GeoHealth

RESEARCH ARTICLE
10.1029/2024GH001209

Special Collection:
Dust and dust storms: From physical processes to human health, safety, and welfare

Key Points:

- High PM10 concentrations measured during short-duration convective dust events in the Phoenix area from July to August 2015 to 2021
- Convective dust events cause significant short-term spikes in PM10 concentrations, often underreported by daily or hourly averages
- Comprehensive guidance is needed to assess short-term PM exposure for short-duration convective dust events that influence air quality

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:
K. Ardon-Dryer,
karin.ardon-dryer@ttu.edu

Citation:
Ardon-Dryer, K., & Aziz, T. (2025). Times matter, the impact of convective dust events on air quality in the greater Phoenix area, Arizona. *GeoHealth*, *9*, e2024GH001209. https://doi.org/10.1029/2024GH001209

Received 8 SEP 2024
Accepted 12 FEB 2025

Author Contributions:
Conceptualization: K. Ardon-Dryer
Data curation: K. Ardon-Dryer
Formal analysis: K. Ardon-Dryer, T. Aziz
Investigation: K. Ardon-Dryer
Methodology: K. Ardon-Dryer
Project administration: K. Ardon-Dryer
Resources: K. Ardon-Dryer
Supervision: K. Ardon-Dryer

Times Matter, the Impact of Convective Dust Events on Air Quality in the Greater Phoenix Area, Arizona

K. Ardon-Dryer[1] and **T. Aziz**[1]

[1]Department of Geosciences, Texas Tech University, Lubbock, TX, USA

Abstract

Convective dust events are common in the greater Phoenix area over the summer. These short-duration dust events degrade the air quality and pose a potential health threat to millions. In this study, 93 convective dust events that occurred in July and August 2015 to 2021 were examined to determine their impact on air quality. Seven PM_{10} stations were used to evaluate the changes in PM_{10} concentrations over different time intervals (10-min, hourly, and daily). Out of these 93 dust events, only 15.1% had a daily average above the EPA PM_{10} daily threshold, however, these daily concentrations were 12.8 and 28 times lower compared to hourly and 10-min concentrations (respectively) at the peak of the dust. 10-minute PM_{10} concentrations were on average 2.2 ± 0.8 times higher than the hourly concentrations. The findings of this study demonstrated that the traditional methods that use daily or hourly averages underestimate the atmospheric PM_{10} concentrations during short convective dust events and therefore lower the estimated exposure. There is a need to consider shorter time intervals to capture the PM concentrations accurately and highlight the importance of real-time monitoring and accurate characterization of short-duration events to assess their impacts on air quality and human health.

Plain Language Summary

Convective dust events caused by thunderstorms often result in poor air quality and potential health risks to millions. This study examined 93 convective dust events in the greater Phoenix area, between July and August 2015 to 2021. Different PM_{10} concentration time analyses (10-min, hourly, and daily average) were performed to understand their impact on air quality. The study found that traditional daily and hourly measurements significantly underestimate the concentration of PM_{10} particles. Shorter time intervals (10-min) revealed much higher concentrations during the peak of dust events, on average 2.2 times higher than hourly concentrations. Only 15% of the events exceeded the daily air quality threshold, but particle concentrations during these shorter periods were far more concerning. These findings emphasize the need for real-time monitoring and shorter measurement intervals to accurately assess the health impacts of dust events and improve air quality assessments.

1. Introduction

Dust events are common in dry and semi-arid areas (Al Zubi et al., 2024; Goudie, 2014; Goudie & Middleton, 2006; Sissakian et al., 2013). Different elements can impact the generation of dust events, including wind speed, vegetation cover, rainfall amount, and soil moisture (Csavina et al., 2014; Kasey et al., 2019; Okin, 2022). The World Meteorological Organization (WMO) defines a dust event as an occurrence with an increase in wind speed that reduces horizontal vision to less than 10 km. In contrast, during dust storms visibility decreased to less than 1 km (World Meteorological Organization, 2019). Dust events and dust storms can be generated by synoptic and convective meteorological disturbances (Ardon-Dryer & Kelley, 2022; Middleton & Kang, 2017; Robinson & Ardon-Dryer, 2024).

Dust events play significant roles in several natural processes. They can influence the atmosphere's chemistry and climatic processes, alter soil and water properties, affect nutrient dynamics, ecosystems, agricultural output, and weather, and impact biogeochemical cycles in marine and terrestrial ecosystems (Akhlaq et al., 2012; Hahnenberger & Nicoll, 2012; Middleton & Kang, 2017). Dust events can negatively affect agriculture by damaging crops removing fertile topsoil, and impairing food production (Middleton, 2019). High densities of microorganisms (fungi and bacteria), as well as plant pollens, have been observed during dust events (Elmassry et al., 2021; Jiang et al., 2003). Dust particles have also a direct and indirect impact on the climate, they reflect and absorb solar radiation (Lau et al., 2020; Wang et al., 2009), play a role as cloud condensation nuclei and ice nuclei particles (Ardon-Dryer & Levin, 2014; Chen et al., 2019; Kok et al., 2012), and even impact the atmosphere vertical electric field (Ardon-Dryer, Chmielewski, et al., 2022).

Validation: K. Ardon-Dryer
Visualization: K. Ardon-Dryer, T. Aziz
Writing – original draft: K. Ardon-Dryer, T. Aziz

Dust events are one of the most significant natural sources of atmospheric particulate matter (PM) (Shahsavani et al., 2012) mainly of PM_{10} and $PM_{2.5}$ (defined as particulate matter with an aerodynamic diameter of up to 10 and 2.5 μm, respectively). During dust events, the concentrations of PM_{10} and $PM_{2.5}$ can exceed the daily threshold level recommended by the World Health Organization (WHO; 45 and 15 $\mu g\ m^{-3}$ for PM_{10} and $PM_{2.5}$, respectively; World Health Organization, 2022) and U.S. Environmental Protection Agency (EPA; 150 and 35 $\mu g\ m^{-3}$ for PM_{10} and $PM_{2.5}$, respectively; EPA, 2023). Studies found that dust events can also continue high concentrations of small particles even <1 μm (Ardon-Dryer & Kelley, 2022; Ardon-Dryer, Kelley, et al., 2022). An increase in dust particle concentrations and changes in particle size and chemistry are considered the cause of health issues linked with dust events, these health issues include respiratory and cardiovascular illnesses (Herrera-Molina et al., 2024; Toure et al., 2019; Trianti et al., 2017), premature delivery, abnormal birthweight, and pregnancy-related toxemia (Bogan et al., 2021; Dastoorpoor et al., 2018; Jones, 2020), conjunctivitis, meningitis, and valley fever (Gorris et al., 2023; Hamza, 2021; Nhung et al., 2017; Tong et al., 2022; Zhang et al., 2016). In extreme cases, exposure to dust particles even resulted in mortality (Díaz et al., 2017; Wang et al., 2020).

