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Effects of Local Meteorology and Emissions on Winter $PM_{2.5}$ Variability in Fresno

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Abstract: The mass composition of Particulate Matter (PM) with an aerodynamic diameter of 2.5 microns ($PM_{2.5}$) in San Joaquin Valley (SJV) is dominated by ammonium nitrate (NH_4NO_3) which is a secondary pollutant. The goal of this research was the investigation of the relationship between emissions, meteorology and $PM_{2.5}$ concentrations in Fresno for the winter season. It was found that the location of sites near emission sources such as freeways compared with residential sites strongly affected measured $PM_{2.5}$ concentrations. It was found that although long-term trends showed declines in both emissions and $PM_{2.5}$ concentrations there was substantial variability between the years in the $PM_{2.5}$/emissions relationship. Much of the yearly variation in the relationship between emissions and $PM_{2.5}$ concentrations can be attributed to yearly variations in weather, such as atmospheric stability, precipitation frequency and average wind speed. There are moderate correlations between $PM_{2.5}$ concentrations and temperature differences between nearby surface stations at varying elevations which explains some of the daily and seasonal variation in $PM_{2.5}$. Occurrence of precipitation was related to low $PM_{2.5}$ although the higher wind speeds and lower atmospheric stability associated with precipitation likely explain some of the low $PM_{2.5}$ as well as washout of PM.

Key Words: Air Pollution; $PM_{2.5}$; SJV; Winter; Stability; Meteorology

1. Introduction

Particulate Matter (PM) is a major contributor to poor air quality in the San Joaquin Valley (SJV; [1,2]). The SJV covers the lower portion of central California extending downward from Sacramento through Fresno until it ends in the Tehachapi Mountains north of Los Angeles, Figure 1. Valleys limit pollutant dispersion and dilution and therefore the topography of the SJV is a factor that contributes to the high PM concentrations, especially during winter [3]. Van Donkelaar et al., [4] found high $PM_{2.5}$ (PM with aerodynamic diameter of <2.5 microns) concentrations across the SJV and the Los Angeles metropolitan area. High spatial contrast in $PM_{2.5}$ is expected due to diverse land cover/use and terrain features and the land/sea interface. California showed a more pronounced $PM_{2.5}$ spatial variation than the eastern U.S. [4,5]. Fresno, a major city in the SJV, has high $PM_{2.5}$ concentrations. Schauer and Cass [6] analyzed source contributions of $PM_{2.5}$ in Fresno and found 43% of the observed $PM_{2.5}$ was due to direct emissions (primary in origin). Much of the mass composition of the PM in the SJV is ammonium nitrate (NH_4NO_3; [7-9]). Pun and Seigneur [10] showed that during the wintertime NH_4NO_3 constitutes 30% of urban $PM_{2.5}$ and 60% of rural $PM_{2.5}$ in SJV.

Figure 1. Location of Fresno in the San Joaquin Valley (SJV) Meteorology has a strong effect on the chemistry of NH_4NO_3 formation. To form NH_4NO_3 particles, oxides of nitrogen (NO_X) must be converted to nitric acid (HNO_3) through photochemical processes and through nighttime gas-phase and heterogeneous chemistry. Photochemical reactions

during the day produce the hydroxyl radical (HO) and the reaction of NO_2 with HO is the most important source of HNO_3 formation during the daytime [11]. Gaseous ammonia (NH_3) and gaseous HNO_3 react to form ambient particulate NH_4NO_3.

$$NH_3(g) + HNO_3(g) \Leftrightarrow NH_4NO_3(g)$$

$$NH_4NO_3(g) \Leftrightarrow NH_4NO_3(s)$$

This equilibrium depends on temperature and relative humidity (RH; [12]). Increasing temperature leads to increasing rate of dissociation of NH_4NO_3(s) and remains constant for a given temperature below deliquescence RH [13]. Above the deliquescence RH, increasing RH leads to rapid decreases of dissociation.

Transport and mixing of emissions affect NH_4NO_3 formation times and these depend on windspeed, terrain, synoptic conditions and other factors. Smith and Lehrman [14] showed that surface transport distances are insufficient to mix NH_3 emissions with NO_x emissions to form secondary NH_4NO_3 in SJV, so wind speed has a minor effect on $PM_{2.5}$ formation. Precipitation may also have a strong effect on PM concentrations [15]. Mixing height is expected to be important because of its effects on the concentrations of gas-phase chemical species and PM [16].

Green et al. [17] found moderate correlations (r^2=0.4-0.6) between heat deficit (a vertical stability quantifier) and $PM_{2.5}$ at several cities in the western United States. However the heat deficit method cannot be determined for Fresno because there are no radiosonde or other long-term measurements of vertical temperature structure. In Reno Nevada daily variation in winter daily average $PM_{2.5}$ was moderately correlated to daily average temperature difference between a site on the valley floor and a slope-side site a few hundred meters above the valley floor (r^2=0.42 for winter 2008-2009 to r^2=0.785 for winter 2009-2010) [18]. A key goal of this research was to investigate the relationship between emissions, atmospheric stability, precipitation and $PM_{2.5}$ in Fresno. For an example, if there is a good relationship between surface temperature difference for nearby sites at varying elevation, we can estimate $PM_{2.5}$ concentration reasonably well.

