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RESEARCH EXTENSION NOTE
NO. 11 – Sept 2017

Trends in fine particulate matter ($PM_{2.5}$) concentrations in Prince George, British Columbia, Canada

By
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Jackson, P.L., Albino, J., Birch, C., Nilson, B, Pawluk, J. & Tereshchak, T. 2017. Trends in fine particulate matter ($PM_{2.5}$) concentrations in Prince George, British Columbia, Canada. Natural Resources and Environmental Studies Institute. Research Extension Note No. 11, University of Northern British Columbia, Prince George, B.C., Canada.

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Abstract

Prince George, in central British Columbia, Canada, periodically experiences high levels of outdoor fine particulate matter (PM) less than 2.5 µm in diameter ($PM_{2.5}$) due to a combination of emissions, meteorological conditions and valley topography. The Prince George Air Improvement Roundtable (PGAIR) outlined several goals for $PM_{2.5}$ reductions by 2013 and 2016 in their Phase III Implementation Plan, which was produced in 2011. Monitoring data from 1998-2016 at the Plaza 400 monitoring site located in downtown Prince George, were analyzed to identify trends and ambient levels of $PM_{2.5}$ and determine whether these goals were met. Although none of the goals were achieved every year, the 2013 goal of annual average $PM_{2.5}$ less than 6 $\mu g\ m^{-3}$ was met in three of the six years from 2011-2016. The $PM_{2.5}$ mean and 98th percentile ambient levels in downtown Prince George have both decreased significantly over time since 2005: by 29% (1.92 $\mu g\ m^{-3}$) for the mean, and by 26% (7.92 $\mu g\ m^{-3}$) for the 98th percentile. These downward trends in overall $PM_{2.5}$ levels were largely driven by even larger decreases when winds came from the east (from the direction of the heavy industrial sector to the east of downtown Prince George), suggesting that source reductions from this sector are having a measurable and positive impact on lowering $PM_{2.5}$ levels in Prince George. It is recommended that PGAIR update the emission inventory and set future goals that are more achievable, measurable, and based on current monitoring technology.

Introduction

Air pollution is an important world-wide health concern. Globally, particulate matter (PM) affects people more than any other ambient air pollutant. According to the World Health Organization (WHO), particulate matter (PM) smaller than 10 µm and 2.5 µm in diameter (PM_{10} and $PM_{2.5}$, respectively) in cities and rural areas contributed to about 3 million premature deaths worldwide in 2012 (WHO, 2016). Many studies have emphasized the link between air pollution, cardiovascular illness and premature death (e.g. Kloog et al., 2013). Particulate matter can have a different composition based on its origin, and is typically a complex mixture of solids and liquids. Particles with a diameter less than 10 µm (PM_{10}) and especially those with a diameter less than 2.5 µm ($PM_{2.5}$) have the most damaging effect on human health as they can penetrate deep inside the lungs and pass into the bloodstream (Kloog et al., 2013). In 2002, the WHO set guidelines recommending that the annual average ambient (outdoor) $PM_{2.5}$ concentration should be less than 10 µg m^{-3} and the 24-hour average $PM_{2.5}$ concentration should be less than 25 µg m^{-3} (WHO, 2016). The WHO notes that achieving such annual and daily targets will significantly lower risks for both chronic and acute health effects from $PM_{2.5}$ air pollution.

Prince George, British Columbia (BC), Canada, has among the highest PM levels in the Province. Community concern for this issue led to the formation of a cross-agency committee in 1998 to come up with solutions to improve ambient air quality. The current committee charged with improving air quality is the Prince George Air Improvement Roundtable (PGAIR), a non-profit society composed of stakeholders from government institutions, industry, community groups, healthcare providers, educational institutions, and the general public. PGAIR's goals are summarized by this statement:

> "*PGAIR is committed to researching, monitoring, recommending and implementing air quality improvements and promoting public awareness and education in the Prince George airshed, with the goal of improving the air quality in the community.*"

To enact these goals, PGAIR promulgated their Phase III Implementation Plan in 2011, with a primary focus on the reduction of $PM_{2.5}$ emissions (PGAIR, 2011). PGAIR set the following aspirational goals for ambient $PM_{2.5}$ concentrations in the Phase III plan:

- by 2013, daily average $PM_{2.5}$ concentrations not exceeding 25 µg m^{-3}, and annual average $PM_{2.5}$ concentrations not exceeding 6 µg m^{-3};
- by 2016, a 40% reduction of all significant sources, and annual average $PM_{2.5}$ concentrations not exceeding 5 µg m^{-3} (PGAIR, 2011).

Notably, these targets proposed by PGAIR in the Phase III Implementation Plan are equal to or more stringent than provincial, national and international standards for ambient air quality. Table 1 compares PGAIR's $PM_{2.5}$ targets with international, national and provincial standards. Although PGAIR has limited powers to directly reduce anthropogenic $PM_{2.5}$ emissions, its diverse composition and community focus uniquely situates it to provide impetus to the public and industry to strive to achieve these targets.

Table 1. Target annual and 24-hour average $PM_{2.5}$ concentrations of PGAIR compared to international, national, and provincial standards (WHO, 2016; BCMoE, 2009; CCME, 2014; PGAIR, 2011).

Organization	Averaging Time	
	Annual (μg m^{-3})	24-hour (μg m^{-3})
PGAIR Targets	2013: 6 2016: 5	2013: 25
WHO Guidelines	2002: 10	2002: 25
Canadian Ambient Air Quality Standards (CAAQS)	2015: 10 2020: 8.8	2015: 28[1] 2020: 27[1]
British Columbia Standards	2009: 8	2009: 25[1]

[1] Achievement is based on a 3-year average of the 98th percentile of the daily 24-hour concentration.

To help PGAIR achieve its targets and critically assess its goals, this paper will analyze trends in ambient $PM_{2.5}$ concentrations measured at the Plaza 400 monitoring site in downtown Prince George, to determine whether the goals of the Phase III Implementation Plan were met. A limitation of this report in regards to assessing the goals of PGAIR, is that it only considers ambient (outdoor) air quality at the Plaza 400 monitoring station. PGAIR's 40% reduction target for all significant sources is based on emissions, not ambient air quality, so the results found in this report cannot directly relate to that target.

Air Pollution Meteorology of Prince George, British Columbia, Canada

The city of Prince George, with a population 74,003 (BCStats, 2016), is situated at the confluence of the Nechako and Fraser Rivers in a valley approximately 150 meters below the BC Central Interior Plateau (Fig. 1). The wind-sheltered valley area of Prince George experiences frequent temperature inversions. These inversions occur when a stable, cold layer of air is overlain by warmer air (BCMoE, 2016). Shallow (~100 m deep), surface-based inversions occur overnight due to surface cooling; deeper, elevated inversions that are more persistent occur due to subsidence associated with anticyclones. Thermal inversions are associated with stagnant air conditions in the valley that often result in elevated pollution levels (Noullett et al., 2006). Winter meteorological conditions can result in more frequent temperature inversions in the valley, less atmospheric mixing from daytime solar radiation heating of the surface, and consequently higher levels of $PM_{2.5}$ pollution (BCMoE, 2016; Noullett et al., 2006). Other meteorological conditions that influence $PM_{2.5}$ concentrations include wind and precipitation events (Stantec, 2010). Although strong winds can displace surface crustal materials into the air (including $PM_{2.5}$), they also disperse and transport air pollutants thus reducing ambient concentrations (Stantec, 2010). Precipitation events scavenge $PM_{2.5}$ out of the air, also reducing ambient concentrations (Stantec, 2010). The topography of Prince George along with these stagnant meteorological conditions can restrict vertical mixing and dispersal of air contaminants, providing many challenges in managing air quality.