In the US one of the states that experiences frequent dust events and storms is Arizona (AZ) (Ardon-Dryer, Gill, & Tong, 2023; Mohebbi et al., 2019). Its proximity to the Sonoran and Chihuahuan Deserts and the Salt River Valley influences the North American Monsoon, leading to the formation of strong convective storms that exacerbate dust emission (Evan et al., 2022a, 2022b; Moreno-Rodríguez et al., 2015; Sandhu et al., 2024). Dust events in AZ are the third leading weather-related cause of death in the state (Beal, 2016). The strongest and most severe dust events in Arizona occur in the summer (Ardon-Dryer, Gill, & Tong, 2023; Clements et al., 2013; Foroutan & Pleim, 2017; Hyde et al., 2018; Sandhu et al., 2024). Most of the dust events last less than an hour (Raman et al., 2014; Sandhu et al., 2024), and many can even be shorter, <20 min (Nickling & Brazel, 1984). High PM concentrations are common during these dust events (Ardon-Dryer, Clifford, & Hand, 2023; Eagar et al., 2017; Huang et al., 2015; Raman et al., 2014; Sandhu et al., 2024). Higher daily average PM_{10} concentrations were found during dust days (57.0 ± 48.9 $\mu g\ m^{-3}$) compared to non-dust days (31.9 ± 18.9 $\mu g\ m^{-3}$), some were even higher than the WHO or the EPA recommended daily thresholds (Sandhu et al., 2024). One of these strong dust events occurred on 5 July 2011, when PM_{10} hourly concentrations reached 1,974 $\mu g\ m^{-3}$ and the daily value was 225 $\mu g\ m^{-3}$ (Raman et al., 2014). Eagar et al. (2017) examined different types of dust storms in the area from 2005 to 2014 and found that maximum PM_{10} hourly concentrations during Haboob dust type were in many cases higher than 1,000 $\mu g\ m^{-3}$, in some cases, it was >5,000 $\mu g\ m^{-3}$. Several studies also found an increase in $PM_{2.5}$ concentration during dust events in the region (Huang et al., 2015; Sandhu et al., 2024). With these high hourly PM concentrations during dust events, we were wondering what the actual concentration of PM in the regions at the peak of the dust, mainly since many of these dust events will be shorter than an hour, can we speculate that the observation of PM which is based on daily and hourly basis will underestimate the concentrations of particles during these dust events and therefore their exposure and impact on human health.

Recent studies indicated that sub-daily exposure may unveil adverse health outcomes that are not observed or may be attenuated when only the daily level is measured and that hourly peak concentration may capture the health effects of ambient PM better than daily averages (Lin et al., 2017; Nguyen et al., 2024). Studies have shown health impact due to short-term exposures to high anthropogenic emissions (Behndig et al., 2006; Chen et al., 2015; Greven et al., 2012; Swiston et al., 2008). For example, Cheng et al. (2021) found aggravation of asthma rate in children in Australia within short (1-hr) exposure windows of $PM_{2.5}$. In China, Lin et al. (2017) found an association between the hourly peak of $PM_{2.5}$ on cardiovascular mortality. However, most of these studies focus on anthropogenic emissions and not natural dust particles (e.g., Lin et al., 2017; Nguyen et al., 2024). To the best of our knowledge, no information is available on the health impact of short-term (<1 hr) convective dust events, perhaps since most observation was based on daily and hourly values, which underestimated the impact of these dust events on PM concentrations and hence on human health. It is noteworthy that the health consequences of such intense but relatively short exposure to dust events are unclear and there are no established guidelines or universally accepted thresholds for evaluating short-term (15–60 min) exposures to PM (Griffiths et al., 2018).

2. Method and Materials

2.1. Research Area

The research was performed in the greater Phoenix area, which is located in Maricopa County in Arizona, U.S (shown in Figure 1). This urban area, which has a population of ~5 million people (US Census Bureau, 2022), is

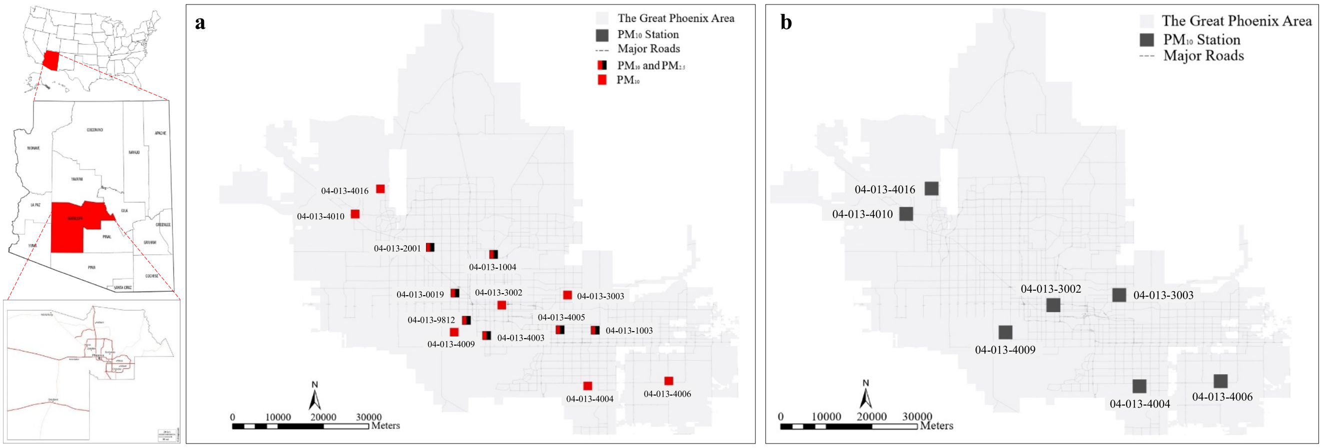

Figure 1. (a) Location of PM stations in the greater Phoenix area examined for the research, rectangle representing station's locations with PM_{10} (in red) and $PM_{2.5}$ (in black). (b) Spatial Distribution of PM_{10} stations utilized for this analysis.

located in the Sonoran Desert. It is defined as a hot and arid climate with an average annual precipitation of 211 mm (Maricopa County, 2022). Most of the precipitation occurs in the summer months due to the impact of the monsoon season.

2.2. Particulate Matter Measurement

Preprocessed (5-min values, which are instantaneous snapshots taken at 5-min intervals) PM_{10} and $PM_{2.5}$ measurements from 14 stations across the Greater Phoenix area were provided by the Maricopa County Air Quality Department (MCADQ) from 3 March 2015 to 31 December 2021. Seven stations had both PM_{10} and $PM_{2.5}$ and the remaining seven had only PM_{10} measurements. All measurements were at local times (UTC-7). Figure 1a Shows the locations of these stations and Table S1 in Supporting Information S1 provides information on each station. Each station was operated by the Tapered Element Oscillating Microbalance (TEOM) method. Seven stations utilized TEOM 1405-DF and the other seven used TEOM 1400ab. TEOM 1405-DF measures PM concentrations from 0 and up to 1,000,000 $\mu g\ m^{-3}$ with a resolution of 0.1 $\mu g\ m^{-3}$ and precision of $\pm 2.0\ \mu g\ m^{-3}$ (for 1 hr averaged). TEOM 1400ab measures PM concentrations from 0 and up to 5,000,000 $\mu g\ m^{-3}$ with a resolution of 0.1 $\mu g\ m^{-3}$ and precision (for 1 hr averaged) of $\pm 1.5\ \mu g\ m^{-3}$ (Thermo Scientific, 2009, 2019). It should be noted that TEOM monitors are not designed for less than hourly values (Thermo Scientific, 2009, 2019) and there are no Federal Equivalency Method (FEM) criteria for the 5-min time interval (Ronald Pope, MCADQ personal communication). Official (postprocessed) hourly PM_{10} and $PM_{2.5}$ values of the same stations were also retrieved from the EPA Pre-Generated Data for the same period (EPA, 2022). These official measurements were used to examine the quality of the preprocessed PM stations as the latter did not pass quality control (quality-assured or validated) and therefore was referred to as preprocessed values. MCADQ inspected and quality-assured the preprocessed values as they transferred to hourly values, following the EPA Quality Assurance guidelines (EPA, 2017) defined in Part 58 (Quality Assurance Requirements for Monitors used in Evaluations of National Ambient Air Quality Standards; EPA, 2024a) to make sure there were no invalidated values before these can be reported to EPA and became the official values presented in EPA Pre-Generated Data. The official EPA Pre-Generated Data provide hourly values without the ability to observe any fluctuation of PM during these hours (e.g., there is no information on hourly standard deviation), on the other hand, observation of the preprocessed PM data allows detection of these shorter time fluctuations, even intervals less than an hour (e.g., 10-min average).

