stations.

Effect of the wood burning restrictions

In an effort to mitigate particulate emissions during periods of reduced air quality, the Utah Division of Air Quality (DAQ) implements varying solid-fuel-burning restrictions. The action forecast informs the community about voluntary or mandatory actions for solid-fuel burning, which are linked to the current and forecasted pollution levels. Voluntary action days are called when levels are predicted to reach 12 $\mu g/m^3$ while mandatory action days are called when levels are forecasted to reach 25 $\mu g/m^3$. Table 1 summarizes the solid-fuel burning restrictions during the study period. Due to the differences in sampling frequency between stations, the Salt Lake City station includes approximately twice the number of days with action regulations.

Figures 5 and 6 present the aged and fresh wood burning contributions during various solid-fuel burning conditions.

Table 1. Number of days with different action levels used to generate Figures 5 and 6.

		Salt Lake City			Bountiful			Lindon	
Year	**yellow/Vol**	**Red/Man**	**No ban**	**yellow/Vol**	**Red/Man**	**No ban**	**yellow/Vol**	**Red/Man**	**No ban**
2007	6	4	29	3	1	15	1	2	17
2008	5	1	31	2	1	16	1	0	13
2009	8	7	25	1	2	11	3	1	15
2010	3	6	27	2	2	16	0	1	17
2011	6	1	30	4	0	16	2	0	16
2012	2	7	23	0	5	15	1	5	14
2013	5	10	24	3	6	11	1	7	12
2014	4	6	27	0	0	6	1	4	13
2015	2	0	33	0	0	17	1	0	10
2016	9	7	24	4	2	11	1	2	17
2017	6	9	20	4	4	11	4	3	8

Yellow: voluntary burn restrictions; Red: mandatory burn restrictions.

Figure 5 shows the contribution of the wood burning without normalizing by HD and the total $PM_{2.5}$ for the days with and without burn restrictions. This contribution of wood burning emissions to total $PM_{2.5}$ varied with burn restrictions. Overall the lowest percent contribution occurred on days when there was a mandatory burning ban, which is likely associated with the increased contribution of secondary nitrate and sulfate to $PM_{2.5}$ on mandatory days when mixing is limited. On the other hand, the highest percent contribution occurred on days when wood-burning was permitted. Nevertheless, while the percent of wood-burning's contribution to $PM_{2.5}$ was lowest on mandatory days, the concentrations ($\mu g/m^3$) on these days were higher than those measured on days without restriction. This is a common trend for the three stations analyzed. These high levels of wood combustion emissions could be associated to increased atmospheric stability together with the noncompliance with the burn restrictions.

When comparing the contributions between voluntary action and no ban restrictions, the trends differ between winter seasons, and no common trend is evident. The contribution of wood burning to $PM_{2.5}$ also fluctuated spatially across all three monitoring stations, with highest contributions being overall recorded at the Salt Lake City station.