2. Methods

Fresno County was chosen for our analysis because it has a large population of 989,255 that is exposed to poor air quality [19]. Therefore, in this study, we focused on how meteorological variables and emissions affect ambient $PM_{2.5}$ concentrations at sites in Fresno County, California (Table 1 and Figure 2). The meteorological measurement sites were located at: Garland, Clovis, Fancher Creek and Trimmer (Table 2). Garland is located in the middle of a large residential area. Fresno-Garland is an active super-site with an extensive amount of data. Clovis is close to a freeway and about 14 km north of Garland. Fancher Creek is about 14 km north of Clovis, and Trimmer is about 15 km north of Fancher Creek. The analysis of data extending between the years 2000 to 2016 was made separately for each of these four sites. We accounted for the background of each separately which makes the findings site specific. Although a more extensive analysis was made for Fresno-Garland due to the greater amount of available data, it should not be assumed to be representative of all the four sites because each site has different topographic features. Another factor that complicates our multiyear analysis of $PM_{2.5}$ concentrations is due to the fact that there have been many emissions reduction programs implemented in California over the last two decades. However these programs allow some evaluation of the impact of the emission reductions on $PM_{2.5}$ concentrations.

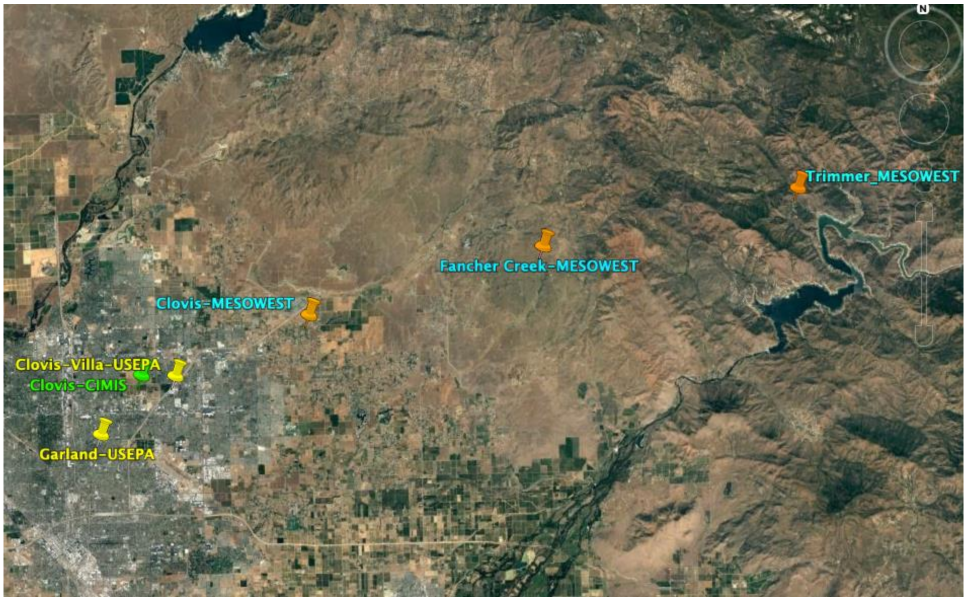

Figure 2. Locations of Garland, Clovis-Villa (USEPA), Clovis (CIMIS), Clovis (MESOWEST), Fancher Creek, and Trimmer sites.

Atmospheric stability is a meteorological factor that we expect to be correlated with $PM_{2.5}$ concentrations in the SJV. There are several methods/techniques to provide atmospheric stability information; radiosondes, rawinsondes, Radio Acoustic Sounding System (RASS), the difference between air and soil temperature, and the difference of temperature between the site of interest and nearby meteorological sites at different elevations. A secondary goal was to determine which stability measurement technique is most correlated with $PM_{2.5}$ concentrations.

$PM_{2.5}$ data was obtained for the stations listed in Table 1. The winter season was defined as the months of November to February. Meteorological data was available at or near the $PM_{2.5}$ measurement sites (Table 2).

Table 1: Fresno area sources of $PM_{2.5}$ data.

Station	Data type	Winter data availability	Temporal resolution	Measurement notes	Station coordinates and Elevation
Site name: Fresno-Garland AQS site ID: 06-019-0011	$PM_{2.5}$	2012 2013 2014 2015 2016 2017	Daily since 1/1/2012 Hourly since 1/8/2012	FRM/FEM This site also has Chemical Speciation Data. Daily (POC=1)- R&P Model 2025 $PM_{2.5}$ sequential air sampler w/VSCC. It uses Gravimetric method. Hourly (POC=3)- Met One Beta Attenuation Monitor-1020 mass monitor w/VSCC.	Lat: 36.785322 Lon: -119.774174 Elevation: 96m
Site name: Fresno-First Street AQS site ID: 06-019-0008	$PM_{2.5}$	1/6/1999-1/31/2012	Daily	For daily data prior to 2012 we used data from the first Street site, at 3425 N First St (450 meters away from Garland). R&P Model 2025 $PM_{2.5}$ sequential air sampler w/VSCC.	Lat: 36.781333 Lon: -119.773190 Elevation: 96m
Site name: Clovis-Villa	$PM_{2.5}$	11/25/2008 - 12/31/2017	Hourly	Used Teledyne Model 602 Beta Attenuation monitor w/VCSS (FEM- POC3).	Lat: 36.82° Lon: -119.72° Elevation: 86 m

Note: AQI-Air Quality Index; FRM-Federal Reference Method; FEM-Federal Equivalent Method; POC-Parameter Occurrence Code
Source: https://www.epa.gov/outdoor-air-quality-data/interactive-map-air-quality-monitors

Table 2. Meteorological data used in this study.