2.2.1. Preparation of Particulate Matter (PM) Data

The first quality control step of the preprocessed (5-min) PM_{10} and $PM_{2.5}$ values included the removal of concentrations that were less than $-10\ \mu g\ m^{-3}$. Each of the stations contained negative values that ranged from -0.1 to $-1,065\ \mu g\ m^{-3}$. Although they represent a very low percentage of the total number of values used (3.0%, depending on the station). We were advised by MCADQ (Ira Domsky, MCADQ personal communication) to remove preprocessed negative values smaller than $-10\ \mu g\ m^{-3}$ since the TEOM minimum detection limit for hourly values is −10 μg m^{-3}, and since the high negative 5-min values could be malfunction or instrument faults (Ray & Vaughn, 2009). The second quality control step required validation of the preprocessed PM_{10} and $PM_{2.5}$ values. Therefore, hourly averages calculated for each station were performed and compared to the official (postprocessed) EPA hourly PM_{10} and $PM_{2.5}$ values. This comparison evaluates which preprocessed stations could be used, and which were problematic and should be removed from future analysis. The evaluation was based on linear regression (commonly used for such analysis, Ardon-Dryer et al., 2020) and had >40,000 hr of comparison. Seven PM_{10} stations had high R^2 values (0.99–1.0), lower RMSE values that range from 0.6 to 2.7 μg m^{-3}, lower MAE values (~0.3 μg m^{-3}), and a slope of 1.0. between the preprocessed and the official EPA stations. A small difference was observed between hourly values, the difference was on average ~0.5 ± 1.4 μg m^{-3}. On average 0.7% of the hourly values had a difference of >1.0 μg m^{-3} for PM_{10} values, which made us confident in using these seven preprocessed stations for the analysis. The remaining PM_{10} stations had lower R^2 values (ranging from 0 to 0.82), with various RMSE, MAE, and slope values (shown in Figure S1 in Supporting Information S1). For example, three PM_{10} stations that had higher R^2 values (R^2 0.79–0.82), had RMSE values that ranged from 12.3 to 23 μg m^{-3}, MAE values from 3.3 to 7.6 μg m^{-3}, and slope from 0.8 to 0.9, making them look good compared to the official stations. But when we examine the difference in PM_{10} hourly concentrations between the preprocessed to the official PM values, some hours had high differences in concentrations (>2,000 μg m^{-3}) and there seems to be a shift in values as they did not align. Four $PM_{2.5}$ stations had low R^2 values (ranging from 0 to 0.05), with high RMSE, MAE, and lower slopes. Three of the $PM_{2.5}$ stations had high R^2 values (0.84–0.89), lower RMSE values that range from 2.4 to 3.0 μg m^{-3}, lower MAE values (1.3 μg m^{-3}), and also higher slope (at 0.9), but when the observation was based on the difference of hourly values of the two, some hourly values had high concentrations in one compared to the other (up to 200 μg m^{-3}). On average 58% of the hourly values had a 1.0 μg m^{-3} difference in $PM_{2.5}$ values. Based on this comparison we decided to include only the seven preprocessed PM_{10} stations that pass the quality comparisons and to remove the remaining stations from any future analysis. These findings were not suppressing as indicated by Ronald Pope (MCADQ personal communication) who stated that the 5-min PM_{10} data (TEOM 1400ab) tend to be the most reliable and in agreement with the official hourly value, while stations with both PM_{10} and $PM_{2.5}$ (TEOM 1405-DF), tend to be less accurate at the 5-min interval. The locations of the selected seven PM_{10} stations are shown in Figure 1b. Additional calculations were made to each of these seven preprocessed stations including 10-min, and daily averages.

2.3. Meteorological Data

Meteorological Aerodrome Reports (METARs) from the Iowa Environmental Mesonet reported by the National Weather Service (NWS) in the Automated Surface Observation System (ASOS) were retrieved from Nine different ASOS stations located in the greater Phoenix area (Iowa State University, 2021). The ASOS data contained 5-min to hourly meteorological measurements including wind speed and wind direction, visibility, and Present Weather Code. The ASOS data was retrieved from 3 March 2015 to 31 December 2021, and times were converted to Local Time (LT; UTC-7). Table S2 in Supporting Information S1 provides information on each of the ASOS units used in this study, and Figure S2 in Supporting Information S1 shows the locations of the ASOS units with the PM stations.

2.4. Software and Statistical Analysis Used

Different calculations were made using Excel and MATLAB, these included hourly, and daily average ± standard deviation (SD) values. In order to examine the similarities between the preprocessed and the official EPA station, comparisons were performed using MATLAB and Excel. These comparisons included R-squared (R^2), Root-Mean-Square Error (RMSE), Mean Absolute Error (MAE) values, as well as the best-fit information including the slope and intercept.

3. Results and Discussion

3.1. Examining PM Concentrations During Dust Events

Using the greater Phoenix area dust events database (Sandhu et al., 2024), we were able to identify 192 dust events that occurred between 3 March 2015 to 31 December 2021 (a period when preprocessed PM values were available). Since we were interested in examining the PM concentration during short-duration dust events, we