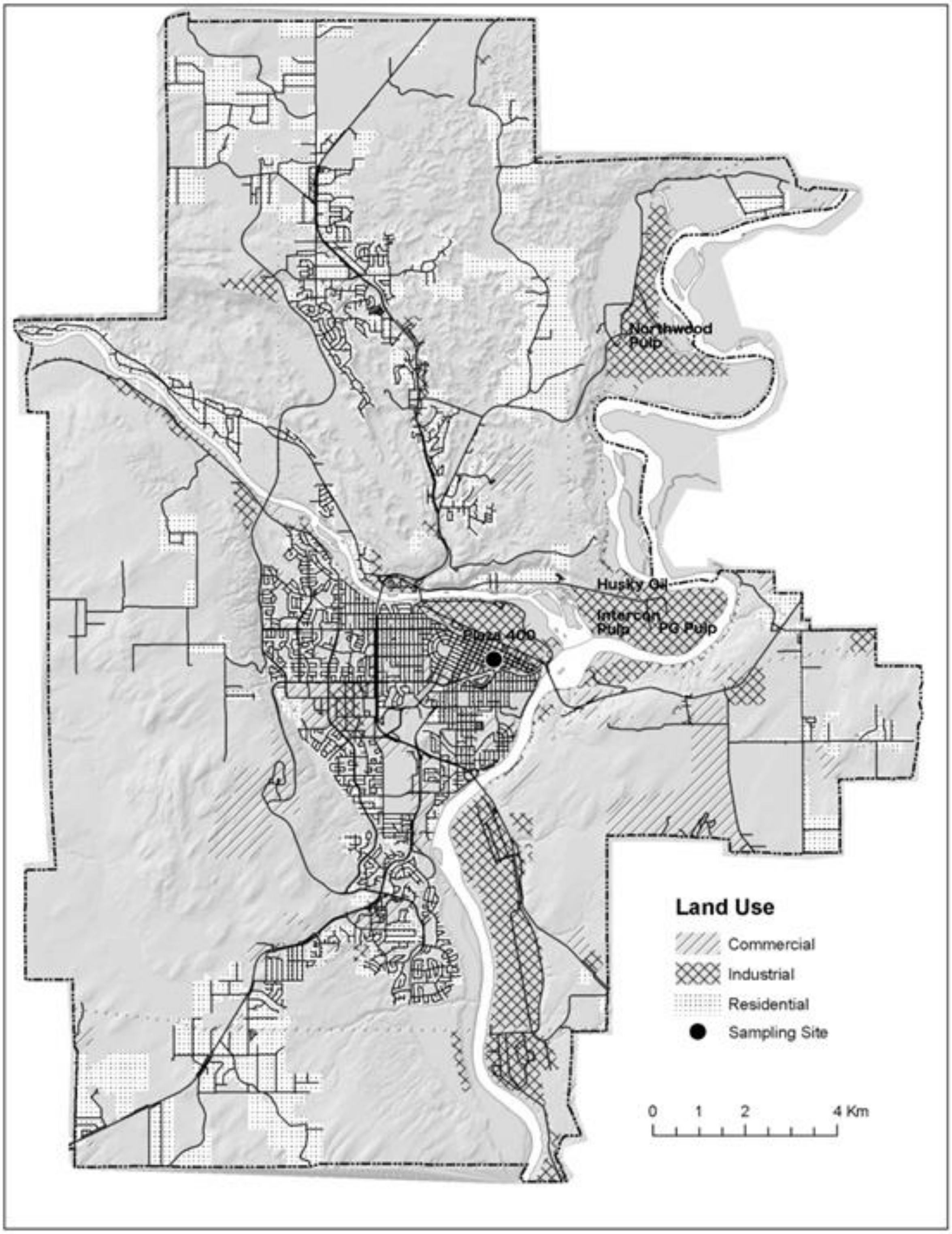

Figure 1. A map of Prince George, B.C. showing land use and the Plaza 400 sampling site location.

Three kraft pulp mills (east and northeast of Plaza 400), and other industrial sources in Prince George contribute significant amounts of $PM_{2.5}$ to the airshed, mainly through combustion of biomass (BCMoE, 2016; Fig. 1). Other important anthropogenic sources of $PM_{2.5}$ in the Prince George area include open burning of wood debris, wood burning for residential heating, cooking from commercial and household stoves, locomotive emissions, and diesel and gasoline vehicle combustion engines (BCMoE, 2016), as well as anthropogenic dust sources such as road dust and fugitive dust. Wood burning for heat occurs primarily during the winter months.

Significant natural sources of $PM_{2.5}$ affecting the Prince George airshed include forest fires and dust (BCMoE, 2016). These natural sources are both emitted in the airshed and also advect into the airshed; they can have a significant effect on both average $PM_{2.5}$ levels as well as episodes of high $PM_{2.5}$. Background air pollution originates from natural sources in the airshed and from both anthropogenic as well as natural sources transported from one airshed to another (Veira et al., 2013). Background concentrations are important to consider because they cannot be managed in an airshed (Veira et al., 2013), yet may contribute to a significant proportion of ambient $PM_{2.5}$. Therefore it is important to know what the background concentrations are, so that the manageable portion of the ambient concentration can be determined and considered in setting any air quality management objectives. In the absence of a background monitor located upwind of an airshed, one way to determine background concentrations is through an assessment of ambient $PM_{2.5}$ levels from wind directions in which there are no major anthropogenic sources. This is possible in smaller communities because there may be no or limited anthropogenic sources when the wind comes from certain directions. Consequently, measurement of background $PM_{2.5}$ pollution can be achieved by ambient air quality monitors, even when they are located in the centre of small cities, such as at the Plaza 400 monitoring site in Prince George, British Columbia

Methods

This paper uses hourly monitoring data from the BC Ministry of Environment Plaza 400 monitoring site located in downtown Prince George (Fig. 1) from 1998 - 2016. Plaza 400 is a comprehensive monitoring site with a long record of both meteorological and air quality data, including $PM_{2.5}$, PM_{10}, Ozone, total reduced sulphur (TRS), NO_x, NO, NO_2, and SO_2 (BCMoE 2016). In 2013, the British Columbia Ministry of the Environment (BCMoE) installed a Synchronized Hybrid Ambient Real Time Particulate (SHARP) monitor alongside the existing Tapered Element Oscillating Microbalance (TEOM) at Plaza 400 (BCMoE, 2016) to measure $PM_{2.5}$. Besides practical reasons for phasing out the TEOM monitor (i.e. discontinued technical support for by its manufacturer), TEOM measurements of $PM_{2.5}$ do not correlate with Federal Reference Method (FRM) measurements as well as SHARP measurements do: TEOM measurements of $PM_{2.5}$ are typically lower than those of both FRM and SHARP (Larsen and Bender, 2014; Hsu et al., 2016), although both monitors are designated as "Federal Equivalent Methods" (FEM) by the US Environmental Protection Agency. Discontinuous, filter-based Federal Reference Method (FRM) monitoring was not used in the present analysis as it is only available every sixth day as a 24-hour average.