	Local site name							
	Fresno-Garland (USEPA)		Clovis (MESOWEST)		Fancher Creek (MESOWEST)		Trimmer (MESOWEST)	
	Latitude: 36.79° Longitude: -119.77° Elevation: 96 m		Latitude: 36.85° Longitude: -119.63° Elevation: 127 m		Latitude: 36.88° Longitude: -119.48° Elevation: 279 m		Latitude: 36.91° Longitude: -119.31° Elevation: 453 m	
Distance from the Garland site (kms)	0		14		28		43	
Availability of data types and periods	Data types	Sample duration	Data types	Sample duration	Data types	Sample duration	Data types	Sample duration
	$PM_{2.5}$	1 hr	T	1hr	T	1 hr	T	1 hr
	Temperature (T)	1 hr						

Note: The site labeled Clovis here is not co-located with the Clovis-Villa site listed in Table 1.

Three different types of plots of hourly average $PM_{2.5}$ values were plotted for the Fresno-Garland and Clovis-Villa sites to analyze the $PM_{2.5}$ variability patterns. The plots were:

1) Hour of the day of each month in each winter (2015-2017) averaged together
2) Hour of the day of same months in different winters averaged together (Note: Black color curves in Figures 3 to 5)
3) Hour of the day of all months in all winters averaged together

We examined how topographical, meteorological, and emission conditions affected $PM_{2.5}$ concentrations in the SJV. We looked how the level of $PM_{2.5}$ varies with surface temperature difference, wind speed, precipitation, and emissions. Since radiosonde data or other vertical temperature data was not available for Fresno, we examined using temperature differences between sites at different elevations as a stability measure.

Emission data for Fresno was obtained from the California Air Resources Board (CARB; [20]). CARB defines the base year of 2012, which means the 2012 inventory year was based on actual/real inventory data and is the anchoring year for hind-casting and forecasting inventory years using growth and controlled factors [21]. In this work, we considered emissions of reactive organic gases (ROG), ammonia (NH_3), oxides of nitrogen

(NO_x), sulfur oxides (SO_x), carbon monoxide (CO), and PM. The inventory contains data for different source types; stationary, areawide, mobile, and natural. Data was downloaded for Fresno County for each winter season from 2000 to 2016. The CARB emissions data used was for winter months, determined by CARB as November-April.

Temperature gradients for Clovis, Fancher Creek and Trimmer were examined with the Fresno-Garland site used as the reference site. To better relate to atmospheric stability, we considered the difference in potential temperature between the sites. A potential temperature difference that is positive between a higher altitude site and a lower altitude site corresponds to stable atmospheric conditions, while negative potential temperature difference represents an unstable atmosphere. The relationships between the $PM_{2.5}$ concentrations measured at the Garland site and potential temperature gradients for winters 2015 through 2017 and 2012 through 2016 were examined in detail. The 24-hr avg $PM_{2.5}$ and 24-hr avg temperature values were available for Garland site but other sites had temperature data with much higher temporal resolution. Mostly, there were three to four readings per every hour and this allowed computation of daily averages for the Clovis, Fancher Creek and Trimmer sites.

3. Results

First, we present patterns of $PM_{2.5}$ and their relationship to meteorology for the winters 2015 – 2017 and for 2012 - 2016. After that we consider how winter average $PM_{2.5}$ varied with emissions and meteorology over the long-term (winter 2001- winter 2017).

3.1 Hourly average $PM_{2.5}$ variation for Garland and Clovis (B) during winter months

Figures 3 and 4 show that Garland and Clovis sites have high $PM_{2.5}$ concentration for December 2017 and January 2018. For December, it is not clear the year in which the lowest concentration occurred for both sites simultaneously. Except for few hours for Garland in January 2017, the lowest concentration for both sites for both January and February (Figure 5) occurred in 2017.

A B

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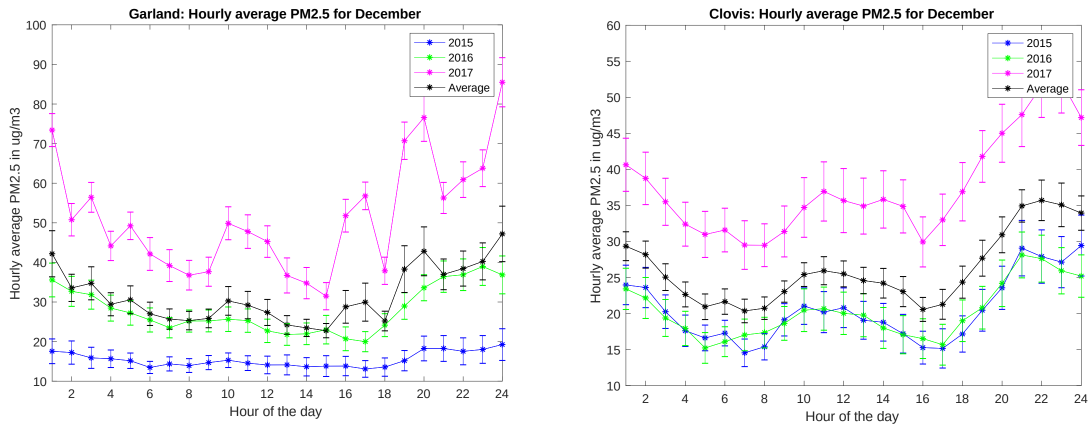

Figure 3. Hourly average $PM_{2.5}$ variation for Garland (A) and Clovis (B) during December.