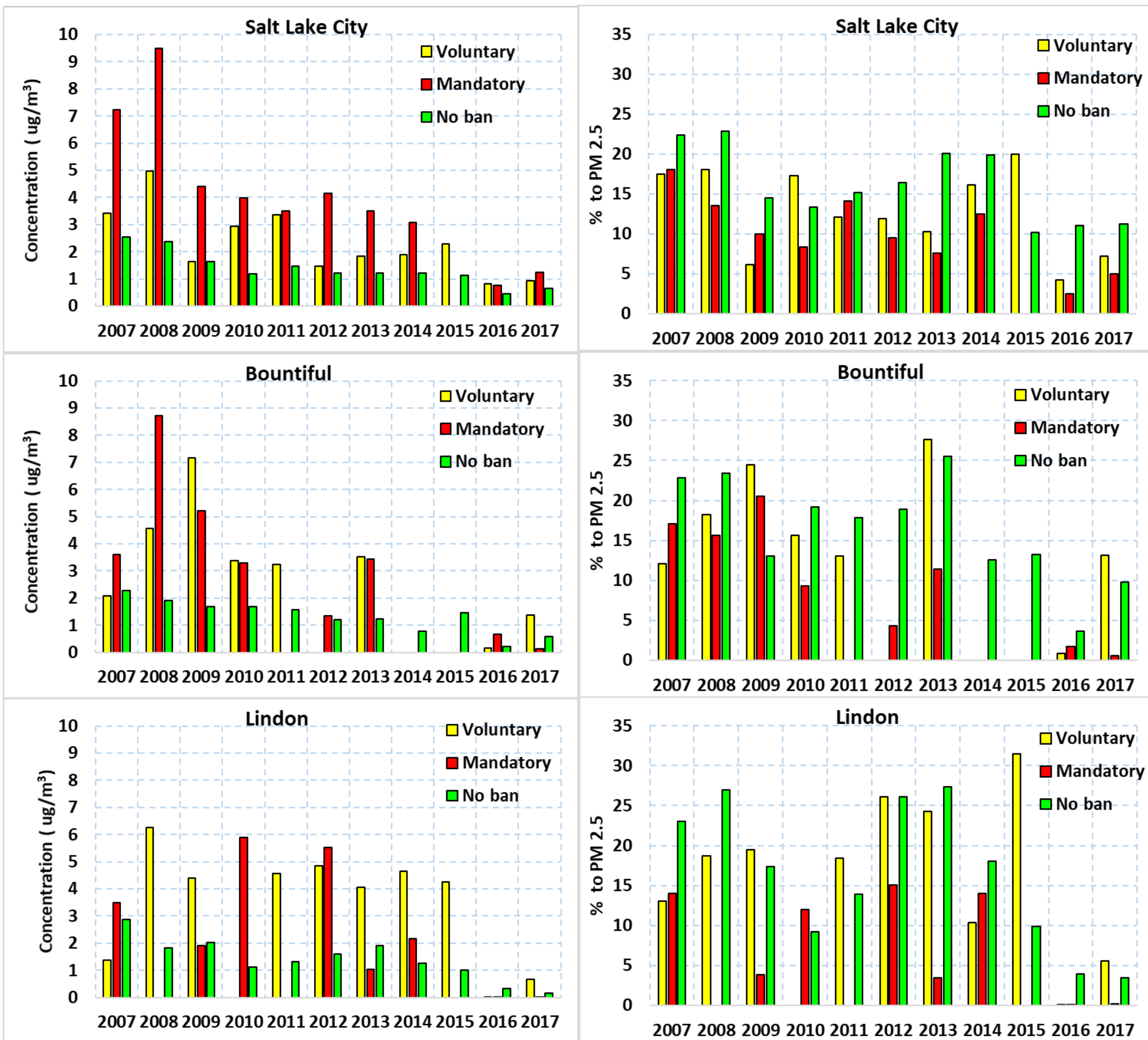

Figure 5. PMF wood burning (aged plus fresh) factor broken down by residential wood-burning restrictions.

Figure 6 shows the comparisons of the wood burning contributions after normalization by the HD for days with and without burning restrictions at the Salt Lake City, Bountiful and Lindon monitoring stations over 2007-2017. As previously mentioned, the decrease in the wood burning emissions across years was clearly identified after normalizing the contributions on burn days by the HD, indicating that the decrease is independent of year-to-year changes in meteorological conditions.

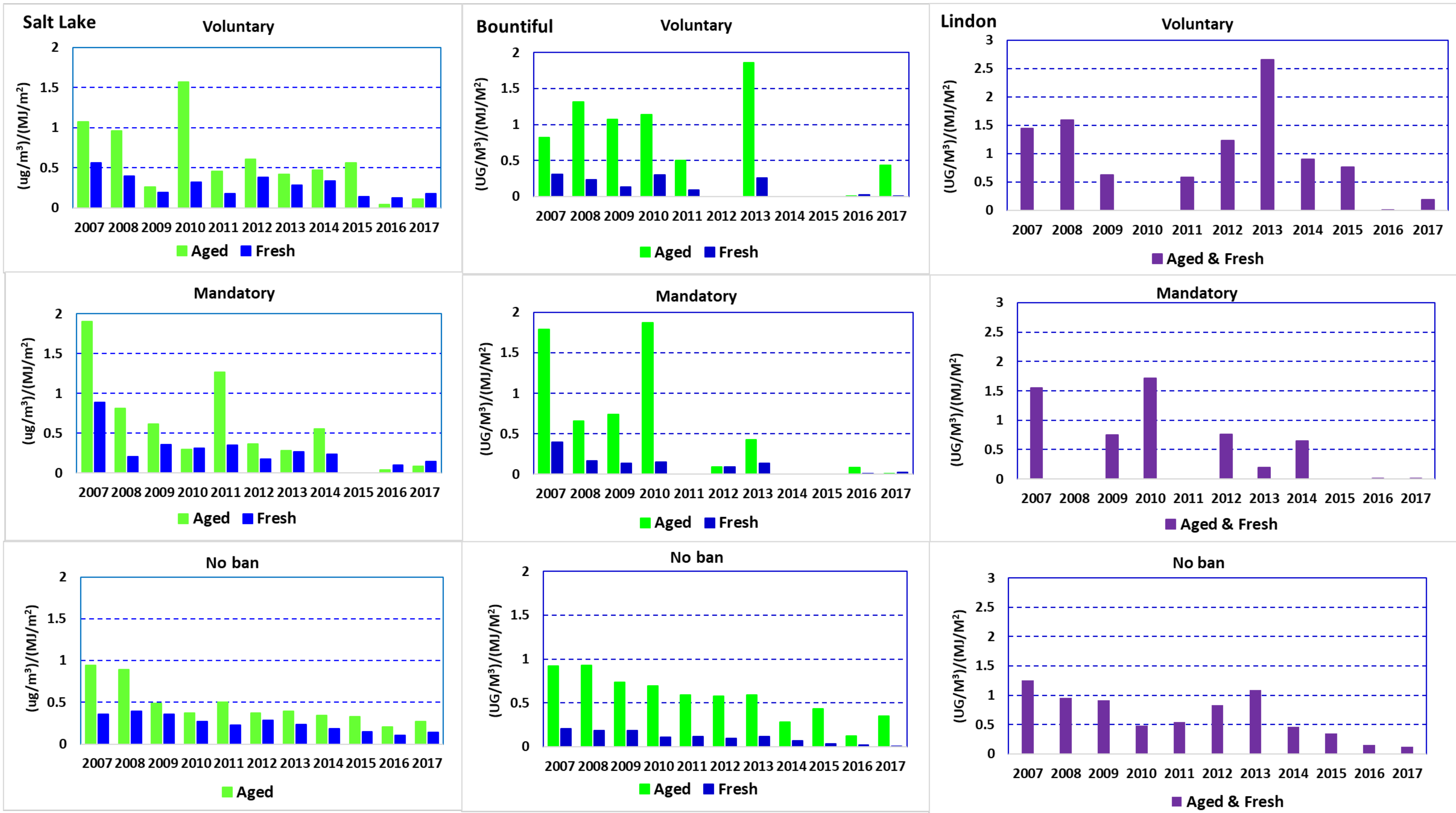

Figure 6. Normalized PMF aged and fresh wood burning factors broken down by residential wood-burning restrictions.

