Long-term Measurements of PM_{2.5} Concentrations in Lubbock, Texas

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ABSTRACT

Aerosol particles, such as PM_{2.5} (particulate matter with an aerodynamic diameter $\leq 2.5 \mu\text{m}$), are an important yet variable component of our atmosphere; their presence defines the air quality and profoundly affects human health. In this project, we examine changes in the PM_{2.5} concentration, which is subject to temporal and spatial conditions and may vary by hour or day, in Lubbock, Texas, from 2001 to 2018. The hourly PM_{2.5} concentrations were measured at the local Texas Commission on Environmental Quality (TCEQ) station, analyzed for diurnal, weekly, monthly, seasonal, and yearly changes, and compared with meteorological parameters (such as the temperature, wind direction or speed, and visibility) recorded by the local National Weather Service station at Lubbock Preston Smith International Airport. In addition, we examined the effects of El Niño and La Niña on the PM_{2.5} concentration. The majority of the average daily PM_{2.5} values fell below the Environmental Protection Agency (EPA) daily threshold of $35 \mu\text{g m}^{-3}$, but many days exhibited high hourly concentrations, mainly due to dust storm events. No correlations were found between the concentrations and various meteorological parameters. Based on the hourly measurements, the diurnal distributions were bimodal, with morning and evening peaks, and the highest monthly averages were observed for April and June. A comparison of the PM_{2.5} concentrations during El Niño and La Niña revealed higher values during the latter, with the maximum concentrations occurring during weak La Niñas.

Keywords: PM_{2.5}; Lubbock, Texas; Bimodal diurnal distribution; Dust storm.

INTRODUCTION

Atmospheric aerosols are a complex mixture of suspended solid and liquid particles with different physical and chemical properties (e.g., size distribution, optical properties, and chemical composition). Particulate matter (PM) can originate both from natural and anthropogenic sources and can be emitted as primary PM, directly from the source, or as secondary PM, in which particles are formed by the chemical reactions of gaseous precursors during atmospheric transport. Some of the primary sources are industrial activities, road traffic, heating, and manmade fires and natural sources, such as dust, volcanoes, sea spray, and wildfires. Some of the secondary sources include sulfur dioxide (SO₂), nitrogen oxides (NO_x) and ammonia (NH₃) (Seinfeld and Pandis, 2006). The presence of PM defines air quality levels, depending on the type, size, and concentration of the particles. PM can also absorb and scatter light, resulting in lower visibilities (Pui *et al.*, 2014), causing transportation hazards (Day, 1993; Ashley *et al.*, 2015; Li *et al.*, 2018) or disruption of aviation

traffic (Baddock *et al.*, 2013). Additionally, PM can cause abrasions to plants, reduction in photosynthesis due to blocking radiation, and changes to soil chemistry (Grantz *et al.*, 2003).

People are exposed to aerosol particles in their everyday lives from outdoor and indoor activities. The health effects from PM exposure are dependent on the particles' size, composition, and concentration (Harrison and Yin, 2000; Davidson *et al.*, 2005), as well as the length of exposure. PM exposure can result in respiratory problems, cardiovascular complications (e.g., heart attack), and even premature death (Ruuskanen *et al.*, 2001; Davidson *et al.*, 2005; Anderson *et al.*, 2012; Pui *et al.*, 2014). PM with aerodynamic diameter $\leq 2.5 \mu\text{m}$ (PM_{2.5}) are one of the leading contributors to the global burden of disease (Lim *et al.*, 2012; Forouzanfar *et al.*, 2015; Cohen *et al.*, 2017). These particles are small enough to penetrate deep into the human lungs (Ling and van Eeden, 2009) and even into the bloodstream (Martinelli *et al.*, 2013); consequently, they have a negative impact on human health (Shiraiwa *et al.*, 2017). The World Health Organization (WHO) estimates that about 4.2 million premature deaths occur globally each year due to PM exposure (WHO, 2016). Therefore, the WHO established a daily threshold for PM_{2.5} of $25 \mu\text{g m}^{-3}$ (Goudie and Middleton, 2006). In the United States, the Environmental Protection Agency (EPA) uses the National Ambient Air Quality Standards (NAAQS) which recommends a PM_{2.5} daily threshold of $35 \mu\text{g m}^{-3}$, and a

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These health concerns have driven many studies to measure the concentrations of PM_{2.5} and determine factors that contribute to their concentrations. Most studies have concluded that there is more than a single factor that can affect PM_{2.5} concentrations, including the time of day, season, meteorological conditions, and the origin of the particles (Tai *et al.*, 2012; Liu *et al.*, 2015; Stout, 2015). Several studies found a high concentration in winter due to anthropogenic emissions from household heaters (Chow *et al.*, 1993; Marcazzan *et al.*, 2001; Vinitketkumnuen *et al.*, 2002; Zhang and Cao, 2015), while others found high concentrations during warmer months associated with dust storm events (Stout, 2001; Zheng *et al.*, 2005; Liu *et al.*, 2015). A combination of many meteorological factors can create a good environment for elevated amounts of PM. Temperature and relative humidity contribute to PM concentrations through amount of moisture. Higher temperatures and lower relative humidity correlated to higher amounts of PM concentrations due to the lack of moisture (Pateraki *et al.*,

The purpose of this work is to study the distribution and patterns of PM_{2.5} concentrations in Lubbock, Texas. Long-term measurements of PM_{2.5} from 2001 to 2018, as well as PM_{2.5} concentration temporal patterns (diurnal, weekly, monthly, seasonal, and yearly), will be discussed. The contribution of different meteorological factors on the PM_{2.5} concentrations in this region, as well as the effect of the El Niño-Southern Oscillation (ENSO), will be presented.