A

B

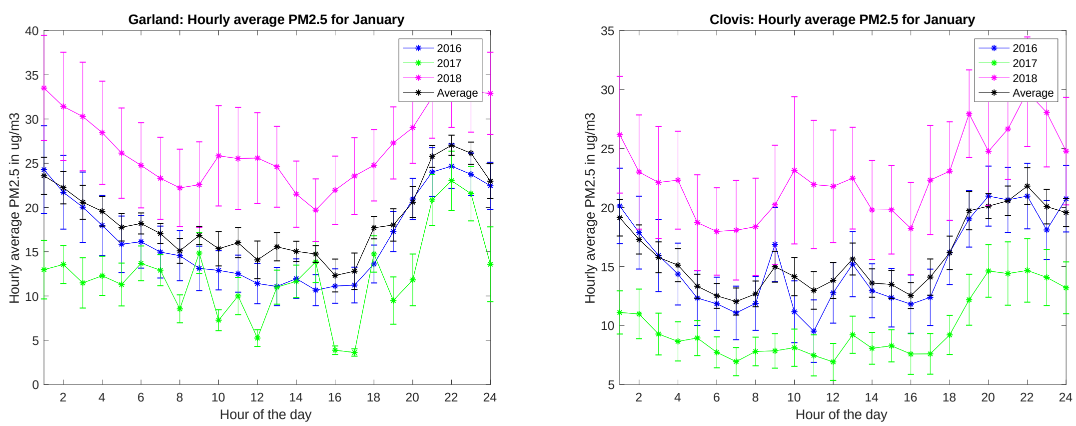

Figure 4. Hourly average $PM_{2.5}$ variation for Garland (A) and Clovis (B) during January.

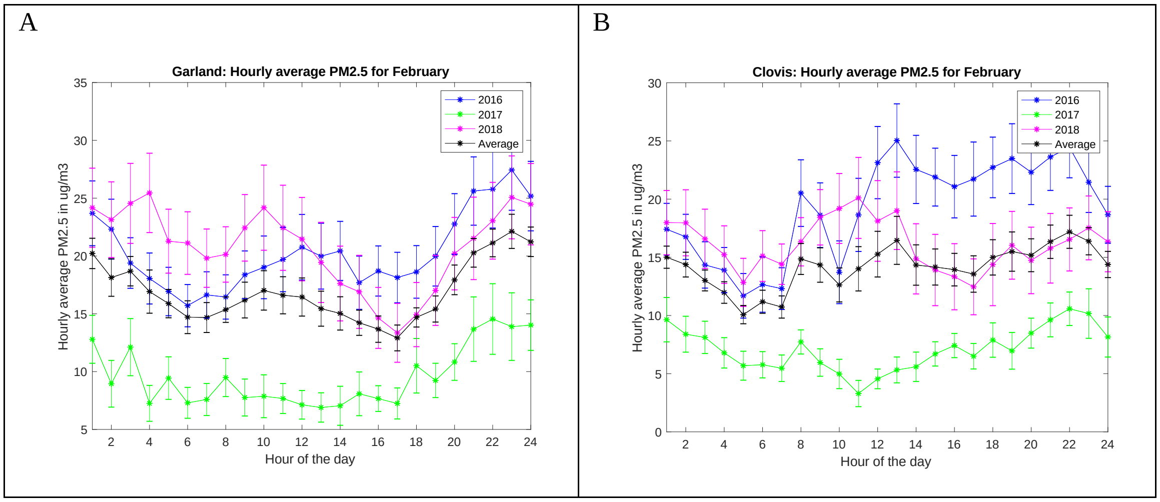

Figure 5. Hourly average $PM_{2.5}$ variation for Garland (A) and Clovis (B) during February.

With all winters averaged together, the hourly average $PM_{2.5}$ variation for both sites is shown in Figure 6. The figure shows that Garland and Clovis sites have quite similar hourly $PM_{2.5}$ variation ranges. Although the Garland and Clovis sites are only about 4 km apart, hourly $PM_{2.5}$ patterns are different. Garland has the lowest $PM_{2.5}$ in the afternoon while Clovis has the lowest in the morning. But if we consider the scale, then the morning and afternoon lowest levels for Clovis are about the same.

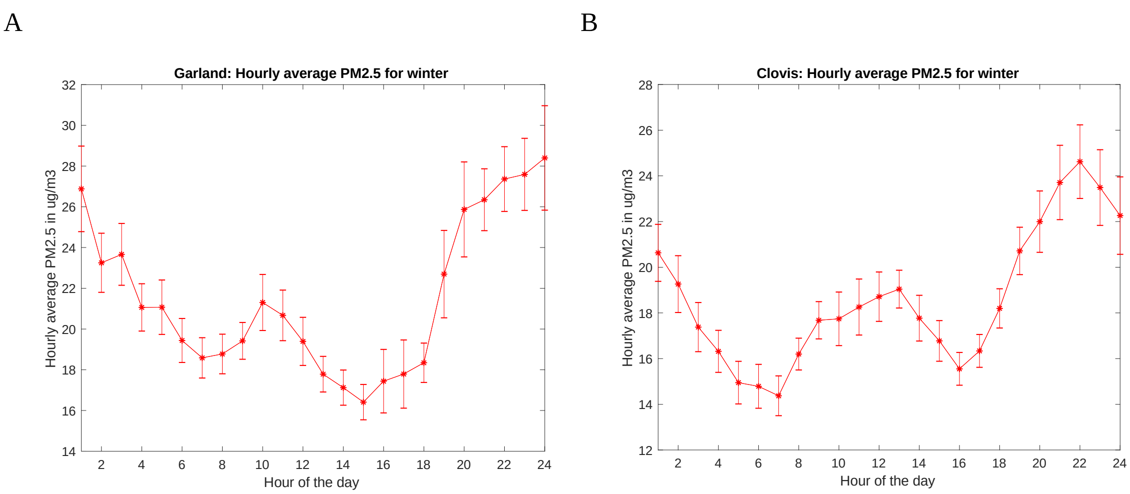

Figure 6. Variation of hourly average $PM_{2.5}$ for Garland (A) and Clovis (B).