Direction of wood burning contributions

The normalized wood burning factors identified by PMF were combined with meteorological data to identify the wind speeds and direction associated with the highest wood burning contribution at the Salt Lake City monitoring station. Figures 7 and 8 show the CPF analysis, presented as polar plots, for the 75th percentile of fresh wood and aged wood burning factors (µg/MJ-m) respectively.

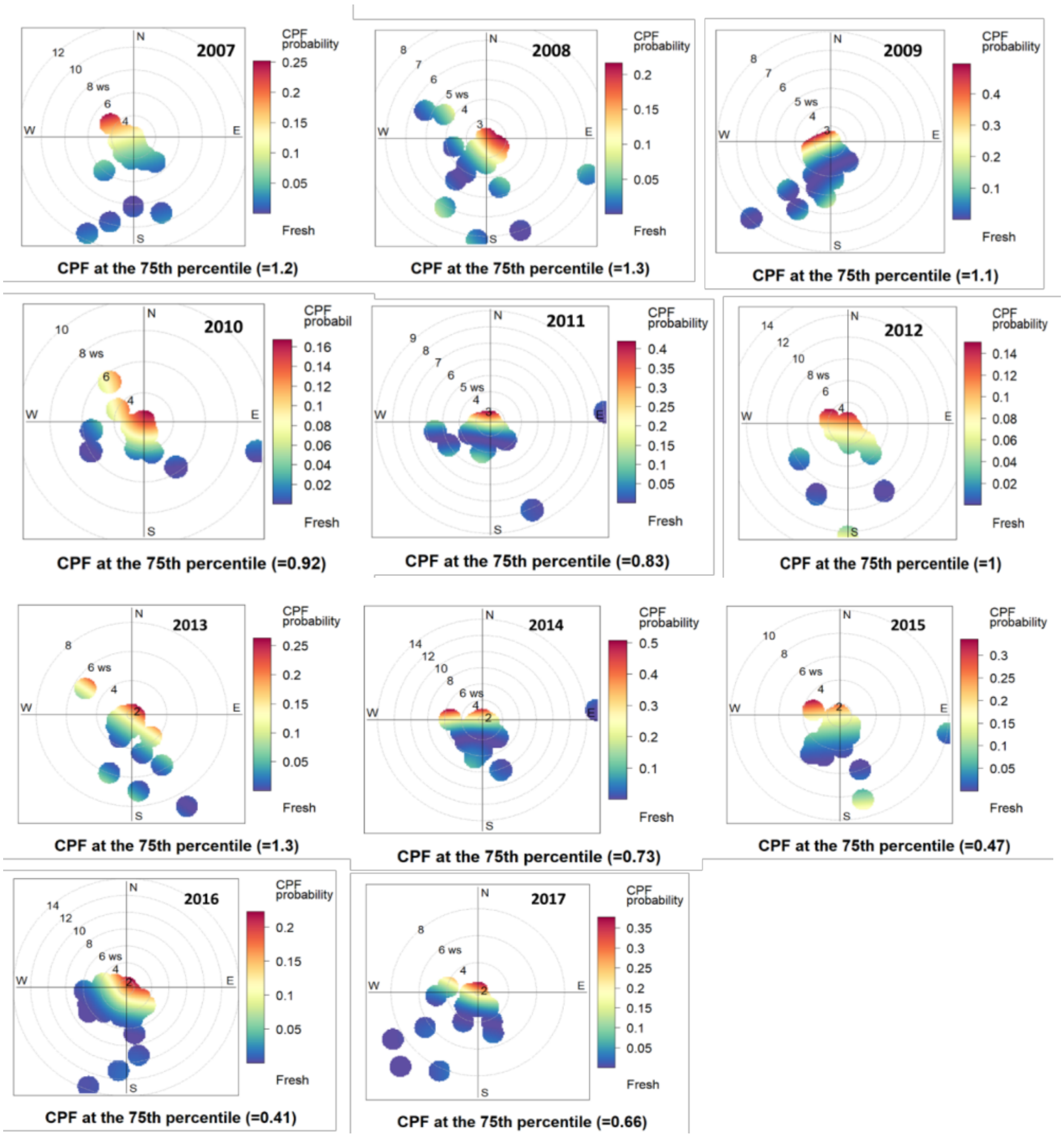

Figure 7. Polar plots of CPF analysis (75th percentile) for the fresh wood burning emissions at Salt Lake City during the winter seasons 2007-2017.