Research Area

Lubbock, Texas, is located in the Southern High Plains (Fig. 1) at an altitude of approximately 1 km above sea level. Lubbock is a rural area with numerous agricultural fields

Fig. 1. Location of the three PM_{2.5} stations with their ID and the NWS meteorological stations. See information on operation and active time of each PM_{2.5} station in the text.

(mostly cotton) surrounding an urban area with a population of nearly 256,000. It is characterized by a semi-arid climate experiences many dust storms due to the combination of frequently strong winds, meager amounts of rainfall, and a lack of surface cover following harvest and periods of bare soil. Unlike corn, sorghum, or wheat, cotton, which is very common in this area, provides little plant residue that could provide surface cover after harvest. Thus, large areas of bare soil provide an opportunity for strong winds to detach and transport dust and sand. This flat area is one of the most persistently windy inland areas of North America and is also considered to be among the dustiest (Orgill and Sehmel, 1976; Deane and Gutmann, 2003).

Measurements of PM_{2.5} and Meteorological Measurement

PM_{2.5} measurements were downloaded from the Texas Commission on Environmental Quality (TCEQ) at the Environmental Agency of Texas (www.tceq.texas.gov). Hourly gravimetric PM_{2.5} concentrations (local conditions, at local Central Standard Time) were measured from 2001 to 2018. The local PM_{2.5} station has changed locations three times from the first measurements in February 2001, as can be seen in Fig. 1. Information on each of these stations can be found in Table 1. The first location (station ID: C306) was active from February 2001 to June 2005, the second (station ID: C325) from August 2008 to November 2014, and the third (station ID: C1028) was established in August 2016 and measured until December 2018. Due to these relocations (made by TCEQ due to various reasons, including modification of land use), there are significant gaps (up to 1.5 years) in the PM_{2.5} measurements. In addition, there are gaps of several hours up to days due to calibration and maintenance of the instrument. Beginning April 2002, meteorological measurements were added to the PM_{2.5} measurements. These meteorological parameters include hourly wind speed, wind gust, wind direction, as well as ambient temperature. On December 20, 2018, the PM_{2.5} measurement was switched from tapered element oscillating microbalance (TEOM) to a Met One BAM-1022 Beta Attenuation Mass monitor type, meaning only the last 10 days of our measurements were used with the BAM-1022 unit. Based on the manufacturer, the TEOM's PM_{2.5} measurements range from 0 up to 1,000,000 $\mu\text{g m}^{-3}$ with a resolution of 0.1 $\mu\text{g m}^{-3}$ and precision of $\pm 2 \mu\text{g m}^{-3}$ per hour, while for the BAM-1022 the measurements range from -15 up to 10,000 $\mu\text{g m}^{-3}$ with a resolution of 0.1 $\mu\text{g m}^{-3}$ and precision of $< 2.4 \mu\text{g m}^{-3}$ per hour. Maintenance of the equipment occurs both monthly and quarterly. The 12 monthly verifications use one annually calibrated set of instruments to check the measurements of the unit. Every quarter, a separate audit of the equipment is conducted using a different set of calibration instruments. All tests must be within tolerance: The pressure

needs to be within 10 mm Hg, the temperature within 2°C, and flow calibration test needs to be within 4% for the system to pass inspection and continue operation. If the instrument did not pass, the equipment was serviced and verified with another audit of all components.

In addition to the meteorological measurements provided by the TCEQ station, meteorological information such as hourly ambient temperature, relative humidity, wind speed, wind direction, wind gust, visibility, station pressure, and precipitation were retrieved from the local National Weather Service (NWS) meteorological station (<https://mesonet.agron.iastate.edu/request/download.phtml>), which is located at Lubbock Preston Smith International Airport (33°39'48.96"N, 101°49'22.8"W), approximately 8 km north from the PM_{2.5} stations (Fig. 1). In addition to the meteorological parameters, the weather observations from METeorological Aerodrome Reports (METARs) were used in order to determine different meteorological events, such as blowing dust, haze, and smoke. All the times from the METARs were converted to Central Standard Time.

El Niño-Southern Oscillation Data

Information on the El Niño-Southern Oscillation, which defines La Niña and El Niño events and their respective strengths (weak, moderate, strong, very strong) with the Oceanic Niño Index (ONI), were obtained for cold and warm episodes from the National Oceanic Atmospheric Administration (NOAA) National Centers for Environmental Prediction Climate Prediction Center (http://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php). The ONI measures a 3-month rolling average sea surface temperature and compares it to the normal sea surface temperature. An event will be defined as five consecutive overlapping 3-month periods (Null, 2019) at or above the $+0.5^\circ$ anomaly (0.5° to $> 2^\circ$) for warm (El Niño) events, and at or below the -0.5° anomaly ($< -2^\circ$ to -0.5°) for cold (La Niña) events. The strength of the event is classified as *weak* (with a 0.5–0.9 SST anomaly), *moderate* (1.0–1.4), *strong* (1.5–1.9) or *very strong* (≥ 2.0). Null (2019) was used for identification of ONI anomaly and strength.