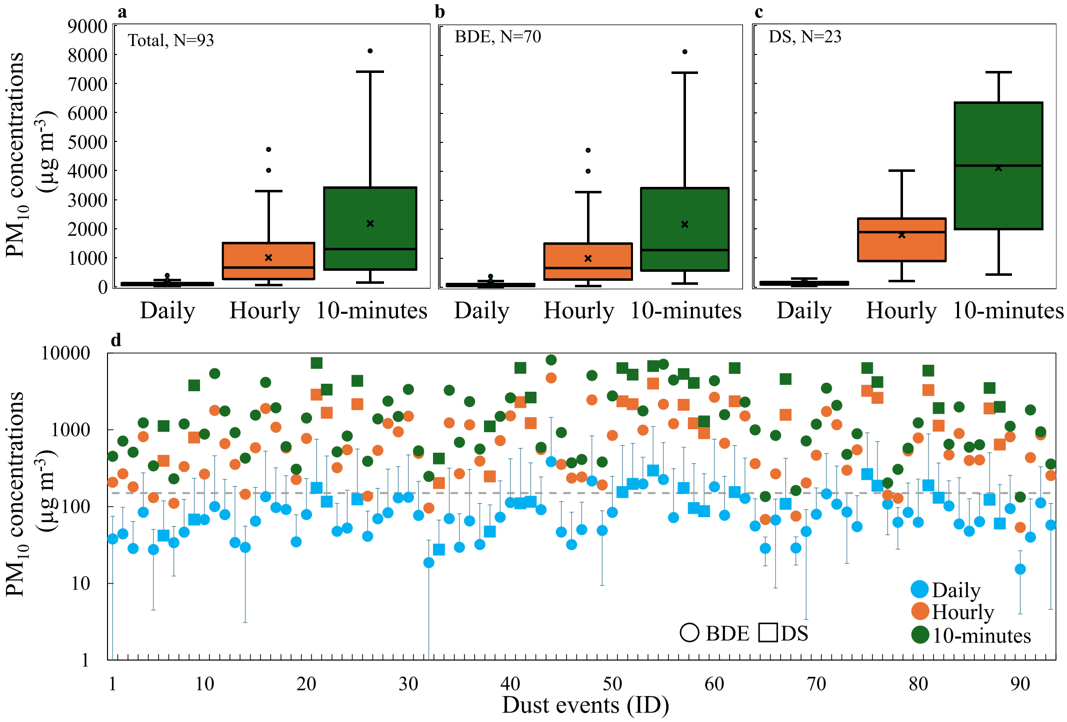

Figure 2. Comparison of PM_{10} concentrations for Daily, hourly, and 10-min concentrations based on Box plot for (a) the entire dust events, (b) Blowing Dust Events (BDE), and (c) Dust storms (DS). (d) Comparison of PM_{10} concentrations for each of the dust events based on 10-min (green), hourly (orange), and daily average concentrations ± SD (light blue). Dash gray lines represent the EPA PM_{10} daily threshold of 150 μg m^{-3}, circles represent BDE and squares represent DS.

decided to focus on summer convective dust events, which are short (<1 hr) and occur mainly in July and August (Sandhu et al., 2024). A total of 123 convective dust events occurred in the greater Phoenix area from 2015 to 2021, 93 of these dust events occurred during July–August which were of interest for this work. 24% of these 93 dust events were in 2018 while 8.6% of these dust events were in either 2019 or 2020. An equal number of events occurred in July versus August. 67.7% of the dust events occurred between 18:00 to 23:00 LT. Most of the dust events (70, 75.3%) were Blowing Dust Events (BDE) with visibility below 10 km but above 1 km, while 23 of the dust events (24.7%) were defined as dust storms (DS) with visibility <1 km. See Sandhu et al. (2024) for definitions of BDE and DS and the differences between these severity dust events.

All the PM_{10} stations that were active during each dust event were examined, and the station with the maximum hourly concentrations was selected to represent the PM_{10} concentrations during the dust event. The daily PM_{10} concentrations of these 93 dust events ranged from 15.3 ± 11.3 μg m^{-3} (on 11 August 2021; defined as BDE with visibility ≥8 km) and up to 385 ± 1,068 μg m^{-3} (on 8 July 2018; defined as BDE with visibility ≥1.2 km). The average of all the daily values was 92.8 ± 64 μg m^{-3} with a mode of 67.7 μg m^{-3}. The hourly PM_{10} concentrations of these 93 dust events ranged from 53.5 μg m^{-3} (on 11 August 2021) and up to 4,729 μg m^{-3} (on 8 July 2018). The average of all the daily values was 998 ± 948 μg m^{-3} with a mode of 2,351 μg m^{-3}. The 10-min average of PM_{10} ranged from 133 μg m^{-3} (on 11 August 2021) up to 8,129 μg m^{-3} (on 8 July 2018). The average of the 10-min PM_{10} concentrations at the peak of the dust for all 93 dust events was 2,174 ± 2,064 μg m^{-3} with a mode of 6,335 μg m^{-3}. Observations of the difference between the daily, hourly, and 10-min averages of PM_{10} concentrations were performed for each of the 93 dust events (Figure 2a). The hourly values at the peak of the dust were on average 9.4 ± 4.4 times higher than the daily average, these values range from 1.3 up to 20.8. The 10-min values at the peak of the dust were on average 20.5 ± 13 times higher than the daily average, these values range from 1.4 up to 62. The 10-min values at the peak of the dust were on average 2.2 ± 0.8 times higher than the hourly values, these values range from 1.0 up to 4.8. Most of the dust events (87%) had 10-min values that were 2 times higher compared to hourly values, and 38% of the dust events had 10-min values that were 3 times higher compared to hourly values. 80% of the events had 10-min values that were 10 times higher than the daily values.

Almost all dust events (99%) had hourly values that were 2 times higher compared to daily values, and 49% of the dust events had hourly values that were 10 times higher compared to daily values.

A similar examination was performed based on the severity of the dust. The daily PM_{10} values for the 70 BDE ranged from 15.3 μg m^{-3} (on 11 August 2021) up to 385 μg m^{-3} (on 8 July 2018). The average daily PM_{10} concentrations of the BDE were 79.8 ± 57.7 μg m^{-3}. The hourly PM_{10} values for the 70 BDE ranged from 53.5 μg m^{-3} (on 11 August 2021) up to 4,729 μg m^{-3} (on 8 July 2018). The average hourly PM_{10} concentrations of the BDE was 737 ± 761 μg m^{-3}. 10-minute concentrations at the peak of the dust for the BDE ranged from 133 μg m^{-3} up to 8,129 μg m^{-3}, average concentration of these times was 1,540 ± 1,623 μg m^{-3}. The comparisons between these different times for all BDE are presented in Figure 2b. 83% of the BDE events had 10-min concentrations that were 2 times higher compared to hourly values, 34% of the BDE had 10-min concentrations that were 3 times higher compared to hourly values (the average between these concentrations 2.1 ± 0.7 times). Most of the BDE (74%) had 10-min values that were 10 times higher compared to daily values (the average between these concentrations was 18 ± 11.7 times). Almost all the BDE (98.6%) had hourly values that were 2 times higher compared to daily values, and 18.6% of them had hourly values that were 10 times higher compared to daily values (the average between these concentrations was 8.3 ± 4). The daily PM_{10} values for the 23 DS ranged from 27.5 μg m^{-3} (on 21 July 2017; defined as DS with visibility of 0.8 km) up to 295 μg m^{-3} (on 7 August 2018; defined as DS with visibility of 0.8 km). The average daily PM_{10} concentration of the DS was 132 ± 67 μg m^{-3}. The hourly PM_{10} values for the DS ranged from 202 μg m^{-3} up to 4,007 μg m^{-3}, while the average hourly PM_{10} concentration was 1,794 ± 1,031 μg m^{-3}. The 10-min concentrations at the peak of the dust storms ranged from 423 μg m^{-3} up to 7,400 μg m^{-3} (on 29 July 2016; defined as DS with visibility of 0 km), the average concentration of the 10-min was 4,102 ± 2,095 μg m^{-3}. A comparison of PM_{10} concentrations at the different times during the DS is presented in Figure 2c. 95.7% of the DS events had 10-min concentrations that were 2 times higher compared to hourly values, on average PM_{10} concentrations 10-min values at the peak of the dust were 2.5 ± 0.9 times higher than the hourly average. All the DS had 10-min values that were 15 times higher compared to daily values. On average 10-min PM_{10} concentrations values at the peak of the dust were 31.5 ± 12 times higher than the daily average, these ranged from 14.7 up to 58.2. All the DS had hourly values that were 5 times higher compared to daily values, average hourly PM_{10} concentrations values at the peak of the dust were 12.9 ± 3.5 times higher than the daily average values, these ranged from 2.5 up to 20.8. A comparison between these different times for the DS is presented in Figure 2c. Observations of daily, hourly, and 10-min PM_{10} concentrations of each of the dust events presented in Figure 2d show the variability among the PM_{10} concentrations. These large differences between the 10-min PM_{10} concentrations compared to those observed for daily and even for the hourly values highlight the fact that observations based on daily and hourly times will underestimate the PM_{10} concentration regardless of whether it was a BDE or a DS.