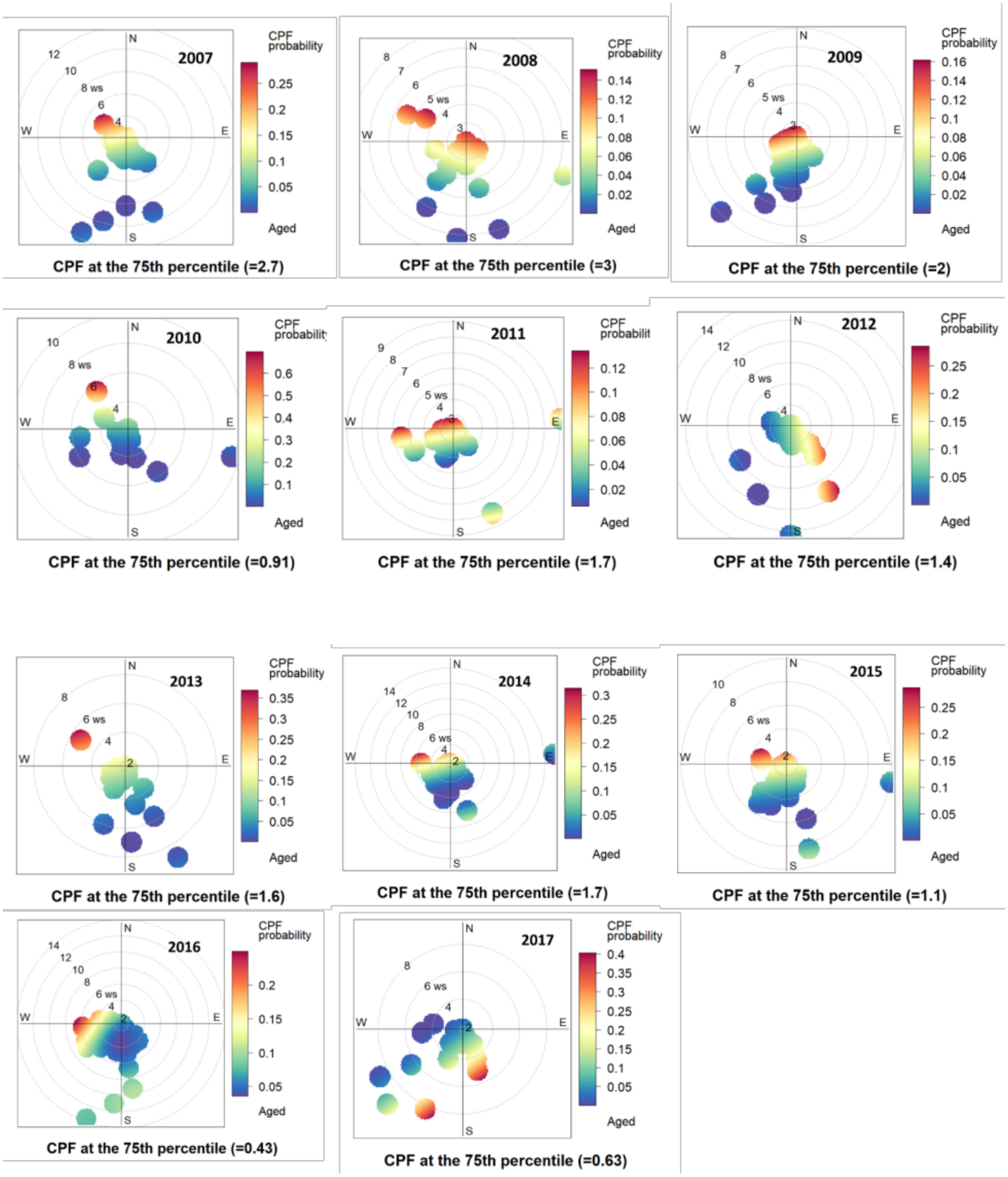

Figure 8. Polar plots of CPF analysis (75th percentile) for the aged wood burning emissions at Salt Lake City during the winter seasons 2007-2017.

The CPF results shown in Figure 7 suggest, as a general trend, that sources contributing to the higher fresh wood burning emissions are close to the monitoring site under wind speeds lower than 5 m/s and for all the wind directions. While, for wind speeds greater than 5 m/s the emissions seem to be transported mainly from the NW direction. Results shown in Figure 8 suggest that for wind speeds greater than 5 m/s, the higher contributions of aged wood combustion are affected by regional transport. However, under low wind speeds (blue color area near the center) and for all wind directions the probability of the contributions from aged wood smoke are near zero, suggesting no contributions from local sources. An exception of that observation is the 2008 winter season, in which the CPF plot clearly reveals that local and regional sources are the potential causes of the higher aged wood smoke levels.

Summary

This study examined the contributions of wood combustion to total $PM_{2.5}$ concentrations. It used chemically speciated $PM_{2.5}$ measurements and EPA's PMF model (study period 2007 to 2017), which allowed the resolution of aged and fresh wood burning contributions. The goal of this study was to understand how wood-burning's contribution to wintertime $PM_{2.5}$ levels have changed over time. The study focused on three air quality-monitoring stations in Hawthorne (Salt Lake City), Bountiful and Lindon. The analysis also considered atmospheric stability (heat deficit) and burning restrictions. As expected, higher wood-burning levels were observed for cooler days, which may be associated with an increased need for heat as well as a decrease in atmospheric mixing. The CPF analysis suggested that contributions from fresh wood burning are mainly produced locally, while the aged wood burning contributions seem to be transported from other areas. The results indicate significant reductions in residential wood combustion with decreases (2007 to 2017) of approximately 79% in Bountiful, 81% in Salt Lake City and 93% in Lindon. These results are also easier to interpret when normalizing by HD because it reduces the influence of meteorology. These reductions in wood burning may be due to improved technology, financial incentives for replacing wood-burning devices with other less-polluting heat sources, public education, and implementation of burning ban restrictions.