RESULTS AND DISCUSSION

In total, 102,019 hours of PM_{2.5} concentrations (4,319 days) were measured during the studied period (2001–2018). Figs. 2(A)–2(B) shows the hourly and daily PM_{2.5} concentrations as measured by each station. Most of the daily values were below the EPA daily standard (35 $\mu\text{g m}^{-3}$); only 12 days (0.28%) exceeded this standard. The daily average concentrations ranged from $0.1 \pm 1.5 \mu\text{g m}^{-3}$ (on October 18, 2018) up to $82 \pm 98 \mu\text{g m}^{-3}$ (on June 20, 2013). Two other days had high daily average concentrations (60 $\mu\text{g m}^{-3}$),

Table 1. Information on each one of the PM_{2.5} locations.

Station ID	Latitude	Longitude	Elevation (meter)	Start date	End date
C306	33°35'27.0"N	101°50'51.0"W	963	February 27, 2001	June 22, 2005
C325	33°35'26.8"N	101°51'1.51"W	963	August 20, 2008	November 17, 2014
C1028	33°35'7.91"N	101°47'13.13"W	501	August 8, 2016	Still active

Fig. 2. (A) Hourly and (B) daily PM_{2.5} concentrations measured from 2001–2018. Each station (A) is represented by the length of the station ID line. Dashed line in (B) represents the EPA daily threshold for PM_{2.5} of 35 µg m⁻³. Corresponding box-and-whisker plots per station for (C) hourly and (D) daily PM_{2.5} concentration.

April 15 and December 15, 2003 (with hourly values of 433 and 486 µg m⁻³, respectively). The majority of the hourly measurements were lower than 10 µg m⁻³ (80%). In several instances, hourly PM_{2.5} concentrations were higher than 100 µg m⁻³ (66 hours), but these cases were less than 1% of the entire measurement period. Although the majority of hourly PM_{2.5} concentrations were low, extreme high-pollution events were also observed. Hourly PM_{2.5} concentrations exceeded 100 µg m⁻³ for 26 days; in 10 of these days, this high concentration was measured for only one hour during the day, but for the rest, these high concentrations lasted several hours (up to 7 hours). 80% (21 days) of these higher concentration days were due to dust, haze, or smoke. 18 (69%) were a result of a dust storm, while 3 days (11%) were due to haze or smoke. There were 101 days that had PM_{2.5} values > 50 µg m⁻³ (total of 271 hours); on average, these concentrations lasted for about 3 hours. For one day, April 16, 2011, these high concentrations lasted for 12 hours. 66% of the days with a concentration greater than 50 µg m⁻³ were a result of dust, haze or smoke. 59 days (58%) were dusty, while 8 days (7.9%) were due to haze or smoke. The exact cause or source of these smoke and haze events is unknown. The majority of the high concentration days are a result of the dust storms that occur in this area.

Since the PM_{2.5} measurements were taken in three different locations, a comparison between the three locations was made. A total of 35,855 hourly (1,523 days) measurements were sampled in the first location (C306), 47,721 hourly (2,016 days) measurements were sampled in the second location (C325), and 18,436 hourly (780 days) measurements were sampled by the third and currently active location (C1028). The hourly and daily PM_{2.5} concentrations from all stations were in the same range as shown by the box-and-whisker plot in Figs. 2(C)–2(D). The average PM_{2.5} hourly

concentration measured by Station C306 was $6.5 \pm 8 \mu\text{g m}^{-3}$, whereas $7.7 \pm 7.5 \mu\text{g m}^{-3}$ and $6.5 \pm 6.5 \mu\text{g m}^{-3}$ were measured by Station C325 and C1028, respectively. The highest hourly PM_{2.5} concentration measured by each station was different; Station C306 had a maximum hourly PM_{2.5} concentration of 486 µg m⁻³, whereas Station C325 and C1028 measured 289 and 256 µg m⁻³, respectively. The daily average concentrations were similar to the hourly average concentration. The daily average concentration measured by Station C306 was $6.4 \pm 4.7 \mu\text{g m}^{-3}$, whereas $7.7 \pm 4.6 \mu\text{g m}^{-3}$ and $6.5 \pm 4.1 \mu\text{g m}^{-3}$ was measured by Station C325 and C1028, respectively. All three stations had similar hourly and daily distributions (Fig. S1). All three stations also had similar distributions of PM_{2.5} values (Figs. 2(C)–2(D)). Based on these similar PM_{2.5} ranges and distributions (hourly and daily values), we expected the three stations will be statistically similar. An ANOVA and an independent *t*-test between the three stations found that Stations C306 and C1028 were similar to each other yet statistically different ($p < 0.001$) from Station C325. These statistical differences were surprising, as the first two stations (C306 and C325) were located in close proximity to each other (separated by a distance less than 0.3 km) in a commercial area near the Marsha Sharp Freeway highway. Station C1028 is located ~6 km southeast from C306 and C325 locations, in an open area near agriculture fields and next to the Texas Loop 289 highway. None of the units were placed in a residential area. No meteorological (temperature and precipitation) differences were found between the three station locations (Fig. S2). Station C325 had a slightly higher total precipitation level compared to the other two (2641 mm compared to 2164 mm and 1095 mm for Stations C306 and C1028, respectively). Station C325 was active for a longer time period (47% of the total measurements) and

had more days with hourly concentrations $> 50 \mu\text{g m}^{-3}$ (58 days compared to 25 and 18 for C306 and C1028, respectively). We suspect that these differences are the cause of the statistical differences between the stations. Since the three stations measure a similar distribution of $\text{PM}_{2.5}$ concentrations, the $\text{PM}_{2.5}$ measurements from the three station locations were combined into one data set.