Analysis of the Plaza 400 $PM_{2.5}$ data was done using the statistical software R (R Core Team, 2016) and the R openair package (Carslaw and Ropkins, 2012; Carslaw, 2015). Hourly meteorological data (wind speed, wind direction, relative humidity (RH), and temperature (T)) from Plaza 400 were obtained for the period of 1998 to the end of 2016. Hourly $PM_{2.5}$ concentration data from the TEOM monitor were collected from January 1998 to July 2015, and SHARP monitor data from August 2010 to the end of 2016. It is important to note that there were several brief periods during the overlap time of the two monitors, where the SHARP monitor was inactive for maintenance; however there were approximately three years of data overlap to compare the monitors to one another.

Quality assurance methods applied to the data include setting any $PM_{2.5}$ values between 0 and -3.49 µg m^{-3} to zero, and any values less than or equal to -3.5 µg m^{-3} to missing, following guidelines used by the BC Ministry of Environment (Gail Roth, 2017, personal communication). In addition, winds were set to 0 speed and direction (or missing, depending on the analysis) when the wind speed was less than 0.5 m s^{-1} since the wind direction is unreliable at low wind speeds. Missing values were omitted during analysis.

Hourly $PM_{2.5}$ concentrations from SHARP were compared with those from TEOM for the period of overlapping measurements from 2013 to 2015. The hourly $PM_{2.5}$ averages of SHARP (9.87 µg m^{-3}) and TEOM (6.77 µg m^{-3}), indicate that SHARP typically measures higher values than TEOM, especially at higher concentrations of $PM_{2.5}$. Based on the difference between the means of the hourly SHARP and TEOM data, it would be reasonable for PGAIR to add an average of ~3 µg m^{-3} (this amount varies seasonally with larger differences in colder seasons) to the former TEOM-based goals to have updated goals based on SHARP $PM_{2.5}$ measurements.

To extend the TEOM $PM_{2.5}$ record from July 2015 when the TEOM was decommissioned, to the end of 2016, it was necessary to adjust the SHARP measured $PM_{2.5}$ concentrations so that they are equivalent to the TEOM measurements. Relating the SHARP to the TEOM data was accomplished with a multivariate linear model using SHARP $PM_{2.5}$ measurements as well as RH and T. The model was tested with all combinations of these variables, comparing R^2 and RMSE values (Table 2). Although all models had similar performance, the model incorporating all three variables was slightly superior and was chosen:

$$TEOM_M = a + b(SHARP) + c(T) + d(RH)$$

where $TEOM_M$ is the modelled TEOM $PM_{2.5}$ level (µg m^{-3}), SHARP is the observed SHARP $PM_{2.5}$ level (µg m^{-3}), T is temperature (ºC) and RH is relative humidity (%). The coefficients a-d were determined by the linear model applied to the overlapping period of TEOM and SHARP $PM_{2.5}$ measurements, and found to be: a = 0.07475, b = 0.82857, c = 0.03640, d = -0.02454.

This model was then applied to the SHARP data, effectively adjusting it to reconstruct TEOM data for trend analysis purposes. The difference

Table 2. Results from various linear models used to fit the hourly SHARP to the hourly TEOM data. R^2 is the coefficient of determination, denoting the fraction of variance in TEOM that is explained by SHARP – effectively how well the data fits the linear regression model (values closer to 1 are better). RMSE is the Root Mean Square Error and is the standard deviation of the differences between modelled TEOM and actual TEOM data (lower values are better). T is temperature (ºC) and RH is relative humidity (%). The linear model in **bold** was the one chosen to extend the TEOM data.

Linear Model	R^2	RMSE (µg m^{-3})
No model applied	0.864	5.63
Modelled using SHARP but not considering T or RH	0.864	4.22
Modelled using SHARP and T but not RH	0.871	4.17
Modelled using SHARP and RH but not T	0.870	4.06
Modelled using SHARP, RH and T	**0.876**	**4.02**

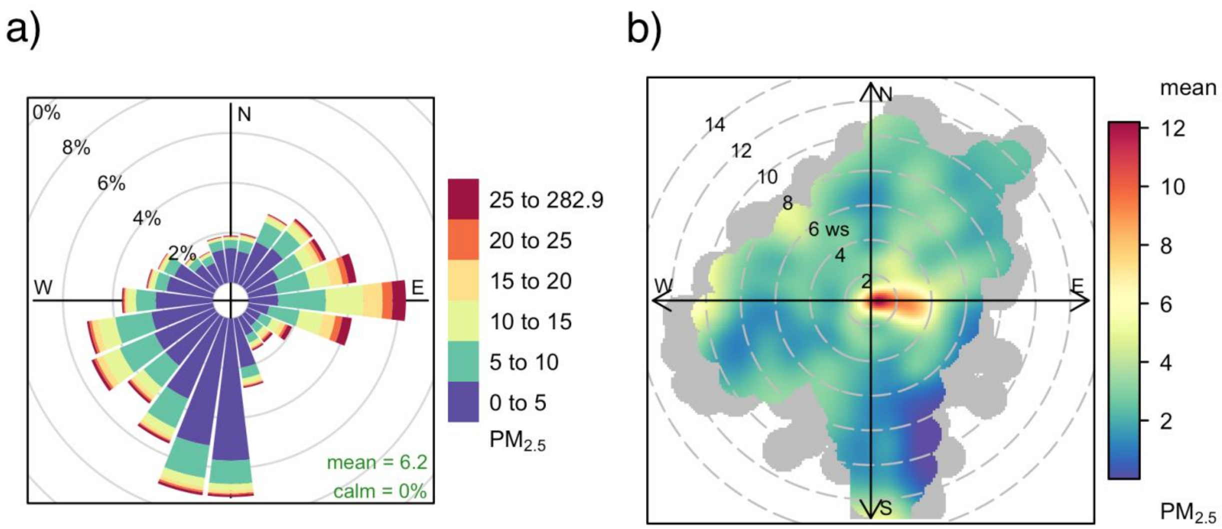

Figure 2. Hourly $PM_{2.5}$ concentrations (µg m^{-3}) at Plaza 400 by wind direction for 2005-2016. a) Pollution Rose in which the radial distance is the frequency at $PM_{2.5}$ concentrations given by the colour key. b) Bivariate polar plot in which the radial distance is wind speed (m s^{-1}) and the colours correspond to the average $PM_{2.5}$ concentration at a particular wind speed and direction. The grey shaded areas indicate values occurring two or fewer times and are not used in this analysis. Note: Data prior to July 2015 use TEOM measurements while from July of 2015 onwards $TEOM_M$ data are used (SHARP data fitted with a linear model to reconstruct TEOM data).

between the fitted SHARP data ($TEOM_M$) and TEOM mean was essentially zero and the difference between the fitted and TEOM median was small (-0.077 µg m^{-3}).