By looking at the locations of the two sites in Figure 2, the results can be explained further. The Clovis site is near the edge of a freeway while the Garland site is in a community/residential area about 2 km away from the freeway. The morning increase in

$PM_{2.5}$ between 7 and 9 am in Garland is about 1 µg/m^3 while for Clovis there is a sharp increase of 3 µg/m^3. This is likely because Clovis gets direct contributions from morning traffic. The daily buildup in $PM_{2.5}$ concentrations at Garland occurs over a time period of about 3 hours while at Clovis it lasts about 6 hours. The morning rise of $PM_{2.5}$ in Garland occurs between 7 and 10 am while for Clovis the increase begins at 7 am but it extends to about 1 pm. The longer period at Clovis is probably due to continuing freeway traffic.

The $PM_{2.5}$ concentrations at Garland decrease gradually between 10 am and 3 pm while for Clovis the concentrations decrease more sharply between 1 pm and 4 pm. This could be due to the effect of traffic of the freeway on surface convection and turbulence.

3.2 The relationship between $PM_{2.5}$ concentrations and potential temperature gradients

Figure 7 shows the relationship between the daily average $PM_{2.5}$ and the potential temperature difference for Garland and the Clovis (A), Fancher Creek (B) and Trimmer (C) sites for winter days 2012-2016. Except for the Clovis site, which has a slightly different elevation from the Garland site, there are moderate correlations (r^2=0.42-0.45) between $PM_{2.5}$ at Garland and potential temperature difference between Garland and elevated sites (Table 3). These correlations are roughly comparable to those obtained between $PM_{2.5}$ and heat deficit for other locations (e.g. [17]).

Table 3. Summary of the relationship strength between $PM_{2.5}$ and potential temperature gradients for different sites in Fresno

Site	Elevation (m)	Distance from Fresno- Garland site (km)	r^2
			$PM_{2.5}$ against potential temperature difference
Fresno-Garland (US EPA)	96	---	---
Clovis (MESOWEST)	127	14	0.0018
Fancher Creek (MESOWEST)	279	28	0.4241
Trimmer (MESOWEST)	453	43	0.4549

Notes: 1) The r^2 value for each site was based on data from winters 2012 to 2016.

2) The next MESOWEST site uphill is Sacata Repeater NE (SEPC1) and it is at an elevation of 1105m.

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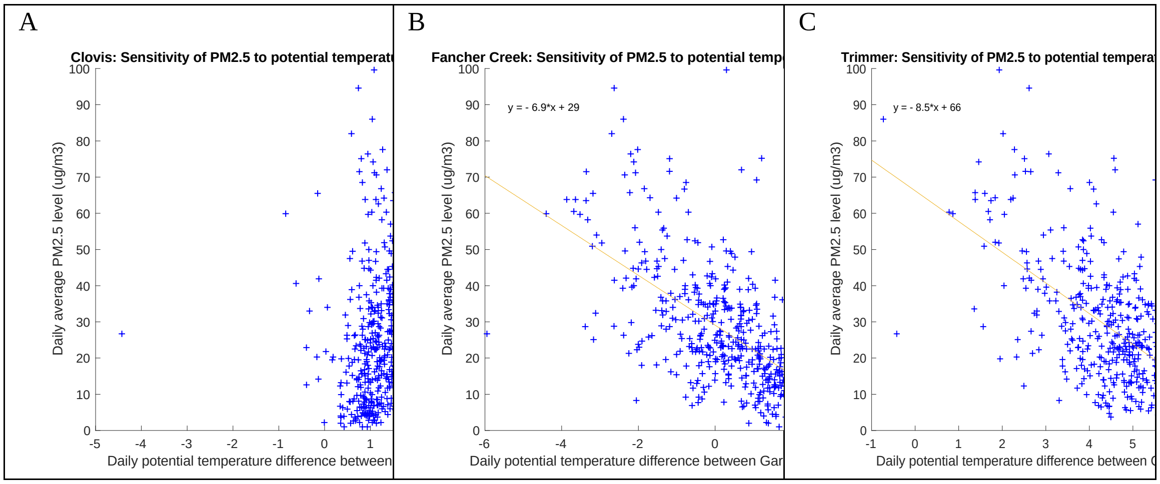

Figure 7. The relationship between the daily average $PM_{2.5}$ and the potential temperature difference between Garland and the Clovis (A), Fancher Creek (B) and Trimmer (C) sites.

3.3 The relationships among wind speed and precipitation and $PM_{2.5}$

Because potential temperature gradients showed only a moderate relationship with $PM_{2.5}$, we now consider other meteorological factors and how they relate to $PM_{2.5}$. Wind speed is expected to decrease $PM_{2.5}$ concentrations due to along-wind dispersion. Precipitation is expected to decrease $PM_{2.5}$ levels due to washout of particulate matter. Average $PM_{2.5}$ concentrations, average Trimmer- Garland potential temperature differences, precipitation frequency and average wind speeds are shown for each month for each year for winters 2015-2017 in Table 4.