After combining all the $\text{PM}_{2.5}$ values, the daily average for the entire period was calculated and was found to be similar to the average hourly concentration ($7 \pm 4.6 \mu\text{g m}^{-3}$ from daily compared to $7 \pm 7.5 \mu\text{g m}^{-3}$ for hourly). Higher standard deviation (SD) values are most likely a result of the wide range of hourly concentrations. The distribution of the $\text{PM}_{2.5}$ concentrations was assessed (Fig. 3). While this work is the first that evaluated $\text{PM}_{2.5}$ in this area, a previous study conducted in Lubbock (from 2003–2007) found similar distributions for total dust concentrations (total suspended particles [TSP]; Stout, 2015). For example, majority of measurements had concentrations lower than $25 \mu\text{g m}^{-3}$. On the other hand, a number of measurements had concentrations above $500 \mu\text{g m}^{-3}$, much higher than the highest $\text{PM}_{2.5}$ concentration found in this work. The cause of these differences is the different size of the particles used for analysis (TSP vs. $\text{PM}_{2.5}$).

We compared the hourly $\text{PM}_{2.5}$ concentrations and different meteorological parameters measured by both the NWS meteorological station and the TCEQ station (see “Method”), in order to determine if there was any correlation between the $\text{PM}_{2.5}$ concentrations and the meteorological parameters. No significant correlations were found between any of the meteorological parameters and the $\text{PM}_{2.5}$ concentrations (Table S1). When comparing the $\text{PM}_{2.5}$ concentrations to two ranges of temperature ($> 25^\circ\text{C}$ and $< 25^\circ\text{C}$) and high

relative humidity ($\geq 75\%$), the correlations were still low ($R^2 < 0.006$). The wind measured by the NWS and TCEQ stations for the time of analysis show that the wind came from all directions, with majority coming from the south (Fig. S3(A)–S3(B)). For days with $\text{PM}_{2.5}$ concentrations greater than $100 \mu\text{g m}^{-3}$, majority of the winds came from the west (Fig. S3(C)–S3(D)). Majority of the days with $\text{PM}_{2.5}$ concentrations $> 100 \mu\text{g m}^{-3}$ were dust storm days (60%). Similar winds patterns were found by Lee *et al.* (1994) for dust storm days, where most of the winds came from the west. Since different wind patterns were observed for days with hourly concentrations of $\text{PM}_{2.5} > 100 \mu\text{g m}^{-3}$, a comparison of the different meteorological parameters for hourly $\text{PM}_{2.5}$ concentrations greater than $100 \mu\text{g m}^{-3}$ was made. No significant correlations were found (Table S1). Even a comparison to wind speed, wind gust, and wind direction showed no significant correlation ($R^2 < 0.05$). Next, we separated $\text{PM}_{2.5}$ concentrations $> 100 \mu\text{g m}^{-3}$ based on wind direction and compared the corresponding $\text{PM}_{2.5}$ concentrations to wind speed and wind gust. We could not find any correlations ($R^2 < 0.06$) between $\text{PM}_{2.5}$ concentrations to wind speed and wind gust for three of the wind directions (north, south, and east). However, when westerly winds were analyzed, stronger correlations were found between the $\text{PM}_{2.5}$ concentrations to wind speed and wind gust ($R^2 = 0.37$ and 0.39 , respectively). The cause for these correlations lay with the meteorological conditions occurring during that time. Most of the days with westerly winds were associated with dust storm days.

Since the geographical research area is considered to be among one of the dustiest in the U.S. (Orgill and Sehmel, 1976; Deane and Gutmann, 2003), we wanted to look at the distribution of $\text{PM}_{2.5}$ concentrations during days with dust

Fig. 3. Histogram of hourly $\text{PM}_{2.5}$ measurements. Observations are binned every $5 \mu\text{g m}^{-3}$ below $150 \mu\text{g m}^{-3}$, and every $50 \mu\text{g m}^{-3}$ above $150 \mu\text{g m}^{-3}$ (marked by the black break).

storms, specifically days that had hourly $\text{PM}_{2.5}$ measurements above $100 \mu\text{g m}^{-3}$. Examples of $\text{PM}_{2.5}$ concentrations' daily distribution with corresponding visibility and wind gust observations (Fig. S4) illustrate that multiple cases were associated with strong wind gusts, a sharp increase in $\text{PM}_{2.5}$ concentrations, and a reduction in visibility. For many of these days, the visibility was below 1 km and the wind gusts were higher than 20 m s^{-1} . In some instances, wind gusts below 20 m s^{-1} had higher visibility (1–5 km) but similar $\text{PM}_{2.5}$ values (e.g., June 20, 2013; Fig. S4(J)).

Several of the days with $\text{PM}_{2.5}$ concentrations greater than $100 \mu\text{g m}^{-3}$ were not associated with any weather observations (haze or dust). These days had low winds and high visibility, suggesting that the pollution source was local. There are several potential sources for particle emission in this region as suggested by TCEQ emission inventory (TCEQ, 2020); the information on the emission is given as a yearly value. Based on these emissions, the local power plants, cottonseed oil mills and cotton ginning sources produce the highest $\text{PM}_{2.5}$ concentrations per year.