An analysis of ambient air pollution levels by wind direction can tell us much about the direction of significant sources from an air quality monitoring station. One graphical form of such an analysis is a pollution rose diagram (Fig. 2a) in which the radial direction is the direction from which the wind is blowing, the radial distance is the frequency of hourly observations from a given wind direction, and the "petals" of the rose diagram are colour-coded to represent the various air pollution levels. The pollution rose diagram tells us the frequency of various air pollution levels by wind direction. The $PM_{2.5}$ pollution rose for the Plaza 400 station shown in Fig. 2a suggests that the most frequent wind directions are from the south, followed by the east, and that the winds from the east have more frequent high $PM_{2.5}$ concentrations. Another graphical analysis that can assist in identifying the direction of significant sources from a monitoring location is a bivariate polar plot of contoured average pollutant concentration with wind speed as the radial distance (Fig. 2b) that also indicates the highest average $PM_{2.5}$ levels occur when (light) winds are from the east. The region to the east of the Plaza 400 monitor is the heavy industrial zone in Prince George where two pulp mills (with a third one further away to the northeast) and an oil refinery are located (Fig. 1).

These graphical analyses can also be used to identify low concentration wind sectors to find background concentration levels using the method of Veira et al. (2013). In this method, background concentrations are inferred from the wind direction and wind speed sectors associated with the lowest recorded $PM_{2.5}$. Since the low concentration wind sectors determined in the present study were similar to those found in Veira et al. (2013) for the Plaza 400 monitoring site, the same low concentration sectors were used at the same wind speed ranges to determine background concentrations in the present study (Veira et al., 2013; Fig. 2b). Specifically, wind speeds greater than 3 m s^{-1} and from the sectors of 350º - 10º, 150º - 170º, and 230º - 250º (Fig. 2b) were used to determine background concentrations.

Quantifying trends in air pollution levels to detect the effects of emission changes over time and evaluate the efficacy of air quality management actions can be difficult for several reasons. One reason is the large variation in atmospheric dispersion both within an annual cycle and between years, which can cause considerable variation in air pollution concentrations even if emissions are constant. Another reason that is especially relevant for $PM_{2.5}$ in the Prince George airshed, is the occurrence of sporadic very high concentrations, mainly for a few days in the summer months, from forest fires, which can be particularly prominent in some years. For example it is well known that in recent years, Prince George was affected by forest fire smoke for periods in the summers of 2010, 2014, and 2017. Even a few days of very high levels of $PM_{2.5}$ from uncontrollable forest fire sources can significantly impact both monthly and the annual mean, and affect the assessment of trends in ambient levels. A third factor that must be taken into consideration in analysing trends in air pollution levels is that the distribution of air pollution concentrations is positively skewed and non-normal, so that non-parametric statistical methods should be used to assess the significance of any trends detected

To resolve these issues, trends are calculated using the non-parametric Theil-Sen method (Theil, 1950; and Sen, 1968; as cited in Carslaw, 2015) using the R openair TheilSen function (Carslaw, 2015). In this method the slope between each pair of points in the time series is calculated, and the estimated slope is the median of all these slopes. This method works well even when the data are non-normal and have non-constant error variances (Carslaw, 2015). The method is also less sensitive to outliers such as very high $PM_{2.5}$ concentrations during forest fires. Trends are calculated using both monthly averages (to assess trends in chronic exposure levels) and the monthly 98th percentile of hourly averages (to assess trends in acute or episodic exposure levels) over the period 2005 to 2016. The monthly values are first de-seasonalized with the R stl function, a seasonal trend decompositor using LOESS regression (Carslaw, 2015).

The 2005-2016 period was chosen for the detailed trend analysis for two reasons. First, and most importantly, it corresponds to a period of time in which the $PM_{2.5}$ measurements from the TEOM are relatively stable. On 15 September 2004 the $PM_{2.5}$ inlet on the Plaza 400 TEOM was changed from a URG head (made by URG Corporation) to a Sharp-Cut Cyclone head (BCMoE, 2013), which more effectively removed larger particles from the air stream and lowered the measured concentration. Using a time period starting before 2005 for trend analysis would either have created an erroneously large downward trend or necessitated application of a correction factor to the earlier TEOM data, introducing its own sources of error. Second, it is a long enough period to provide a reasonable estimate of trends when deseasonalized monthly mean values are used (n = 144 months) instead of just annual means.

In the results that follow, the analysis of $PM_{2.5}$ concentrations at Plaza 400 is presented over three time periods. Annual averages and exceedances of PGAIR's 24-hour average goal of 25 μg m^{-3} are presented graphically for the full period of available data (1998-2016). Because of the previously discussed changes in the TEOM monitor's inlet in 2004, the full period of record is not suitable for quantitative trend analysis. Consequently, the period 2005-2016 is used for the detailed trend analysis and the analysis of pollutant levels by wind direction. In addition, because the PGAIR Phase III Implementation Plan pertains to the 2011-2016 period, some of the results are presented for this 5-year period.

Results

Analysis of ambient 24-hour hour average $PM_{2.5}$ concentrations for the period relevant to PGAIR's Phase III Implementation Plan (2011-2016) reveals large variation in concentrations. Values are usually under PGAIR's goal of 25 μg m^{-3}, with episodic exceedances of this value. The number of daily average $PM_{2.5}$ exceedances of 25 μg m^{-3} decreases after 2004 (Fig. 3), however this could