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Table 4. $PM_{2.5}$, delta ϴ, precipitation frequency and wind speed average by month for winter 2015-2017

Month/Year	**$PM_{2.5}$ (μg/m^3)**	**delta ϴ (^{0}C)**	**Precipitation frequency* (%)**	**Wind speed (ms^{-1})**
November				
2015	**21.60**	1.34	18	**3.57**
2016	21.54	**1.92**	14	4.02
2017	21.18	1.80	**13**	4.15
December				
2015	22.20	1.67	27	4.18
2016	25.62	2.08	23	3.94
2017	**51.70**	**2.95**	**3**	**2.69**
January				
2016	16.43	1.45	52	4.71
2017	10.19	1.20	57	6.42
2018	**27.44**	**2.55**	**17**	**4.06**
February				
2016	19.14	**1.50**	**7**	**3.27**
2017	8.10	0.66	46	7.21
2018	**19.44**	1.09	12	4.47
Entire winter				
2015	19.91	1.49	25	3.92
2016	17.02	1.51	33	5.28
2017	**30.51**	**2.14**	**11**	**3.81**

Notes: 1) Precipitation frequency is the percentage of days in the month with at least 0.01 inches of precipitation recorded at the Fresno Airport.

2) The highest $PM_{2.5}$ for each month is shown in bold. Also shown in bold for each month are the value with the most potential to contribute to high $PM_{2.5}$ (e.g. highest delta ϴ, lowest precipitation frequency, lowest wind speed).

December, 2017 and January, 2018 had the highest average $PM_{2.5}$ concentrations of any months in the three winter periods examined, far exceeding the $PM_{2.5}$ levels in the other two Decembers and Januaries. These months also had higher potential temperature differences, lower wind speeds and lower precipitation frequencies compared to the other two Decembers and Januaries. The winter of 2017 (November 2017-February 2018) had the highest average $PM_{2.5}$, potential temperature difference, lowest frequency of precipitation and lowest wind speed of the three winters. The three Novembers had very similar average $PM_{2.5}$ concentrations and relatively similar values for the other factors. February 2017 had the lowest $PM_{2.5}$ of the three winters and also had the lowest potential temperature difference, greatest precipitation frequency and highest wind speed. It appears that use of potential temperature difference, precipitation frequency and wind speed together can explain why some months and years are especially high or low in $PM_{2.5}$. Later we show that potential temperature difference, precipitation frequency and wind speed are related as well (precipitation days have higher winds speeds and less potential temperature differences compared to dry days).

3.4 Emission inventory, meteorology and $PM_{2.5}$ concentrations at the Fresno-Garland site

Figure 8 shows how the emissions of NO_x, ROG, NH_3, $PM_{2.5}$ primary emissions, SO_x and total emissions related to $PM_{2.5}$ concentrations over a 17-year period at Fresno First Street and Garland sites. All these pollutants might be expected to contribute to primary or secondary $PM_{2.5}$ concentrations although formation of $PM_{2.5}$ from gaseous precursors will vary greatly based on meteorological and other factors. Note that the winter season for $PM_{2.5}$ measurements at Fresno is from November to February while for emission data it is from November to April. Primary $PM_{2.5}$ emissions had the highest correlation with annual average winter $PM_{2.5}$ concentrations at r=0.72, with other compounds having somewhat lower correlations.

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Figure 8. Long-term timeseries of atmospheric $PM_{2.5}$ level with NO_x (A), ROG (B), NH_3 (C), primary $PM_{2.5}$ (D), SO_x (F) emissions and total of NO_x, ROG, NH_3, primary $PM_{2.5}$ and SO_x emissions.

Figure 8 can also be used to provide insight about the variation range of emissions (in Tons/day) for different pollutants over the 17-year period; NO_x (~100), ROG (~60), $PM_{2.5}$ (~15), NH_3 (~5), SO_x (~2). It is noticeable that the trend of emission pattern for NH_3 is different compared to other pollutants. It increases till 2011 and suddenly drops and continue at a lower level thereafter. That is because the SJV APCD Rule 4570 was applied for various farming operation categories such as dairy cattle and feedlot cattle beginning with the calendar year 2012 [22].

Apart from that, it is clear that the $PM_{2.5}$ variation pattern is not smooth over the years. Gorin et al. [23] emphasized that frequent precipitation events occurred during winter 2003 was the reason for uncommonly low $PM_{2.5}$ concentrations in 2003. On the other hand, California experienced its worst drought in over a century between 2011 and 2015. The 2013-2014 winter was by far the driest winter during that time period. Air pollution generated from wildfires was enormous and resulted in periods of excessively high $PM_{2.5}$ concentrations [24].

Figure 8F shows how daily average $PM_{2.5}$ vary with total emissions of the pollutants together over the years. There is a clear downward trend of total emissions per year, but not well correlated with yearly average winter $PM_{2.5}$. Thus, we next look at meteorological conditions each year to better explain the year-to-year variability in the $PM_{2.5}$/emissions relationship.

3.5 Year-to-year variability in $PM_{2.5}$ and average yearly meteorological variables

Here we consider how meteorological variables are related to year-to-year variation in average $PM_{2.5}$. From Figure 8, it is seen that $PM_{2.5}$ emissions and $PM_{2.5}$ show declines over the years. The correlation coefficient between $PM_{2.5}$ and $PM_{2.5}$ emissions was 0.72. The correlation between $PM_{2.5}$ and year was -0.69. The correlation between $PM_{2.5}$ emissions and year was -0.97 making year is a good proxy for $PM_{2.5}$ emissions. This is likely due to steady progress on emissions control.