Observations of the increase of PM_{10} concentrations of each of the dust events were performed based on the difference of PM_{10} concentrations at the peak of the dust from the concentration recorded right before (also defined as background) the dust reaches (and recorded by) the station. These differences were performed based on two times hourly and 10-min measurements. Observations of hourly PM_{10} concentrations before the dust were on average 33.2 ± 29.9 μg m^{-3}, while observations based on 10-min before the dust were similar, with an average of 36.1 ± 15.8 μg m^{-3}. However, the increase in PM_{10} concentrations was different. It was 965 ± 944 μg m^{-3} based on hourly values and 2,138 ± 2,064 μg m^{-3} based on 10-min values. PM_{10} concentrations at the peak of the dust were on average 79.3 ± 137 times higher compared to the times before the dust (background) based on 10-min values, lower values were found when observations were made based on hourly values (37.1 ± 37.2 times). These differences highlight the significance that observations based on 10-min have during such short-term dust events, as it highlights the significant impact of exposure to such high particle concentration at such short times.

Most of the dust events (85%) examined were below the EPA PM_{10} daily threshold, and only 15% had a daily average above the EPA PM_{10} daily threshold (150 μg m^{-3}). Out of the days above the EPA daily threshold, 36% were BDE and 64% were DS. The average hourly values for these 14 days with PM_{10} daily values >150 μg m^{-3} was 2,708 ± 905 μg m^{-3}, and the average of 10-min PM_{10} values was 5,737 ± 1,609 μg m^{-3}, 12.8 and 28 times above the daily values (hourly and 10-min, respectively). The highest hourly PM_{10} value for these days was 4,729 μg m^{-3}, while the 10-min PM_{10} value was 8,129 μg m^{-3}. However, 79 days had PM_{10} daily values below the EPA PM_{10} daily threshold, PM_{10} concentrations based on hourly (695 ± 553 μg m^{-3}), and 10-min (1,542 ± 1,382 μg m^{-3}) values were 8.8 and 20 times above the EPA daily threshold (respectively). For example, 11 August 2015, had daily values of 67.7 ± 166 μg m^{-3}, hourly concentrations during this dust storm

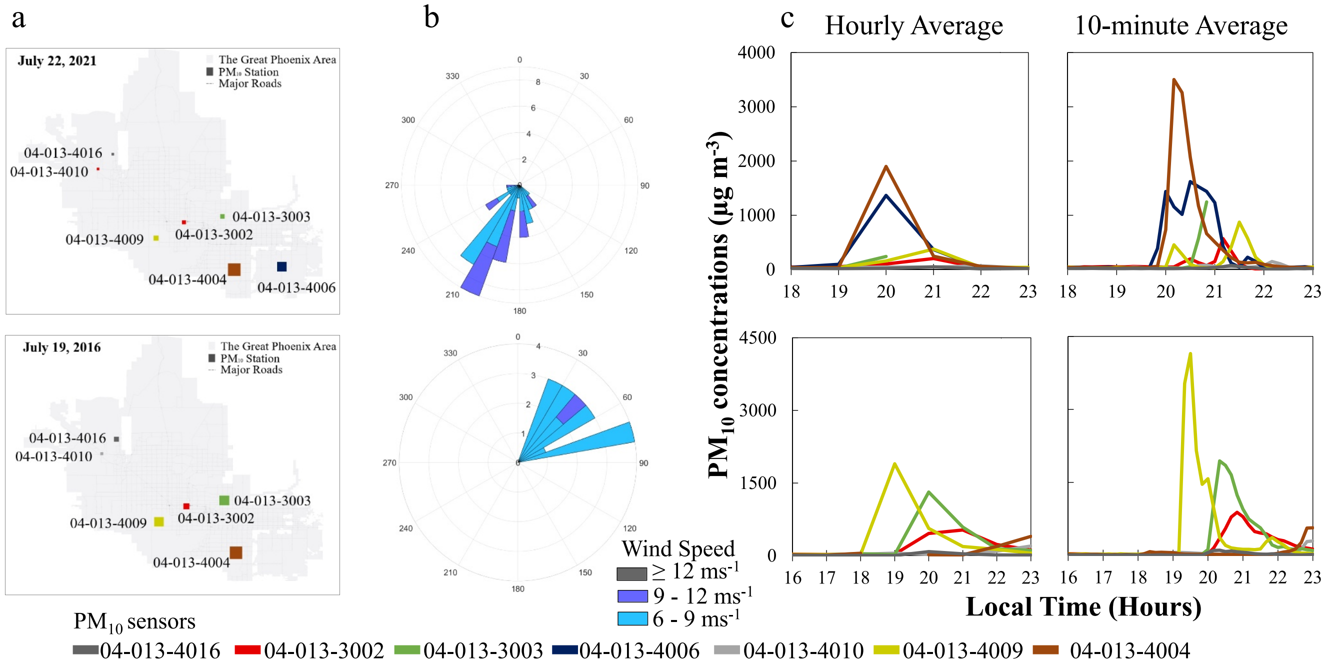

Figure 3. Example of two dust events that did not exceed the EPA daily threshold along with spatial distribution of the PM_{10} stations. (a) Spatial distribution of PM_{10} stations, rectangle size represents the maximum hourly values measured. (b) A wind rose during dust times and (c) distribution of hourly and 10-min average of PM_{10} values for each of the stations.

went up to 793 µg m^{-3} while 10-min concentrations went up to 3,788 µg m^{-3} (10-min concentrations were 56 times and 4.8 times higher compared to the daily and hourly values, respectively). Observations were also made based on the updated WHO PM_{10} daily threshold (45 µg m^{-3}). Only 20% of the dust events (19 dust events) presented were below the WHO PM_{10} daily threshold. However close look at these dust events reveals that many had very high hourly and 10-min PM_{10} concentrations. On average the PM_{10} concentrations of these 19 dust events were 209 ± 117 µg m^{-3} and 523 ± 407 µg m^{-3} based on hourly and 10-min values, respectively. Hourly and 10-min values were 4.6 and 11.6 times higher compared to daily values (respectively). To highlight this difference 31 August 2016, the dust event had daily values of 41.0 ± 46.3 µg m^{-3}, hourly concentrations during this dust went up to 136 µg m^{-3} while 10-min concentrations went up to 390 µg m^{-3}. If observations were only based on days above the EPA or WHO PM_{10} daily threshold, many of these days would have gone under the radar and would not be flagged as problematic days with high PM concentrations and therefore with potential health impacts.