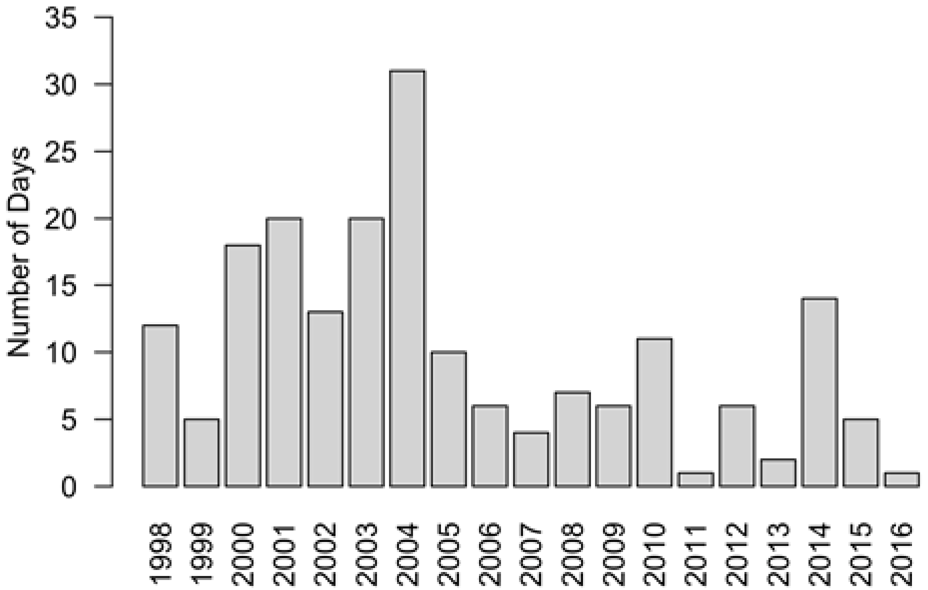

Figure 3. Number of days per year where the 24-hour average $PM_{2.5}$ concentration exceeded PGAIR's goal of 25 µg m^{-3} at Plaza 400. Note: Data prior to July 2015 use TEOM measurements while from July of 2015 onwards $TEOM_M$ data are used (SHARP data fitted with a linear model to reconstruct TEOM data). Some years are affected by forest fires more than others – notably 2010 and 2014. Prior to 2005, the TEOM used a different inlet that results in higher readings.

be due in part to the change in the TEOM $PM_{2.5}$ sampling inlet from a URG to a Sharp-Cut Cyclone head on 15 September 15 2004 (BCMoE, 2013) that was discussed previously. Nevertheless, it can be stated that PGAIR's daily average target was not met during this period, as there was at least one exceedance of the daily 25 µg m^{-3} ambient concentration each year. Between 2011 and 2016, the 24-hour average of 25 µg m^{-3} was at the 98.7th percentile, meaning that this level was exceeded an average of 4.83 days per year.

Annual $PM_{2.5}$ concentrations have shown a decreasing trend from 1998 to 2016 (Fig. 4), although as previously mentioned the TEOM sensor from 1 January 1998 to 15 September 2004 used a different inlet that would have resulted in higher measured concentrations. Fig. 4 suggests a weak relationship between annual average wind speed and $PM_{2.5}$ concentration: higher annual average wind speeds correspond with reduced annual average $PM_{2.5}$ concentrations. This relationship illustrates the importance of variation in year-to-year meteorological conditions on air pollution levels. Although PGAIR's annual $PM_{2.5}$ concentration goals of less than 6 µg m^{-3} by 2013 and less than 5 µg m^{-3} by 2016 were not achieved every year, the 6 µg m^{-3} annual goal was achieved in 2011, 2015, and 2016. Figure 4 also displays the annual average $PM_{2.5}$ concentrations partitioned into 'manageable' and 'background' concentrations. Background concentrations are estimated using the Veira et al. (2013) method, and are estimated to account for 18% to 35% of the total yearly average concentration measured at Plaza 400, and ranged from approximately 1µg m^{-3} to 3 µg m^{-3}. Thus, the manageable portion of the average annual concentrations ranges from approximately 3.5 µg m^{-3} to 8 µg m^{-3} over the 19-

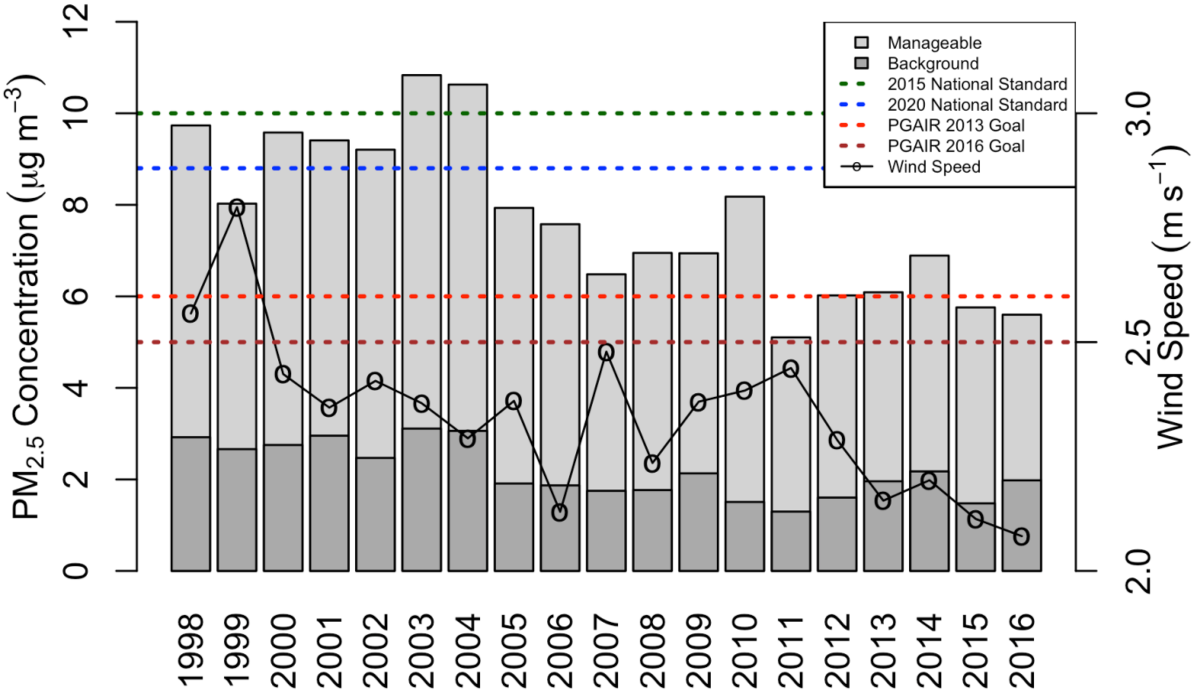

Figure 4. Annual average PM$_{2.5}$ concentration (µg m^{-3}) on the left y-axis, and wind speed (m s^{-1}) on the right y-axis, at Plaza 400. PGAIR goals for 2013 and 2016 as well as National Standards for 2015 and 2020 are indicated with horizontal dashed lines for reference. The *background* portion of the annual average concentration is calculated using the method of Veira et al. (2013). The *manageable* portion of the concentration represents the difference between the observed concentration and the calculated background concentration. Note: Data prior to July 2015 use TEOM measurements while from July of 2015 onwards *TEOM$_M$* data are used (SHARP data fitted with a linear model to reconstruct TEOM data).

year period. The annual average manageable concentrations have decreased since 1998, and appear relatively steady since 2011 (Fig. 4).

The trend in deseasonalized average monthly PM$_{2.5}$ concentrations at Plaza 400 (representing chronic exposure levels) from 2005-2016 shown in Fig. 5a is -0.16 µg m^{-3} per year, which is statistically significant ($p < 0.001$). This represents a decrease in the mean by 1.92 µg m^{-3} (29% of the overall average of 6.62 µg m^{-3}) over the 12-year period, and a decrease in the mean by 0.8 µg m^{-3} (12%) over the 2011-2016 period. The trend in 98th percentile levels (representing episodic levels for acute exposure) shown in Fig. 5b is also downward and larger than the mean trend: -0.66 µg m^{-3} per year, which is also statistically significant ($p < 0.001$). This represents a decrease in the 98th percentile by 7.92 µg m^{3} (26% of the overall 98th percentile of 30.01 µg m^{-3}) over the 12-year period, and a decrease in the 98th percentile by 3.3 µg m^{-3} (11%) over the 2011-2016 period.