First consider how meteorological variables are related to $PM_{2.5}$ and each other. Previously it was shown that for the winters of 2015 and 2016 potential temperature differences ($\Delta\Theta$) between the Fresno Garland site and the Trimmer site were moderately correlated to $PM_{2.5}$ concentrations on a daily basis and monthly average $\Delta\Theta$, wind speed and precipitation frequency helped explain year-year variability in monthly average $PM_{2.5}$ for 2015-2017.

The correlations between $PM_{2.5}$ and emissions weighted $PM_{2.5}$ to wind speed and $\Delta\Theta$ are shown in Table 5. Also shown is the correlation between $\Delta\Theta$ and wind speed. On a daily basis $PM_{2.5}$ and $\Delta\Theta$ are moderately correlated (r=0.44). When accounting for the change in $PM_{2.5}$ emissions over time, the $PM_{2.5}$, $\Delta\Theta$ relationship strengthens a bit (r=0.51).

Wind speed is a bit more correlated to $PM_{2.5}$ than is ΔΘ with r=-0.55 for $PM_{2.5}$ and -0.57 for emissions weighted $PM_{2.5}$.

Table 5. Correlations (r) among $PM_{2.5}$ and emissions normalized $PM_{2.5}$ and delta Θ and wind speed.

Parameter	delta Θ	Wind speed
$PM_{2.5}$	0.44	-0.55
Emissions normalized $PM_{2.5}$*	0.51	-0.57
Wind speed	-0.35	

*The emissions normalized $PM_{2.5}$ is calculated by dividing the $PM_{2.5}$ concentration for each day by the yearly level of $PM_{2.5}$ primary particle emissions from the CARB emissions inventory.

The relationships between precipitation and $PM_{2.5}$, wind speed and ΔΘ are indicated by Table 6. Average $PM_{2.5}$ decreases as precipitation increases. With increased precipitation wind speeds also increase and ΔΘ decreases. Because increased precipitation is linked to decreased stability and increased wind speed, it is difficult to know how much of the decrease in $PM_{2.5}$ is due to washout of particles versus greater vertical and along wind dispersion implied by the ΔΘ and wind speed changes.

Table 6. Relationship between precipitation category and $PM_{2.5}$, ΔΘ and wind speed.

Precipitation amount (inches)	Average $PM_{2.5}$ (μg/m^3)	Average ΔΘ (C°)	Average wind speed (m/s)	Number of observations
<0.01	32.0	2.2	3.0	1422
0.01-0.10	18.7	1.4	5.9	385
>0.10	12.7	1.1	7.0	230

Let us look at how the $PM_{2.5}$ to $PM_{2.5}$ emissions varied along with the meteorological variables by year (2001-2016) for year with all variables available. Table 7 and Figure 9 show the z-score for each winter for emissions normalized $PM_{2.5}$, ΔΘ, precipitation frequency and wind speed. The z-score is the yearly number of standard deviations from the mean of each variable averaged over all years. Four of the sixteen years had normalized $PM_{2.5}$ concentration greater than 1 standard deviation from the mean (z-score >1 or <-1). The three years with normalized $PM_{2.5}$ z-score>1 (2011, 2013, 2014) all had increased stability (ΔΘ), lower precipitation frequency and lower wind speed than average. The one year (2003) with normalized $PM_{2.5}$ z-score<-1 had decreased stability (ΔΘ), higher precipitation frequency and higher wind speed than average. Years whose $PM_{2.5}$ concentrations significantly depart from the long-term trend can be explained by the variations in these meteorological parameters.

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Table 7. Yearly z-scores for emissions normalized $PM_{2.5}$, ΔΘ, precipitation frequency and wind speed.

Year	$PM_{2.5}$/emissions of $PM_{2.5}$	ΔΘ	Precipitation frequency	Wind speed
2001	-0.53	-0.30	-0.15	0.94
2002	-0.07	-1.11	-0.11	0.03
2003	**-1.15**	-0.55	1.28	0.80
2004	-0.90	-0.51	0.67	0.37
2005	-0.20	-0.09	-0.60	0.62
2006	-0.01	0.02	0.11	0.51
2007	-0.46	0.09	0.16	0.04
2008	-0.25	-0.24	0.62	-0.54
2009	-0.29	-0.73	0.63	-0.49
2010	-0.64	-0.42	0.16	-0.50
2011	**1.14**	0.84	-1.83	-1.39
2012	0.28	1.87	-0.23	-0.97
2013	**2.95**	2.59	-1.84	-1.37
2014	**1.04**	0.19	-1.18	-0.79
2015	-0.12	-0.85	0.51	0.20
2016	-0.79	-0.81	1.80	2.55