Changes of $\text{PM}_{2.5}$ Values over Time (Daily, Weekly and Monthly)

Diurnal changes of $\text{PM}_{2.5}$ concentrations were calculated based on hourly concentrations. A bimodal distribution was observed (Fig. 4(A)) with high $\text{PM}_{2.5}$ concentrations in the early morning (7:00–8:00 a.m.), and evening (7:00–9:00 p.m.). The highest concentration was measured at 8:00 p.m. ($8.5 \pm 7.7 \mu\text{g m}^{-3}$), while the lowest was at noon ($5.8 \pm 8.5 \mu\text{g m}^{-3}$). Higher hourly $\text{PM}_{2.5}$ concentrations were found by other studies at various locations including Iran (Shahsavani *et al.*, 2012), Italy (Pateraki *et al.*, 2012) and India (Pillai *et al.*, 2002). Although the hourly average concentration is low, there is a large range in concentrations as can be seen by the high SD values; nine hours had SDs greater than the average.

Similar trends were observed when each station was observed separately (Fig. 4(B)). Other studies also observed a bimodal pattern (Pillai *et al.*, 2002; Liu *et al.*, 2015). Similar $\text{PM}_{2.5}$ diurnal variations were measured by Liu *et al.* (2015) in Beijing, China, with a peak between 7:00 a.m. and 8:00 a.m., resulting from anthropogenic emissions during morning rush hour and another peak around 7:00 p.m. and 11:00 p.m. They also found a minimum $\text{PM}_{2.5}$ concentration at approximately noon.

We assumed that the morning peak is a result of vehicular emissions due to the morning commute; for example, more than 21,600 cars drive every day to the Texas Tech University (TTU) campus (TTU Parking Service, 2019 personal communications) which is considered to be one of the bigger employers in Lubbock. Previous studies also observed this increase of $\text{PM}_{2.5}$ concentrations due to morning commute (Marcazzan *et al.*, 2001; Pateraki *et al.*, 2012; Liu *et al.*, 2015; Zhang and Cao, 2015). We expected another peak to occur in the afternoon around 4:00–6:00 p.m., coincident with the afternoon commute, but such an increase did not occur until evening hours (7:00–9:00 p.m.). According to Orgill and Sehmel (1976), who analyzed hourly visibility observations recorded at U.S. weather stations, higher frequencies of airborne dust occurred in the afternoon from 12:00 p.m. to 8:00 p.m., which could explain the secondary peak. We noticed that dust storm events occurred over this period, as suggested by Orgill and Sehmel (1976) and detailed by daily $\text{PM}_{2.5}$ distributions (Fig. S4). In order to examine if the winds and dust particles were the contributor of the second peak, we examine the diurnal changes of all the dust storm days (as identified by METAR), Fig. S5(A) and diurnal changes of the corresponding wind speed and wind gust (as measured by the TCEQ), Fig. S5(B)). A single peak in similar times was found by Orgill and Sehmel (1976) and Stout (2015), yet this peak occurred earlier than the evening peak,

Fig. 4. (A) Diurnal changes of $\text{PM}_{2.5}$ concentrations. (B) Diurnal variation of $\text{PM}_{2.5}$ concentrations by station location. $\text{PM}_{2.5}$ average concentrations (C) by day of the week and (D) per month.

meaning that the dust events did not contribute to it. We found that even when the daily distribution of all days without dust storm days (Fig. S5(C)) or days with $\text{PM}_{2.5}$ daily average $< 5 \mu\text{g m}^{-3}$ (Fig. S5(d)) were examined, a similar bimodal distribution was observed. The evening peak was observed in the non-dusty days and even in the extreme clean cases. The source of this evening peak remains unknown; chemical analysis of the evening hours (which was not part of this work) would help to discover the sources of this evening peak.

While the daily distribution of all days was different from that reported by Stout (2015), the distribution of the dust storm days (Fig. S5(A)) was similar to the daily distribution found by Stout (2015), but the time of peak was different. Stout (2015) found the highest concentration at 2 p.m.; yet in this work, the highest concentration of the dust storm days was several hours later at 6 p.m. One possible reason for the different observations is the different times; analysis of a similar time frame (2003–2007; not shown) as in Stout (2015) shows a similar distribution and peak time.

Weekly Changes in $\text{PM}_{2.5}$ Values

The weekly distribution of $\text{PM}_{2.5}$ concentrations, calculated based on hourly concentrations, had on average 14,578 hours (617 days) per day of the week. Overall the weekly distributions showed similar daily average concentrations, ranging from $6.7 \pm 7.1 \mu\text{g m}^{-3}$ on Sunday up to $7.4 \pm 8.1 \mu\text{g m}^{-3}$ on Tuesday (Fig. 4(C)). While there were very small changes in the average concentration during the week, there is a slightly lower concentration during the weekend (Saturday and Sunday), most likely due to less commuters. A comparison based on hours of the day (data not shown), found that Sunday had lower concentrations during the morning peak compared to other days, while Saturday had lower concentrations from

12 p.m. to 6 p.m. Regardless, all days had a bimodal distribution with similar morning and evening peaks.