An examination of the trends in monthly average concentrations by wind direction (Fig. 6) suggests source sectors that are most important to the overall downward trend. The centre rose diagram

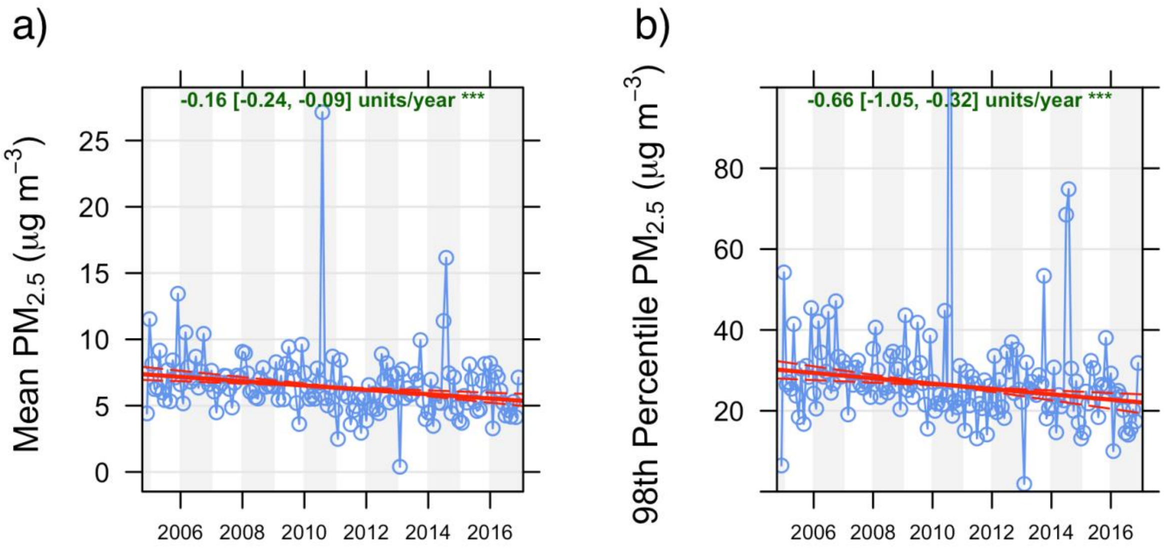

Figure 5. Deseasonalized monthly $PM_{2.5}$ concentrations (µg m^{-3}) at Plaza 400 from 2005-2016 for a) mean, and b) 98th percentile. The red line is the Theil-Sen estimated slope of -0.16 µg m^{-3} per year for the mean and -0.66 µg m^{-3} per year for the 98th percentile which are both significantly different from zero ($p<0.001$). The dashed lines are the 95% confidence limits on the slope. Note: Data prior to July 2015 use TEOM measurements while from July of 2015 onwards $TEOM_M$ data are used (SHARP data fitted with a linear model to reconstruct TEOM data).

in Fig. 6 shows the proportion each wind direction by $PM_{2.5}$ concentration level contributes to the mean at Plaza 400 and illustrates the importance of sources to the east of the Plaza 400 monitoring location. These sources would include the heavy industry (two pulp mills and an oil refinery) located near the junction of the Fraser and Nechako Rivers shown in Fig. 1. The largest decreasing trends are with winds from the east (-0.41 µg m^{-3} per year), northeast and southwest (both at -0.15 µg m^{-3} per year). Over the five-year period from 2011-2016 these represent decreases of 2.05 µg m^{-3} from the east sector, and 0.75µg m^{-3} from the northeast and southwest sectors.

Trends in the 98th percentile concentrations can be used to represent how episodic $PM_{2.5}$ levels (acute exposure) are changing over time. The eight outside sub-plots in Fig. 7 show trends in the deseasonalized monthly 98th percentile concentration by wind direction. The centre sub-plot shows the 98th percentile conditional probability over all wind directions. The conditional probability is the ratio of the number of samples in the given direction that are equal to or higher than the overall 98th percentile, divided by the total number of samples in that wind direction and shows the probability of having a $PM_{2.5}$ measurement equal to or greater than the 98th percentile for each wind direction. The Fig. 7 centre sub-plot illustrates the importance of the east sector on episodic (98th percentile) $PM_{2.5}$ levels at the Plaza 400 monitoring site. The largest decreasing trends in the monthly 98th percentile is from the east sectors at -1.01 µg m^{-3} per year, corresponding to a decrease of 5.05 µg m^{-3} over the 5-year period from 2011-2016.