3.2. Spatial Impacts of Dust Evet on PM Concentrations

The examination of PM concentrations during dust storms and events presented in the previous Section 3.1 was based on one station with the highest recorded PM_{10} concentrations, however, most of the dust events had multiple stations with high hourly PM_{10} concentrations (>100 µg m^{-3}). Most of the dust events (90%) had an increase in hourly PM_{10} concentrations by multiple stations, regardless of whether the dust events were defined as BDE or DS. 34.4% of dust events observed an increase of PM_{10} concentrations (>100 µg m^{-3}) in all of the active PM stations, 35% of them were defined as DS. Two dust events were selected to present the behavior and spatial and temporal changes of PM_{10} concatenations during the dust events. One is defined as DS, and one is defined as BDE. These two dust events remained below the EPA PM_{10} daily threshold. Locations of each station and changes of PM_{10} concentrations based on hourly and 10-min averages as well as Windrose (highlighting the movement of the dust particles) during these dust events presented in Figure 3.

On 19 July 2016, dust event only six of the PM_{10} stations were active, and four stations detected the dust particles. During this event, the lowest visibility value recorded was 1.6 km, defining it as BDE. The daily average for the four stations that experience the dust events ranges from 84 ± 134 µg m^{-3} for 04-013-3002 up to 135 ± 393 µg m^{-3} for 04-013-4004. The dust was generated by a thunderstorm that originated southeast of the area, and the dust particles moved northwest reaching first station 04-013-4004 at 19:20 LT. The PM_{10} 10-min average concentration was 3,533 μg m^{-3}, 63 times higher compared to concentrations measured just 10-min earlier (56 μg m^{-3}). Station 04-013-4009 detected the dust 30 min later at 19:50 LT when 10-min average concentrations increased from 41 to 161 μg m^{-3}. By 20:10 both stations 04-013-3003 and 04-013-3002 detected the dust. Station 04-013-4004 had its peak PM_{10} concentration at 19:30 with 10-min PM_{10} values of 4,147 μg m^{-3} (74 times higher than before the dust, just 20 min earlier). The other stations had lower PM_{10} concentrations at their peak with 2,024, 1,940, and 884 μg m^{-3} for 04-013-4009, 04-013-3003, and 04-013-3002, respectively. Hourly values at the peak of the dust were 1.5–2.2 times lower than the peak based on the 10-min average. It took time for each of the stations to get back to background concentration. The duration of the event (when PM was high) exceeded 3.5 hr in total. Among the observed stations, station 04-013-3003 had the longest exposure, lasting for 3 hr. Conversely, station 04-013-4004 experienced the event for the shortest duration, which amounted to 1.5 hr. Stations 04-013-4011 and 04-013-4016 remained unaffected by the presence of dust particles throughout the entire duration of the event, as they did not see any increase in PM_{10} concentrations.

The second dust event was on 22 July 2021, it was defined as a DS as visibility by one of the meteorological ASOS stations reported on 0.8 km. All seven PM_{10} were active that day, but only five of them were able to detect the dust particles. One station (04-013-3003) stopped its operation during the dust event. None of the stations exceeded the EPA daily threshold for PM_{10}, the highest daily PM_{10} concentrations measured was 123 ± 381 μg m^{-3} (by station 04-013-4004). The dust came from the southwest and traveled through the northeast with greater impact on stations 04-013-4004 and 04-013-4006. The initial detection of the dust event occurred by station 04-013-4006 at 19:50 LT, where PM_{10} concentrations rapidly increased from 34 to 388 μg m^{-3} within a span of just 10-min. As the dust propagated, additional stations within the area began detecting its presence. Consecutively, station 04-013-4004 detected dust at 20:00 as PM_{10} concentrations increased from 60 to 733 μg m^{-3}. In only 10-min the senor reached a peak with 3,502 μg m^{-3}. Station 04-013-4004 reached its peak much faster than 04-013-4006, which had concentrations >1,000 μg m^{-3} for 30 min until it reached the maximum PM_{10} concentrations of 1,620 μg m^{-3}. Interestingly these high PM_{10} concentrations >1,000 μg m^{-3} continued even after the peak, and they lasted for a total of one hour. Stations 04-013-3003, 04-013-3002, and 04-013-4009, detected the dust at 20:40, 21:00, and 21:10 LT respectively. Some of the stations observed the dust for durations exceeding 2 hr. Each of the stations exhibited a distinct timing for its peak concentration. The maximum 10-min PM_{10} concentrations measured during the peak of the dust event varied across the area, ranging from 569 μg m^{-3} (by station 04-013-3002) up to 3,502 μg m^{-3} (by station 04-013-4004). On average, the peak PM_{10} concentrations across the stations that actively detected the dust was 1,562 ± 1,154 μg m^{-3}. The maximum hourly PM_{10} concentrations during the peak of the dust event ranged from 202 μg m^{-3} (by station 04-013-3002) to 1,900 μg m^{-3} (by station 04-013-4004). Comparing the maximum concentrations recorded based on 10-min averages to those based on hourly values revealed that the hourly PM_{10} concentrations were 1.2–5.2 times lower than the corresponding 10-min averages.

3.3. Impact and Implication of These Short Dust Events With High PM Concentrations

Short convective dust events have been documented across the world. Such dust events have been observed in Africa mainly in the Sahel and Sahara area (Kaly et al., 2015; Marticorena et al., 2010; Pantillon et al., 2015; Roberts & Knippertz, 2014), in the Middle East, including Iran (Firouzabadi et al., 2019; Karami et al., 2017), Israel (Crouvi et al., 2017) the Arabian Peninsula (Anisimov et al., 2018; Miller et al., 2008), at South Asia in India (Banerjee et al., 2021) as well as in central and north Asia (Takemi, 1999) and in Australia (Strong et al., 2011). Short convective dust events have been observed across the U.S. in the Southern High Plains, including Oklahoma, Colorado, Kansas, New Mexico (Kasey et al., 2019), and Texas (Chen & Fryrear, 2002; Robinson & Ardon-Dryer, 2024; Robinson et al., 2024), as well as in Westen U.S. in Utah (Hahnenberger & Nicoll, 2014), California (Lei & Wang, 2014) and Arizona (Raman et al., 2014; Sandhu et al., 2024; Vukovic et al., 2014).

Several studies of convective dust events (e.g., Ardon-Dryer & Kelley, 2022; Bouet et al., 2019; Marticorena et al., 2010; Vukovic et al., 2014) also found much higher PM concentration when the observations were made at short-time intervals (5- or 10-min). In the study conducted by Bouet et al. (2019), in Tunisia, the daily mean PM_{10} concentration during a convective dust event was 125 μg m^{-3}, while the 5-min concentration was extremely higher (3,398 μg m^{-3}), 27 times higher than the daily average. Marticorena et al. (2010) observed a high 5-min PM_{10} concentration during convective dust in Mali (Western Africa), PM_{10} concentration increased by two orders of magnitude in less than 10-min, and the 5-min average values reached up to 14,000 μg m^{-3}. In Phoenix Arizona, Vukovic et al. (2014) presented PM_{10} concentration from the 5 July 2011 dust storm, the 5-min average at the peak of the dust reached 9,000 μg m^{-3}, while hourly PM_{10} concentrations were ∼5,000 μg m^{-3}. In Lubbock Texas, Ardon-Dryer and Kelley (2022) measured PM_{10} concentration during two convective dust events (June 5 and 21, 2019) and found hourly PM_{10} concentrations of 280 and 230 μg m^{-3}, respectively. These hourly concentrations were 4–5 times lower compared to the 10-min values (1,403 and 927 μg m^{-3}, respectively). Convective dust events are known to be localized and impact a smaller area. Some of these short-term convective dust events might impact only one part of the city but not another. The two examples presented in Figure 3 highlight the spatial and temporal changes of PM_{10} concatenations during the convective summer dust events in the greater Phoenix area. As shown in Figure 3 and described in Sandhu et al. (2024) the spatial impact of some of these convective dust events was very localized, impacting only a few of the cities in the greater Phoenix area or even just some neighborhoods. For example, Vukovic et al. (2014) found variability in PM_{10} concentration across stations in the Phoenix area of almost two orders of magnitude during the 5 July 2011, dust storm. These findings indicate how localized some of these dust events could be. Such findings have been observed in previous studies in this region (Raman et al., 2014; Sandhu et al., 2024). Since many studies examine the health effects during dust events using zip codes, these localized effects should be taken into account and considered, mainly if the zip code area is bigger than the area impacted by the dust event.