Monthly Changes in $\text{PM}_{2.5}$ Values

The monthly distribution of $\text{PM}_{2.5}$ concentrations, calculated based on hourly concentrations, were also examined to determine the months with the highest and lowest concentrations (Fig. 4(D)). February had the lowest number of hourly measurements (7,505 hours), while May had the highest (9,426 hours). The lowest monthly $\text{PM}_{2.5}$ concentration occurred in November, with an average $\text{PM}_{2.5}$ concentration of $5.2 \pm 4.0 \mu\text{g m}^{-3}$. April and June had the greatest $\text{PM}_{2.5}$ concentrations, averaging $8.5 \pm 6.9 \mu\text{g m}^{-3}$ and $9.6 \pm 11.2 \mu\text{g m}^{-3}$, respectively (Fig. 5). The high measurements in April are consistent with other local studies (Lee et al., 1994; Stout, 2001). However, the high average concentration in June was not expected since previous measurements in Lubbock have not observed a high concentration of PM_{10} (Stout, 2001) or TSP (Stout, 2015) in the month of June. Two years (2013 and 2018) had very high $\text{PM}_{2.5}$ concentrations in June (Fig. S6); the monthly $\text{PM}_{2.5}$ concentrations were double compared to other months during those two years. These two months also had very high SD values, which shows the wide range in concentrations for these months. When we examined April and June weather observations, we found that multiple dust storm events were observed during these months, which could explain the high monthly average concentrations.

The varying monthly $\text{PM}_{2.5}$ concentrations could be associated with pollution events such as haze, biomass burning, and dust storms, the latter being most common in Lubbock. Dust storms in the Southern High Plains are observed in different months. Lee and Tchakerian (1995)

Fig. 5. Seasonal patterns of diurnal hourly $\text{PM}_{2.5}$ concentration for (A) winter, (B) spring, (C) summer, and (D) fall.

reported on dust storm events in Lubbock during 1947–1989 and showed that the highest-magnitude dust storm events occurred in January, March, April, and December. Lee *et al.* (1994) observed dust storms events in January, February, March, May, and December, with March having the highest number of dust storm events. Based on PM_{10} measurements from 1996–1997, Stout (2001) found that March and April had more dust storm events compared to other months. During 2003–2007, using TSP observations, Stout (2015) observed dust storm events in January, February, March, April, May, September, and December. We also identified dust storm events with high $PM_{2.5}$ concentrations (Fig. S4) during February, March, April, May, June, and December, similar to previous studies. The monthly averages found in this work were much lower than those measured in other locations that also experienced dust storms (Pillai *et al.*, 2002; Liu *et al.*, 2015).

Seasonal Changes in $PM_{2.5}$ Concentration

Using the hourly $PM_{2.5}$ concentrations (based on the month of occurrence), we calculated concentration changes by season to determine the season with the lowest and highest $PM_{2.5}$ concentration. Overall changes of $PM_{2.5}$ concentrations for winter (December, January, and February), spring (March, April, and May), summer (June, July, and August) and fall (September, October, and November) were calculated (Table 2) from the hourly concentrations. More than 24,000 hours of $PM_{2.5}$ measurements were available in each season to calculate the seasonal $PM_{2.5}$ average concentration. Summer and spring had high $PM_{2.5}$ concentrations of $8.5 \pm 7.6 \mu\text{g m}^{-3}$ and $8.1 \pm 8.5 \mu\text{g m}^{-3}$, respectively, whereas winter had the lowest $PM_{2.5}$ concentration ($5.4 \pm 7.6 \mu\text{g m}^{-3}$). The high spring and summer concentrations were a result of the high number of measured dust storm events during these seasons. An ANOVA test between the different seasons found each to be significantly different from the other ($p < 0.001$).

Several studies found higher $PM_{2.5}$ concentrations in colder seasons (Marcazzan *et al.*, 2001; Zhang and Cao, 2015; Arhami *et al.*, 2017). However, these studies occurred in large metropolitan areas (e.g., Milan, Italy, and Tehran, Iran) with high anthropogenic emissions, which resulted in higher PM concentrations during the cold months from an increase in household heating (Chow *et al.*, 1993; Marcazzan *et al.*, 2001; Vinitketkumnuen *et al.*, 2002; Zhang and Cao, 2015). In contrast, our cold season had the lowest $PM_{2.5}$ concentrations. Other studies conducted in arid and semi-arid areas found that the warmer seasons had higher PM concentrations compared to the colder seasons (Stout, 2001; Zheng *et al.*, 2005; Liu *et al.*, 2015). The increase of PM in the warm season was associated with dust storm events.

During some warm seasons, if less precipitation occurs, the ground can become severely dry and any weather event with strong wind speeds can contribute to the development of dust storms (Sidwell, 1938; LaPrade, 1957; Lee *et al.*, 1994; Stout, 2001) and high PM concentrations.

While our analysis found summer and spring to have high $PM_{2.5}$ concentrations, previous measurements in Lubbock by Stout (2015) found relatively high particle concentrations in winter and spring, with spring having the highest PM concentrations. One of the main differences between our work and Stout (2015) was the seasonal calculation. While we categorized the seasons based on meteorological seasons, Stout (2015) used astronomical seasons, which are based on the equinox and solstice times. When we altered our seasonal calculation to be consistent with the astronomical seasons (data not shown), the seasonal distributions behaved in similar ways as to those in Stout (2015). A contributing factor to the initial differences was the month of June, which had very high $PM_{2.5}$ concentrations and was categorized as part of summer in our original seasonal calculation and part of spring in the augmented analysis.