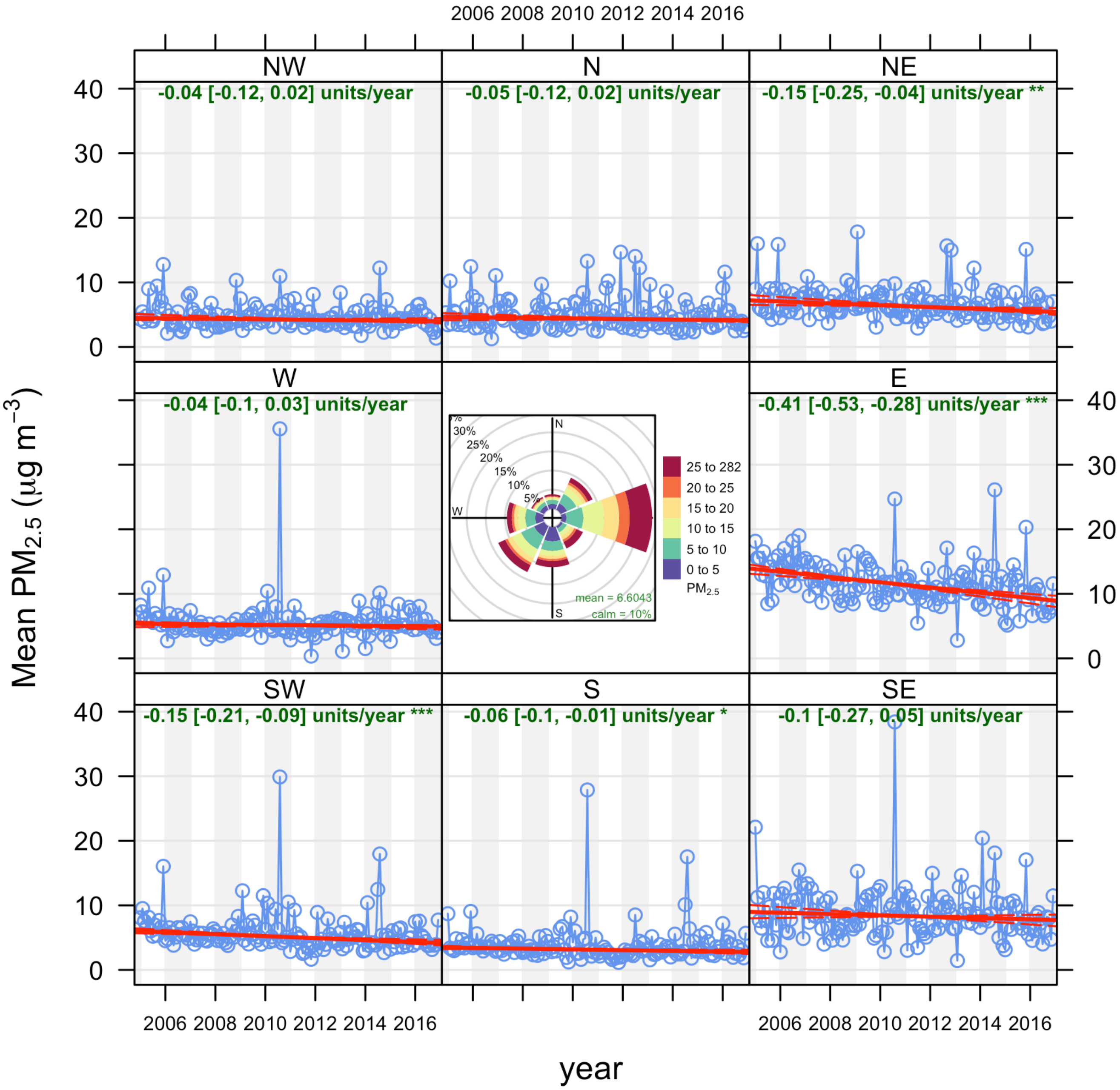

Figure 6. Deseasonalized monthly average $PM_{2.5}$ concentrations (µg m^{-3}) at Plaza 400 from 2005-2016 for 8 wind directions. The centre rose diagram shows the proportion each wind direction and $PM_{2.5}$ concentration contributes to the mean. The red line in each sub-plot is the Theil-Sen estimated slope with dashed lines showing the 95% confidence limits on the slope. The numerical values of the slope in µg m^{-3} per year and 95% confidence limits are shown at the top of each sub-plot. The symbols shown next to each trend estimate relate to how statistically significant the trend estimate is: p<0.001=∗∗∗, p<0.01=∗∗, p<0.05=∗ and p < 0.1 = +. Note: Data prior to July 2015 use TEOM measurements while from July of 2015 onwards $TEOM_M$ data are used (SHARP data fitted with a linear model to reconstruct TEOM data).

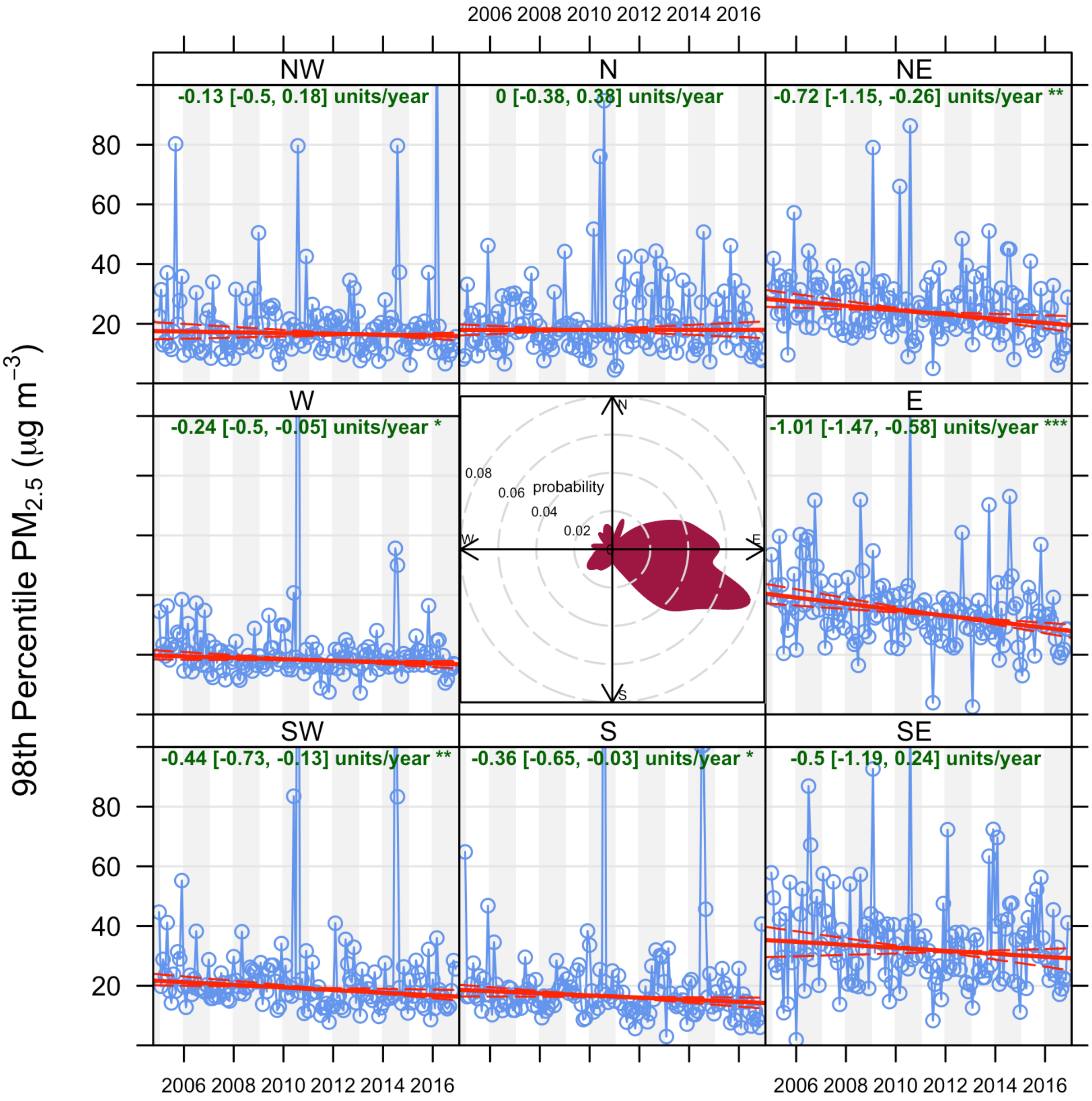

Figure 7. Deseasonalized monthly 98th percentile $PM_{2.5}$ concentrations (µg m^{-3}) from 2005-2016 for 8 wind directions (around the outside edges). The centre plot shows the 98th percentile conditional probability over all wind directions. It is the ratio of the number of samples in the given direction that are higher than the 98th percentile over all wind directions, divided by the total number of samples in that wind direction. The red line in each sub-plot is the Theil-Sen estimated slope with dashed lines showing the 95% confidence limits on the slope. The numerical values of the slope in µg m^{-3} per year and 95% confidence limits are shown at the top of each sub-plot. The symbols shown next to each trend estimate relate to how statistically significant the trend estimate is: $p<0.001=***$, $p<0.01=**$, $p<0.05=*$ and $p < 0.1 = +$. Note: Data prior to July 2015 use TEOM measurements while from July of 2015 onwards $TEOM_M$ data are used (SHARP data fitted with a linear model to reconstruct TEOM data).