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Final Report

Wood-burning Compliance estimation based on hourly 7-channel aethalometer and heat-deficit data

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A compliance estimation for mandatory action days (no burning) was calculated using hourly 7-channel aethalometer measurements and using the estimated organic matter concentrations from wood burning emissions with potassium as a tracer (OM_{wbk}) for measurements collected at Smithfield, Bountiful and Lindon. The calculated heat deficit (HD) was used to account for atmospheric stability effects on the measured delta-C and OM_{wbk} concentrations. In addition, a Conditional Probability Function (CPF) analysis was applied to the aethalometer dataset with the objective to identify the wind speeds and directions associated with the highest contributions of wood burning emissions during no-burning days.

Background

Several counties along Utah's Wasatch Front have reported elevated $PM_{2.5}$ levels associated with winter- time persistent cold air pools (PCAPs). To reduce particulate emissions during PCAPs, the Utah Division of Air Quality (DAQ) restricts the solid-fuel burning on days forecasted to be affected by the inversions. Previous studies have estimated the contribution of wood smoke to winter-time $PM_{2.5}$ levels along the Wasatch Front [1-4] and have reported a significant decrease in the emissions of wood burning for the last winter seasons [4]. The DAQ has developed a method based on HD estimation and 24-hr levoglucosan measurements, but the value of this method may be limited by the 24-hr resolution of the measurements.

The incomplete combustion of carbonaceous fuels produces soot particles with strong optical absorption properties commonly referred to as black carbon (BC) [5]. The optical absorption properties of BC vary depending on conditions comprising particle size, combustion fuel type, combustion conditions, and particle age. Organic components of wood smoke particles such as polycyclic aromatic hydrocarbons (PAHs) and other brown carbon materials have been found to better exhibit light absorbance at 370 nm relative to 880 nm in two wavelength aethalometer black carbon (BC) measurements [6-7]. Subsequently, several studies have used this difference in response, which is defined as delta-C, to estimate the contributions of wood combustion to the total winter $PM_{2.5}$ levels [8-9]. Other studies have used the wood burning molecular markers such as levoglucosan and fine particle soluble potassium [10-12] to estimate the contributions.

Objective

The main goal is to develop a strategy for estimating wood-burning compliance using hourly 7-channel aethalometer data, heat-deficit information and the chemically speciated $PM_{2.5}$ measurements. This method is intended to refine DAQ's estimates of compliance rate that were based on 24-hour measurements.

Methods

Data

The Delta-C and heat deficits values were obtained from the University of Utah's Aethalometer Dashboard available at https://kelly-1.chemeng.utah.edu/. This tool uses the concentrations collected by the Magee Scientific Model AE33 aethalometer monitors located at Smithfield, Bountiful, and Lindon UDAQ stations and reports the Delta-C in ng/m^3. The heat deficit (HD) value is calculated from twice-daily rawinsonde data collected at the Salt Lake City airport and is available through the University of Wyoming. Additional information regarding the delta- C and HD values is provided by Glisson et al. 2019 [13]. The $PM_{2.5}$ chemically speciated composition collected at Bountiful, Lindon and Smithfield was obtained from https://aqs.epa.gov/aqsweb/documents/codetables/methods_speciation.html. In addition, the summary of the wood-burning restrictions dates was provided by UDAQ.

Results

Compliance rate based on Delta-C values

The delta-C values were normalized before using them in the compliance rate calculation. The HD and the minimum positive delta-C value for the previous day were included in the normalization approach to account for the variation in atmospheric stability and residual delta-C concentration remaining from previous days, respectively. The normalized delta-C values were estimated by applying the equation (1)

$$\boldsymbol{N} = \frac{\boldsymbol{24H\ average\ delta{-}C\ \ {-}minimun\ positive\ delta\ for\ the\ previous\ day}}{\boldsymbol{HD}} \qquad \textbf{(1)}$$

On some occasions, negative delta-C concentrations were obtained for the three stations. These negative values were larger and more prolonged at the Bountiful station, and they indicate no impact from wood burning emissions. These negative delta-C values typically occur when semi-volatile species collected on the filter-tape start desorbing. This usually occurs when a relatively clean air event follows a high pollution one or due to changes in humidity. Assuming that the negative delta-C values are not influenced by wood burning emissions, only the positive values were considered in estimating the minimum delta-C for each day.

The delta-C concentrations were broken down based on solid-fuel burning restrictions, and the compliance rate was calculated as a ratio of normalized delta-C relative to the no ban days by using equation (2)

$$\boldsymbol{Compliance\ rate}\ (\%) = \left\{\left(\boldsymbol{1} - \frac{\boldsymbol{Ndelta\ C_{24\ H\ average}\ Vol\ or\ Man\ ban}}{\boldsymbol{Ndelta\ C_{24\ H\ average}\ NO\ BAN}}\right)\right\} * \boldsymbol{100} \qquad \textbf{(2)}$$

Compliance rates estimated for winter seasons 2018-2019 and 2019-2020 are presented in Tables 1 and 2.