Each hourly $PM_{2.5}$ concentration was aggregated within a season to examine the diurnal patterns. Seasonal patterns of hourly $PM_{2.5}$ concentrations support our aforementioned findings that spring and summer have higher $PM_{2.5}$ concentrations (Fig. 5). In winter, the morning peak occurs between 8:00–9:00 a.m., but 12:00–2:00 p.m. had high SDs. Spring and summer have a morning peak around 7:00 a.m., but an evening peak around 8:00–9:00 p.m., similar to the maximum found in the aggregated diurnal pattern (Fig. 4(A)). The fall season also had a morning maximum at 7:00 a.m., with an evening peak that was less pronounced than those in other seasons. Winter had high SDs around 1:00 p.m., while the highest SDs in summer shifted to the evening (around 6:00 p.m.). A maxima shift was also observed in Stout (2015), whereas maxima in $PM_{2.5}$ concentrations shifted from early morning in the winter to later afternoon in spring and summer.

Annual Changes in $PM_{2.5}$ Concentration

The hourly $PM_{2.5}$ concentrations were averaged to evaluate annual average $PM_{2.5}$ concentrations from 2001–2018 (Fig. 6). There were several years (2006, 2007, and 2015) with no measurements due to station relocation. Years on either side of relocation gaps had relatively low $PM_{2.5}$ concentrations as well; 2005, 2008 and 2016 had 4,098, 1,835 and 2,930 hours of $PM_{2.5}$ concentrations, equivalent to only 172, 56 and 90 days, respectively. All other years had nearly a full year of $PM_{2.5}$ measurements, as can be seen in Table S2.

Table 2. Changes of $PM_{2.5}$ as a function of seasons.

Season	Number of hours with $PM_{2.5}$ measurement per season (hours)	Season average $PM_{2.5}$ concentration and standard deviation ($\mu\text{g m}^{-3}$)
Winter	24,437	5.4 ± 7.6
Spring	26,924	8.1 ± 8.5
Summer	25,730	8.5 ± 7.6
Fall	24,928	6.0 ± 5.5

Fig. 6. Annual changes of PM_{2.5} average concentrations. Black and white pattern represent years with less than 182 days (half a year) of measurements. Gray dashed line represents a trend line of the data, while the black dashed line represents the EPA annual standard values of 15 µg m⁻³.

The highest annual average PM_{2.5} concentration was measured in 2005 with an average of $9.1 \pm 6.7 \mu\text{g m}^{-3}$, but this year had just below six months of measurements. A similar annual concentration of $9.1 \pm 8 \mu\text{g m}^{-3}$ was measured in 2012; the SD this year was higher than in 2005. Similar concentrations were measured in 2011, but the SD was considerably higher ($8.9 \pm 9.2 \mu\text{g m}^{-3}$). The highest annual SD was in 2003, most likely the result of having two days with the highest PM_{2.5} concentrations (as shown in Fig. 2(A)). The lowest annual PM_{2.5} concentration was measured in 2002, with a concentration of $5.2 \pm 5 \mu\text{g m}^{-3}$. A previous study in Lubbock, which measured the hourly average particle concentrations (TSP) during 2003 up to 2007, found 2003 to have the highest PM concentrations (Stout, 2015). Although we found 2005 to have higher annual PM_{2.5} concentrations compared to 2003, we suspect the cause is only six months of measurements during 2005 (January–June), which excluded months which generally have lower concentrations. Therefore, the 2005 concentrations are biased and cannot be reliably evaluated. Measurements in 2003 and 2011 recorded the highest annual PM_{2.5} concentration along with the largest SDs. These two years also had the fewest precipitation days (Table S2), leading to a dry environment, which may have contributed to an increase in dust storm events.

The annual average concentrations of PM_{2.5} measured at five sites in Beijing were much higher ($101 \mu\text{g m}^{-3}$) than any of the annual values from this study (Zheng *et al.*, 2005). Our annual values were also lower than those measured in three big cities in the U.S., Pittsburgh (Wittig *et al.*, 2004), Houston (Tropp *et al.*, 1998) and Baltimore (Landis *et al.*, 2001). The annual PM_{2.5} concentrations were below the EPA annual standard ($15 \mu\text{g m}^{-3}$), yet many years had SD magnitudes that exceeded the EPA annual standard.

No trends in PM_{2.5} concentrations were discovered over the measured period ($R^2 = 0.003$, and the slope = 0.036), as shown in Fig. 6. Stout and Lee (2003) presented a trend of

TSP concentrations in Lubbock between 1961–1986, documenting a reduction of TSP concentrations over time. They found that TSP concentrations decreased due to the implementation of mitigations in order to reduce dust particle emissions from the surrounding agricultural fields. Some of the mitigation practices include leaving the crop residues on the soil surface during the winter, not tilling until early in the spring, and where feasible, use conservation tillage methods (Osmond and Line, 2017; U.S. EPA, 2020). The frequency of dust storm events was more pronounced in these years (1961–1986) compared to what was observed in this study. Over the last 20 years, although the city has grown in size and population (there has been an increase of 50,000 residents since 2000; World Population Review, 2020), no changes in mitigations were made in this region, substantiating the lack of concentration trends in this study area.