Discussion

Discrepancies between the SHARP and TEOM are thought to be due to differences in the measurement principle between the instruments and different sensitivities to RH and temperature (Larsen and Bender, 2014; Hsu et al., 2016). Since for the majority of the period, only TEOM measurements were available, this report relied mainly on the TEOM data. However, the statistical model relating SHARP to TEOM allowed for analysis of trends after the decommissioning of the TEOM monitor.

Daily average $PM_{2.5}$ concentrations varied considerably during the period relevant to PGAIR's Phase III Implementation Plan (2011 to 2016). Meteorological variability and seasonal source factors likely account for episodic exceedances of PGAIR's 24-h average goal of 25 $\mu g\ m^{-3}$. Specifically, exceedances can usually be attributed to atmospheric stagnation events associated with thermal inversions and smoke from forest fires during the summer. Since both meteorological variability and the occurrence of forest fires are almost entirely out of human control, a goal of zero exceedances is not realistically attainable. Nevertheless, since these conditions can be anticipated in most cases, it could be possible to implement strategies to reduce the negative effects of poor air quality days. It should also be reiterated that the abrupt downward shift in yearly exceedances and annual average levels after 2004 (Figs. 3 and 4) may be at least partly due to a change in the inlet of the TEOM monitor from a URG to a Sharp-Cut head.

Due to the impact of variations in wind speed and other meteorological factors on dispersion of air pollutants, it can be challenging to determine whether source emissions have increased or decreased based on ambient air concentration data alone. However results of the trend analysis between 2005-2016 suggests that both mean and 98th percentile $PM_{2.5}$ levels have decreased significantly (Fig. 5), and that the decreases are largest when winds are from the east (Figs. 6 and 7). This implies that source reductions in the heavy industrial sector to the east of Plaza 400 (BCMoE, 2016) have resulted in a measureable and significant reduction in both mean and episodic ambient $PM_{2.5}$ at the Plaza 400 monitoring location. Notable air emissions improvements in the east and northeast sectors include \$180M in upgrades to the three pulp mills since 2010 (Canfor, 2015). An alternate explanation for the relatively large downward trend in $PM_{2.5}$ when winds are from the east could be a trend of stronger winds from the east; however an assessment of trends in wind speed by direction (not shown) indicated no trend in easterly wind speeds from 2005-2016. This leads us to conclude that the downward trends are most likely a result of source reductions.

Analyses of trends in both emissions and ambient levels of most air pollutants, including $PM_{2.5}$, in most developed countries indicate a downward trend and improving air quality. For example, in the United States, trends in annual average ambient $PM_{2.5}$ levels from 480 monitoring sites show a decline in the annual average $PM_{2.5}$ of 11.0 $\mu g\ m^{-3}$ by 37%, or 2.3% per year, between 2000-2015 (EPA, 2017). In Canada, the annual average $PM_{2.5}$ level measured at 177 stations in the National Air Pollution Surveillance Program (NAPS) between 2000-2014 is 7.7 $\mu g\ m^{-3}$ with no significant trend found (ECCC, 2016), although an earlier study based on discontinuous monitors showed that $PM_{2.5}$ declined by 54%, or 2.2% per year between 1984-2008 (ECCC, 2013). At the Plaza 400 site between 2005-2016, the average $PM_{2.5}$ level was 6.62 $\mu g\ m^{-3}$ and the decline over the 12-year period was 29% or 2.4% per year, which is similar to the average trends in the US and Canada between 1984 and 2008. $PM_{2.5}$ levels at 54 urban or suburban sites in Europe declined by an average of 0.21 $\mu g\ m^{-3}$ per year between 2002-2011, while rural and background sites showed small but increasing trends (Guerriero et al. 2014). At the Plaza 400 site, the annual rate of decline was slightly lower, at 0.16 $\mu g\ m^{-3}$ per year. In many parts of the developing world air pollution levels are much higher and are increasing. For example, an analysis of $PM_{2.5}$ levels and trends across China using a combination of satellite data and surface-based monitors, found that country-wide average $PM_{2.5}$ levels are 32.90 $\mu g\ m^{-3}$ in summer and 72.24$\mu g\ m^{-3}$ in winter with levels increasing by 0.22 $\mu g\ m^{-3}$ per year between 2004-2013 (Ma et al., 2016).

Conclusions and Recommendations

Managing ambient pollutant concentrations in an airshed with multiple sources is challenging. PGAIR has managed to meet their 2013 annual average $PM_{2.5}$ concentration goal of 6 μg m^{-3} for 3 out of 6 years since 2011. The overall trends in $PM_{2.5}$ levels for both the monthly mean and monthly 98th percentile are downward, and both trends are statistically significant. These downward trends are largely driven by even larger downward trends when winds are from the heavy industrial sector to the east of Plaza 400. This suggests that emission reductions that have occurred there are having a significant and positive impact on $PM_{2.5}$ average and episodic levels in downtown Prince George. This report was based only on an analysis of ambient $PM_{2.5}$ data from the Plaza 400 monitoring station, and therefore was unable to assess the PGAIR goal of a 40% reduction from significant sources.

In light of this report's findings, there are several recommendations that PGAIR might consider moving forward. PGAIR should review the best available information prior to setting future goals, so that more realistic, flexible, measureable and achievable targets may be set. Since annual average background concentrations range from about 1-3 μg m^{-3}, it may be difficult to attain an annual average goal of 5 or 6 μg m^{-3} every year – especially during years when uncontrollable natural emissions from forest fires inflate the annual average. With knowledge of the manageable $PM_{2.5}$ portion, PGAIR may be able to set more achievable and better defined goals for the future. For example, allowing a certain number of exceedances of daily objectives per year should be examined. Perhaps PGAIR could adopt a similar strategy to the Canadian Ambient Air Quality Standards (CAAQS) and use the 98th percentile value, which allows a 2% exceedance per year for 24-hour average $PM_{2.5}$ levels. In addition, perhaps the annual average goals could be changed to achieving the target average $PM_{2.5}$ concentration for two out of three years, rather than for all years. PGAIR should also consider investigating why exceedances occurred and whether they could have been managed.

Another important consideration is the effect of the transition from TEOM to SHARP at the Plaza 400 site on future goals. This report determined that adding approximately 3 μg m^{-3} to the TEOM-based goals would be realistic for new goals based on SHARP data. Lastly, it is recommended that an updated emissions inventory for the airshed be produced to update the microemission inventory in Stantec (2010) that itself has been updated as part of the ongoing dispersion modelling study. This would provide PGAIR with a clearer understanding of the emission sources within and outside the Prince George airshed as well as providing a basis for future dispersion modelling to understand the contribution of specific sources to ambient air quality across the airshed

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