Table 1. Compliance rate (%) for the 2018-2019 winter season

	Smithfield	# days*	Lindon	# days*	Bountiful	# days*
Mandatory	**30**	29	**9**	20	**26**	20
Voluntary	**7**	17	**12**	15	**22**	12
No ban days		40		51		51

*number of days included in the calculation

Table 2. Compliance rate (%) for 2019-2020 winter season

	Smithfield	# days*	Lindon	# days*	Bountiful	# days*
Mandatory	**38**	17	**0**	26	**30**	10
Voluntary	**5**	25	**4**	9	**17**	18
No ban days		31		48		54

*number of days included in the calculation

The compliance rate estimates for both winter seasons suggest a similar trend, in which higher rates were obtained for Smithfield during mandatory action level, with 30 % of compliance during 2018-2019 and 38 % during the 2019-2020 season. Comparable compliance rates of 26% during 2018-2019 and 30% during 2019-2020 season were calculated for the Bountiful site. However, very low rates were obtained for samples collected at Lindon site, with 9 % during 2018-2019 season and negative rate, meaning no estimated compliance, obtained for the season 2019-2020.

Compliance rate based on chemical tracers

Pearson correlations between the delta-C concentrations (ng/m^3) and wood burning tracers such as organic carbon (OC), higher temperature OC fractions, potassium ion, total potassium, and elemental carbon (EC), were used to examine their relationships. The correlations coefficients are shown in Table 3.

Table 3. Pearson correlation coefficients OC, potassium, potassium ion and delta-C concentrations

	Delta-C BV	Delta-C SM	Delta-C LN
OC4	0.51	0.70	0.39
OC3	0.80	0.75	0.64
OC2	0.79	0.67	0.45
OC1	0.70	0.55	0.56
K+	0.41	0.13	0.62
K	0.74	0.66	0.66
EC1	0.83	0.74	0.79
EC2	0.21	0.38	0.12
EC3	0.45	0.41	-0.35

Results in Table 3 show higher correlations between the delta-C and the OC and EC concentrations, and modest correlations with potassium for the three monitoring sites. Previous studies have also reported discrete correlations between K and levoglucosan and between delta-C and K, and these discrete correlations have been attributed to differences in emissions of these species during flaming and smoldering combustion processes and to the presence of additional sources of K interfering with the relationship [13]. Lee et al. [14] reported that emissions of K+ were higher under flaming conditions compared to smoldering conditions. Elemental potassium (K) and soluble potassium (K+) are often used as tracers of wood burning emissions [14-17]; but they also can be emitted from other sources including dust, sea salt and meat cooking which can interfere with the wood burning emissions identification [18-20].

A method to apportion the contribution of wood burning to organic matter (OM) using potassium as a tracer has being widely used in the literature [21-23]. These published studies rely on ratios of OC and K (K+) based on source profiles studies and represent mostly primary (fresh) emissions and do not reflect atmospheric processing. This study contemplates the aged wood-smoke contributions by using the ratio of OC and total potassium obtained from Positive Matrix Factorization (PMF) Source Apportionment Model. The PMF source attribution analysis was executed by Dr. Robert Kotchenruther from the EPA Region 10 for the chemically-speciated measurements collected at Lindon, Hawthorne and Bountiful monitoring stations. The OC to Kwb ratio for Ln and BV were obtained from the PMF results while the ratio for SM corresponds to the averaged ratio for LN, BV and HW. The ratio of OM to OC typically fluctuates between 1.4-2.1 [13,18,24] value varying depending on the aerosol aging time. This study uses an average value of 1.8.

The OM contribution from wood burning based on total potassium as a tracer OM_{wbk} was obtained by the equation (3) which is the result of combining (4) and (5).

$$OM_{wbk} = \left(\frac{OC}{K_{wb}}\right) * 1.8 * K \quad (3)$$

$$\left(\frac{OC}{K_{wb}}\right)_{LN} = 86.0\,;\ \left(\frac{OC}{K_{wb}}\right)_{BV} = 83.4\,;\ \left(\frac{OC}{K_{wb}}\right)_{SM} = 81.7 \qquad (4)$$

$$\frac{OM}{OC} = 1.8 \qquad (5)$$

The OM_{wbk} values calculated from the $PM_{2.5}$ speciation data where normalized by HD and then used to estimate the compliance rates for the 2018-2019 winter season. The results are presented in Table 4.

Table 4. Compliance rates using the normalized OM_{wbK} for 2018-2019 winter season.

	Smithfield	# days*	Lindon	# days*	Bountiful	# days*
Mandatory	**30**	12	**31**	5	**35**	5
No ban days		8		6		7

*number of days included in the calculation

The compliance rates calculated by using the OM_{wbk} are comparable to those estimated rates obtained with the aethalometer data for Smithfield and Bountiful sites. However, the rate estimated for Lindon was much higher and similar to the 29% estimated compliance rate developed by DAQ using 24-hour levoglucosan measurements. One of the limitations of this approach is that fewer days have chemically speciated measurements (every 3rd or 6th day) that could be matched with burn restrictions compared with those with delta-C measurements (every day). This method also assumes that K is mainly derived from wood-burning emissions, and it may be underestimating contributions from aged wood smoke.

CPF results

The CPF plots based on delta-C data analysis were used to identify the wind speeds and directions associated with the highest contributions of wood burning emissions during no-burning days are shown in Figures 1 to 3. The color indicates the probability that the wood burning concentrations measured at a given wind speed and direction fell within the 75th percentile of all wood burning concentrations measured at that site (the CPF probability color bar). Wind speeds are denoted in the concentric circles (m/s). Red and orange indicate that concentrations within the 75th percentile are more probable. For three sites in this study, the majority of the concentration levels at 75th percentile occurred at very low wind speeds that are associated with stable and stagnant conditions.