Many studies found that exposure to dust particles during dust events (BDE and DS) has a negative impact on human health. These impacts include an impact on blood pressure levels (Ishii et al., 2020), cause of cardiovascular disease (Domínguez-Rodríguez et al., 2021; Herrera-Molina et al., 2024), stroke (Herrera-Molina et al., 2024), and respiratory diseases including asthma and acute bronchitis (Crooks et al., 2016; Grineski et al., 2011; Hefflin et al., 1994; Herrera-Molina et al., 2021; Rublee et al., 2020), which could lead to mortality (Crooks et al., 2016; Domínguez-Rodríguez et al., 2021; Seihei et al., 2024; Stafoggia et al., 2016). However, not all studies showed a health impact, or at least a significant one, as summarized by Zhang et al. (2016). Some differences could be attributed to different definitions or methods used to identify the dust events. Some studies used the PM_{10} daily average to define a day as a dust event when the health impact of dust events was examined. For example, in Kuwait Al-Taiar and Thalib (2014) defined dust storm days when the daily PM_{10} concentrations exceeded 200 μg m^{-3}. Shahsavani et al. (2020) defined dust days in Iran when daily PM_{10} concentrations were >150 μg m^{-3}. Rublee et al. (2020) indicate that daily PM_{10} concentrations of 400 μg m^{-3} will define a severe dust storm in the U.S. In this study, none of the dust events had a daily average above 400 μg m^{-3} threshold, and only a small portion of dust events examined (5.4%) had a daily average >200 μg m^{-3}. Many studies used daily average PM concentration when examining the impact of dust on health (Badeenezhad et al., 2020; Crooks et al., 2016; Ishii et al., 2020; Rublee et al., 2020; Stafoggia et al., 2016). The usage of daily PM values has been quested by Staniswalis et al. (2005) who suggested that the daily average, which reflects the total daily dose, may obscure the hourly resolution of the dose rate, lead to a loss of information on high acute exposure which may lead to underestimating of the impact the particles will have on people health, similar to the findings presented in this study. Recent studies used daily maximum PM concentration based on hourly values (Herrera-Molina et al., 2021, 2024). In El Paso, Texas Herrera-Molina et al. (2021) used PM_{10} hourly concentration >100 μg m^{-3} to identify dust events. Other differences between the studies could be based on the methods used to define the dust event itself, some studies used horizontal visibility values based on meteorological stations to identify the dust days (Ishii et al., 2020), while others used weather codes along with visibility values (Grineski et al., 2011). Some studies used back trajectory maps and PM concentrations to identify dust events (Samoli et al., 2011). In Cyprus, Middleton et al. (2008) used a combination of PM_{10} hourly concentration >100 μg m^{-3} and weather codes to identify dust storm days. Some studies used the NWS Storm Events Database (Crooks et al., 2016; Jones, 2020; Rublee et al., 2020), however, a recent study questioned the reliability of this database and suggested that it should be used with caution as its potential limitations might affect the findings (Ardon-Dryer, Clifford, & Hand, 2023).

Another difference could be exposure term, these health impacts of dust events were examined in both short-term (Badeenezhad et al., 2020; Herrera-Molina et al., 2024; Ishii et al., 2020; Moreira et al., 2020; Rublee et al., 2020; Stafoggia et al., 2016) and long-term (Jones, 2020; Seihei et al., 2024). Short-term, also known as acute exposure, is normally defined as exposure on the day of the dust (known as lag 0) and up to several days after the dust, short-term may cause immediate and severe damage. Long-term, which is also known as chronic or persistent exposure may last for months or years and lead to permanent illnesses or injuries. Most of the studies that found a health impact due to exposure to dust (BDE/DS) found a short-term impact (Achilleos et al., 2019; Shahsavani et al., 2020). For example, Samoli et al. (2011) found a higher impact on children's asthma during dust days (lag 0), while Herrera-Molina et al. (2024) found a higher hospitalization rate for asthma on the day of the dust but for acute respiratory disease only 4 days after the dust. However, there are different definitions for short-term exposure. The Occupational Safety and Health Administration (OSHA) defines short-term exposure as the average exposure in which a person may be exposed typically for 15–30 min (Occupational Safety and Health Administration, 2024). EPA has a longer definition with time exposure of more than 24 hr, up to 30 days (EPA, 2011), although acute exposure guideline levels defined by EPA have relatively short exposure periods of 10 min, 30 min, 1 hr, 4 hr, and 8 hr which are differentiated from air standards that are based on longer or repeated exposures (EPA, 2024b).

The interpretation of sub-daily PM data and their practical applications to public health remains uncertain (Nguyen et al., 2024). The utilization of short-term observations, predominantly focused on 1-hr timescales, has emerged as a pivotal approach in elucidating the implications of episodic air pollution events on exposure to particulate matter mainly from anthropogenic pollutant sources (Brilli et al., 2021; Deary & Griffiths, 2021; Griffiths et al., 2018). There is a need to develop comprehensive guidance for assessing short-term PM exposure (Deary & Griffiths, 2021). Deary and Griffiths (2024) highlight the need to establish a 1-hr guideline value for PM to facilitate timely public health interventions, highlighting the need to review the regulatory and technical controls. Deary and Griffiths (2024) focus on industrial urban fire, while Deary and Griffiths (2021) provide observations of dust storms in Arizona and New Mexico. Although the hourly values represented the dust events in a better way than the daily values, yet, as shown in this study, even the hourly PM_{10} values underestimate the true exposure and potential health impact of the dust particles. Our findings show that 10-min concentrations were 2 times higher than hourly values, and 20 times higher than daily values. Perhaps sub-hourly guidelines will be more efficient in this case as they will allow us to evaluate the health consequences of such intense short-exposure dust events (Griffiths et al., 2018). Bouet et al. (2019) indicate that the health consequences of short exposure to intense dust events require the spatial definition of air quality standards, which should account for the intermittency of dust emission, mainly in regions where such phenomena strongly control the air quality, as the one presented here for the greater Phoenix area. The finding from this study highlights the fact that convective dust events (BDE and DS) have much higher particle concentrations than expected. The impact of such dust events on air quality and people's health might be higher than we estimate. These issues have been raised by Ardon-Dryer, Clifford, and Hand (2023) who indicated that daily averages and hourly values may mask the severity and true impact of such dust events. It is therefore suggested that relying solely on daily or hourly observations may lead to an underestimation of the impacts of these convective dust events. The standard temporal resolutions currently used do not adequately capture the true magnitude of these dust events highlight the importance of real-time monitoring that can capture particle concentrations every 5- to 10-min, which will help to accurately characterize these short-duration dust events and will help assess their impacts on air quality and human health.