Effect of El Niño-Southern Oscillation on PM_{2.5} Concentration

Since we could not find any trends in the concentrations, we wondered if El Niño or La Niña events might affect the local PM_{2.5} concentrations. Based on the ONI, the hourly PM_{2.5} concentrations were separated by the occurrence of El Niño and La Niña events, and average PM_{2.5} concentrations were calculated accordingly. PM_{2.5} measurements were recorded for over 18,700 hours during El Niño events and more than 24,000 hours in La Niña events. Higher PM_{2.5} concentrations were observed during La Niña, with an average of $7.1 \pm 7.0 \mu\text{g m}^{-3}$, whereas El Niño events averaged $5.6 \pm 5.2 \mu\text{g m}^{-3}$ (Fig. 7(A)). The differences between the two samples are statistically significant ($p < 0.001$).

We then divided each ENSO event based on their strength, weak, moderate, and strong, based on the magnitude of the SST anomaly (Null, 2019). There were no PM_{2.5} measurements during very strong ENSO events during the time of analysis. All six categories had more than 1,450 hours of PM_{2.5}

measurements (Table S3). A weak La Niña had the highest average $\text{PM}_{2.5}$ concentration ($7.4 \pm 7.6 \mu\text{g m}^{-3}$), while moderate and strong La Niña events had lower $\text{PM}_{2.5}$ concentrations (Fig. 7(B)). During El Niño events, the lowest $\text{PM}_{2.5}$ concentration occurred during moderate El Niño events ($4.6 \pm 3.6 \mu\text{g m}^{-3}$), whereas the highest concentrations were in a weak El Niño ($6.0 \pm 5.8 \mu\text{g m}^{-3}$).

ENSO events last for long periods of time and cause different effects all over the globe (Carlowicz and Schollaert Uz, 2017). The biggest impact on the U.S. from ENSO events is the location of mid-latitude jet streams (Lindsey, 2017). During La Niña events, the jet stream, over the United States, moves north, while during El Niño, it moves south. Due to the northward movement of the jet stream during La Niña, the southern portions of the United States experience drier and warmer conditions (Lindsey, 2017), which may explain the higher $\text{PM}_{2.5}$ concentrations during La Niña (Fig. 7(A)). On the other hand, El Niño events are associated with an increase in precipitation (Table S3) and lower $\text{PM}_{2.5}$ concentrations. Cole and Cook (1998) examined how ENSO events affected drought conditions back to the late 1800s. They found that La Niña correlated more with drought across the southwest. In contrast, during El Niño, the Southwest experienced wetter conditions than normal. Through their study, Cole and Cook (1998) also found that La Niña events were associated with drought conditions over the Great Plains. Precipitation observations during our study period support these conditions. For example, all the El Niño events had a high total precipitation of 2,738 mm (108 inches), whereas La Niña events had a lower total precipitation of 795 mm (31.3 inches). This confirms the conclusions of Cole and Cook (1998) that the southern Great Plains receives less rainfall than normal during La Niña events. Okin and Reheis (2002) conducted a study from 1973 to 1999 on the effects of ENSO on dust concentrations in the southwestern United States. They found an increase in dust events after strong La Niña years. They stated the decrease in precipitation in the southwestern United States is what contributed to the increase in dust storms. Similar connections were found when a comparison was made between the different ENSO events based on weather observation from

the METARs. The local NWS station reported 82 days with blowing dust during La Niña compared to only 14 days during El Niño. Out of all the La Niña blowing dust events, 77% occurred during a weak La Niña.

CONCLUSIONS

This study examined a total of 102,019 hourly $\text{PM}_{2.5}$ measurements conducted at the TCEQ station located in Lubbock, Texas, from 2001 to 2018. Substantial gaps in the data were a result of multiple station relocations. The hourly concentrations reached as high as $486 \mu\text{g m}^{-3}$, although the majority were below $25 \mu\text{g m}^{-3}$. 271 hours displayed $\text{PM}_{2.5}$ concentrations above $50 \mu\text{g m}^{-3}$, and the concentrations for 66 of those hours exceeded $100 \mu\text{g m}^{-3}$. No strong correlations were observed between the $\text{PM}_{2.5}$ concentrations and various meteorological parameters (wind speed, wind gust, wind direction, temperature, relative humidity, and visibility) recorded by nearby weather stations, even for the high concentrations ($> 100 \mu\text{g m}^{-3}$).

Our analysis of the diurnal $\text{PM}_{2.5}$ concentrations revealed a generally bimodal distribution, with an early morning peak and an evening peak; this distribution was present even on very clean days (when the daily concentration was below $5 \mu\text{g m}^{-3}$). However, dust storm days displayed a different distribution, with a single peak during the afternoon. Furthermore, lower $\text{PM}_{2.5}$ values were observed during the weekend, although similar bimodal distributions were found for all the days of the week. Due to the highest $\text{PM}_{2.5}$ concentrations occurring during April and June, spring and summer possessed the highest seasonal average concentrations. No annual trends in the concentration were detected during the study period, but several years showed higher average values.

Finally, the $\text{PM}_{2.5}$ concentrations were higher during La Niña than El Niño events, with weak La Niñas (determined by categorizing the ENSO events as weak, moderate, or strong) displaying the maximum values. The elevated concentrations during La Niña resulted from warmer and drier conditions in the southwestern United States, which corresponded to less precipitation and a higher frequency of dust storm events.

Fig. 7. (A) Average $\text{PM}_{2.5}$ concentrations in El Niño (black) and La Niña (orange) events with (B) their respective strengths. Asterisks indicate significant differences ($p < 0.001$) between the different event cases based on ANOVA.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at <http://www.aaqr.org>.

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