For the Smithfield site, during restricted burning days, the plots suggest some influence from sources transported from the SE direction when wind speed are between 3.5 and 4.5 (m/s), while local sources are the major contributors under wind speeds lower that 3.5 m/s. During days with no burning restrictions, the contributions from wood burning emissions appear to be from local sources. For the Bountiful site, the contributions of the wood burning appear to be local with an exception of mandatory ban days for the 2019-2020 winter season, when the highest contributors under low speed winds seems to be transported from the SW. For Lindon site, the plots show no significant difference between burning and non-burning restriction days, and all the sources contributing to the emissions seem to be local.

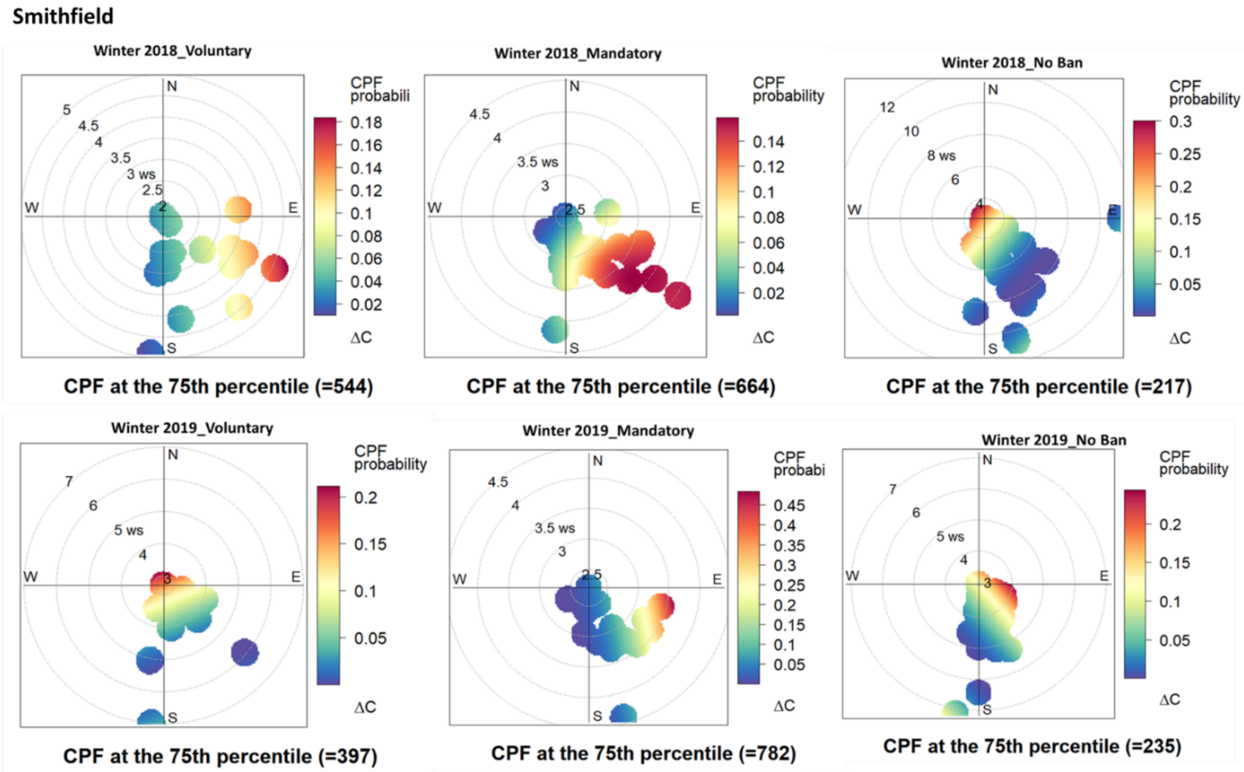

Figure 1. CPF bivariate probability function plots for the delta-C collected at Smithfield station.