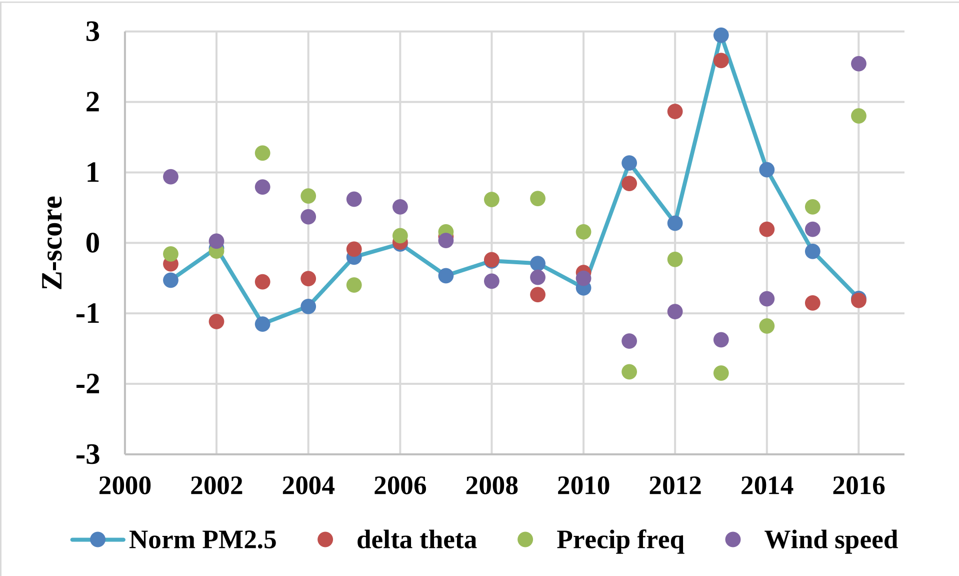

Figure 9. Z-score for winter average emissions normalized $PM_{2.5}$, Trimmer- Garland potential temperature difference, precipitation frequency and wind speed.

Yearly average emissions normalized winter $PM_{2.5}$ correlated best with precipitation frequency (r=-0.84), followed by ΔΘ (r=0.79) and wind speed (r=-0.67). Multiple linear regression was performed with annual winter average $PM_{2.5}$ concentrations as the dependent variable and winter average $PM_{2.5}$ emissions, ΔΘ, precipitation frequency and wind speed as the independent variables. The initial regression with all variables showed a shared variance (r^2) of 0.884 between predicted and measured $PM_{2.5}$. However, the regression coefficients were statistically significant only for $PM_{2.5}$ emissions and precipitation frequency, probably due to the moderately high correlations (multicollinearity) among the meteorological variables. The regression was then done using only $PM_{2.5}$ emissions and precipitation frequency for the independent variables. The P values were less than 10^{-5} for each variable. The shared variance was 0.871 between predicted and observed $PM_{2.5}$. The comparison of predicted and measured $PM_{2.5}$ by year is shown in Figure 10. Because $PM_{2.5}$ emissions and year are highly correlated (r=-0.97), prediction of $PM_{2.5}$ using only year and precipitation frequency in the regression gave similar results as using $PM_{2.5}$ emissions and precipitation frequency (r^2=0.852).

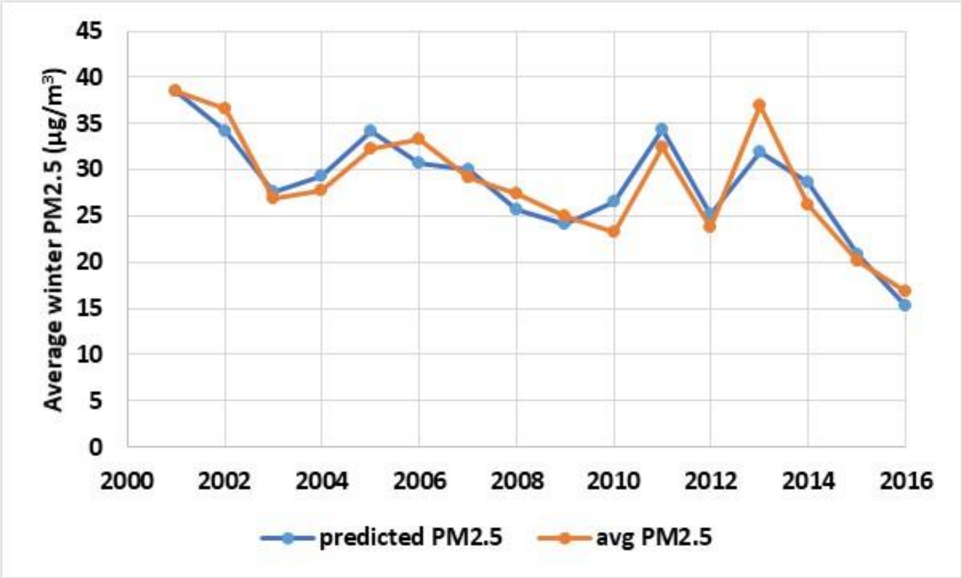

Figure 10. Winter average measured and regression predicted $PM_{2.5}$ at Fresno-Garland for winters 2001-2016.

4. Conclusions

A key goal of this research was to investigate the relationship between emissions, meteorology and $PM_{2.5}$ concentrations in Fresno for the winter season. The Garland and Clovis sites have quite similar hourly $PM_{2.5}$ concentration variation ranges. For the winters of 2015-2017 the highest $PM_{2.5}$ concentrations occurred during December 2017 and January 2018. These months also had high atmospheric stability, light winds and little precipitation. The $PM_{2.5}$ concentration and its diurnal variation at the Clovis site were strongly affected by the site's location near a freeway compared with the Garland site. There was a strong variation in the monthly $PM_{2.5}$ between the three years which could be explained by year-to-year variations in monthly precipitation frequency, atmospheric stability and wind speed. There are moderate correlations (r^2=0.42-0.45) between $PM_{2.5}$ at Garland and potential temperature difference between Garland and elevated sites. These correlations are roughly comparable to those obtained between $PM_{2.5}$ and heat deficit that we have calculated for Fairbanks and Beijing. Year-to-year monthly $PM_{2.5}$ levels and annual variations in $PM_{2.5}$ levels can be largely explained by considering emissions levels, atmospheric stability ($\Delta\Theta$), precipitation frequency and wind speed.

Author contributions

This paper was written by Thishan Dharshana Karandana Gamalathge with a significant contribution by Mark C. Green and William R. Stockwell.

Conflicts of Interest

The authors declare no conflicts of interest.

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