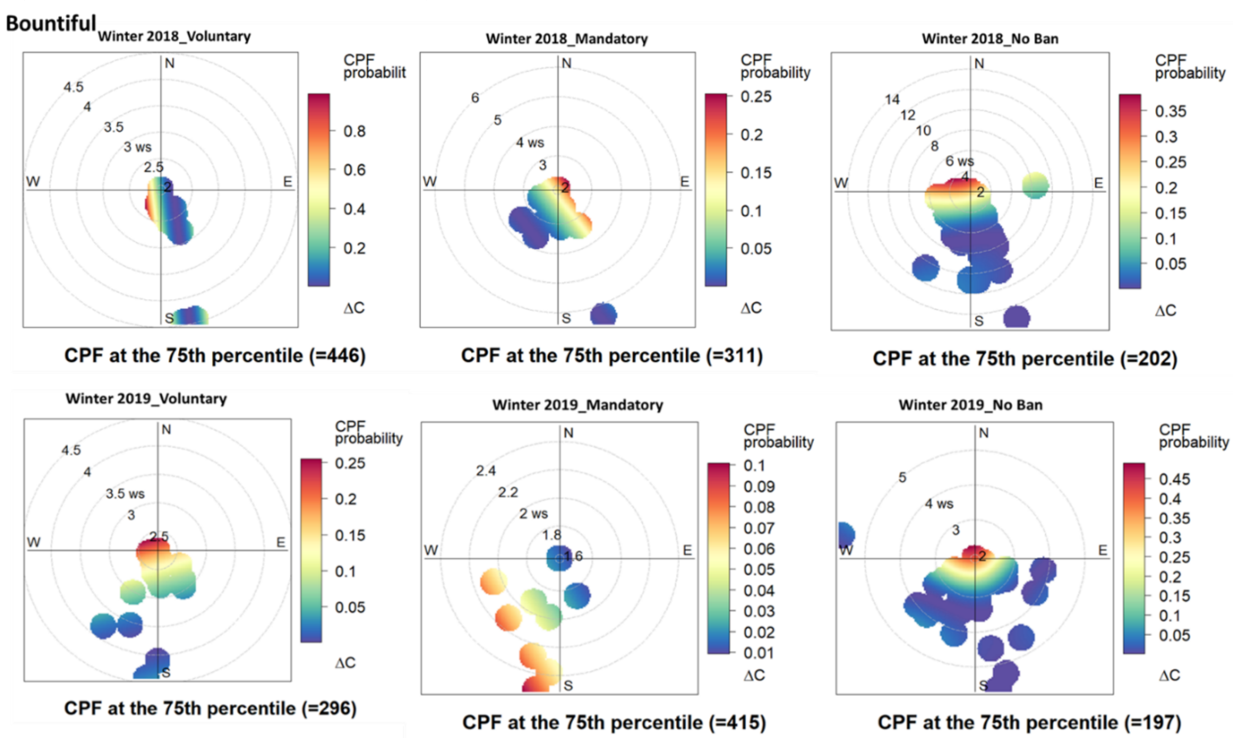

Figure 2. CPF bivariate probability function plots for the delta-C data collected at Bountiful station.

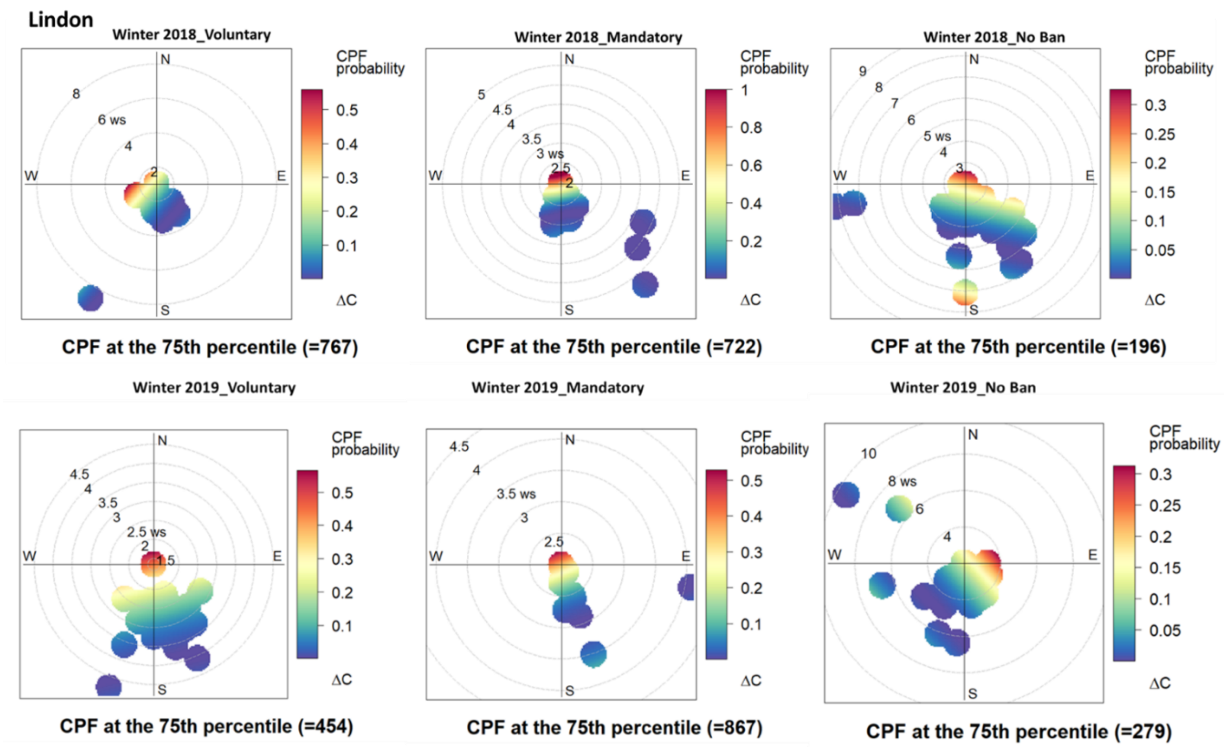

Figure 3. CPF bivariate probability function plots for the delta-C data collected at Lindon station.

Summary

This study explored two different approaches to estimate the compliance rates, one based on the differences in light absorption of brown carbon relative to BC and the other based on wood burning molecular markers. The approach based on chemical tracers was developed to validate the compliance rates obtained from the aethalometer measurements. Despite the fact that both approaches rely on different assumptions, estimated rates were comparable for Smithfield and Bountiful sites. The approach using delta-C concentrations was validated by comparing the compliance rates for two winter seasons, 2018-2019 and 2019-2020, which resulted in similar estimated rates for both seasons. The results suggest that compliance rates may be in the range of the rates estimated in this analysis. The lower compliance rates for no-burn days suggest that the contribution of wood combustion emissions on no-burn days are close to those measured when restrictions were not issued. A CPF analysis showed that high concentrations occurred with low wind speeds.

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