4. Conclusions

This study focused on the behavior and changes in PM_{10} concentrations during 93 short-duration convective dust events in the greater Phoenix area during the summer months of July and August from 2015 to 2021. Comparison of these dust events based on daily, hourly, and 10-min average concentrations reveals how daily but also hourly averages mask the atmospheric PM_{10} concentration during the peak of these dust events. PM_{10} concentrations during the peak of the dust events were significantly higher based on 10-min intervals compared to hourly (on average 2.2 ± 0.8 times higher) and daily (on average 20.5 ± 13 times higher) values. Most of these dust events were below the EPA daily threshold and would have passed under the radar not considered as days with potential health impacts. Two specific dust events were selected to examine the temporal and spatial variations in PM_{10} concentrations using multiple stations. These dust events highlight how localized some of these dust events could be, impacting only a small part of the area. The high 10-min PM_{10} concentrations during the peak of the dust (compared to daily and hourly averages) were observed by multiple stations regardless of whether the dust events were categorized as DS (visibility <1 km) or as BDE (visibility ranging from 1 to 10 km). The duration and spatial distribution of dust propagation exhibited remarkable heterogeneity across the analyzed events, shedding light on the intricate and multifaceted dynamics inherent in these dust events. Highlights the importance of real-time monitoring and accurate characterization of short-duration dust events to assess their impacts on air quality and human health.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Preprocessed (5-min) PM_{10} and $PM_{2.5}$ measurements were provided by the Maricopa County Air Quality Department (MCADQ). Official (postprocessed) hourly PM_{10} and $PM_{2.5}$ values were retrieved from the EPA Pre-Generated Data for the same period (EPA, 2022). Meteorological data were retrieved from Iowa State University (2021). A list of dust events can be found in Sandhu et al. (2024).

Acknowledgments

The authors would like to thank Ira Domsky and Ronald Pope from the Maricopa County Air Quality Department (MCADQ) for providing us with the preprocessed (5-min) PM_{10} and $PM_{2.5}$ measurements, and details about these measurements. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for profit sectors.

References

Achilleos, S., Al-Ozairi, E., Alahmad, B., Garshick, E., Neophytou, A. M., Bouhamra, W., et al. (2019). Acute effects of air pollution on mortality: A 17-year analysis in Kuwait. *Environment International*, *126*, 476–483. https://doi.org/10.1016/j.envint.2019.01.072

Akhlaq, M., Sheltami, T. R., & Mouftah, H. T. (2012). A review of techniques and technologies for sand and dust storm detection. *Reviews in Environmental Science and Biotechnology*, *11*(3), 305–322. https://doi.org/10.1007/S11157-012-9282-Y/TABLES/5

Al-Taiar, A., & Thalib, L. (2014). Short-term effect of dust storms on the risk of mortality due to respiratory, cardiovascular and all-causes in Kuwait. *International Journal of Biometeorology*, *58*(1), 69–77. https://doi.org/10.1007/S00484-012-0626-7

Al Zubi, R., Gill, T. E., Lee, J. A., Ardon-Dryer, K., & Kandakji, T. (2024). Spatiotemporal analysis of sand and dust emission point sources detected from satellite imagery in Syria, Jordan, and Iraq. *Science of the Total Environment*, *949*, 175157. https://doi.org/10.1016/j.scitotenv.2024.175157

Anisimov, A., Axisa, D., Kucera, P. A., Mostamandi, S., & Stenchikov, G. (2018). Observations and cloud-resolving modeling of haboob dust storms over the Arabian peninsula. *Journal of Geophysical Research: Atmospheres*, *123*(21), 12147–12179. https://doi.org/10.1029/2018JD028486

Ardon-Dryer, K., Chmielewski, V., Bruning, E. C., & Xueting, X. (2022). Changes of electric field, aerosol, and wind covariance in different blowing dust days in West Texas. *Aeolian Research*, *54*, 100762. https://doi.org/10.1016/J.AEOLIA.2021.100762

Ardon-Dryer, K., Clifford, K. R., & Hand, J. L. (2023). Dust under the radar: Rethinking how to evaluate the impacts of dust events on air quality in the United States. *GeoHealth*, *7*(12), e2023GH000953. https://doi.org/10.1029/2023GH000953

Ardon-Dryer, K., Dryer, Y., Williams, J. N., & Moghimi, N. (2020). Measurements of $PM_{2.5}$ with PurpleAir under atmospheric conditions. *Atmospheric Measurement Techniques*, *13*(10), 5441–5458. https://doi.org/10.5194/amt-13-5441-2020

Ardon-Dryer, K., Gill, T. E., & Tong, D. Q. (2023). When a dust storm is not a dust storm: Reliability of dust records from the storm events database and implications for geohealth applications. *GeoHealth*, *7*(1), e2022GH000699. https://doi.org/10.1029/2022GH000699

Ardon-Dryer, K., & Kelley, M. C. (2022). Particle size distribution and particulate matter concentrations during synoptic and convective dust events in West Texas. *Atmospheric Chemistry and Physics*, *22*(13), 9161–9173. https://doi.org/10.5194/ACP-22-9161-2022

Ardon-Dryer, K., Kelley, M. C., Xueting, X., & Dryer, Y. (2022). The aerosol research observation station (AEROS). *Atmospheric Measurement Techniques*, *15*(8), 2345–2360. https://doi.org/10.5194/amt-15-2345-2022

Ardon-Dryer, K., & Levin, Z. (2014). Ground-based measurements of immersion freezing in the eastern Mediterranean. *Atmospheric Chemistry and Physics*, *14*(10), 5217–5231. https://doi.org/10.5194/ACP-14-5217-2014

Badeenezhad, A., Baghapour, M. A., Azhdarpoor, A., Keshavarz, M., Amrane, A., Goudarzi, G., & Hoseini, M. (2020). The effects of short-term exposure to selected heavy metals carried by airborne fine particles on neural biomarkers during dust storms. *Human and Ecological Risk Assessment: An International Journal*, *27*(5), 1–15. https://doi.org/10.1080/10807039.2020.1833299

Banerjee, P., Satheesh, S. K., & Moorthy, K. K. (2021). The unusual severe dust storm of May 2018 over Northern India: Genesis, propagation, and associated conditions. *Journal of Geophysical Research: Atmospheres*, *126*(7), e2020JD032369. https://doi.org/10.1029/2020jd032369

Beal, T. (2016). *Dust is third-deadliest weather hazard in Arizona*. Arizona Daily Star. Retrieved from https://tucson.com/news/local/dust-is-third-deadliest-weather-hazard-in-arizona/article_cd72fcb9-f341-5c06-a619-24cdb6587f34.html

Behndig, A. F., Mudway, I. S., Brown, J. L., Stenfors, N., Helleday, R., Duggan, S. T., et al. (2006). Airway antioxidant and inflammatory responses to diesel exhaust exposure in healthy humans. *European Respiratory Journal*, *27*(2), 359–365. https://doi.org/10.1183/09031936.06.00136904

Bogan, M., Al, B., Kul, S., Zengin, S., Oktay, M., Sabak, M., et al. (2021). The effects of desert dust storms, air pollution, and temperature on morbidity due to spontaneous abortions and toxemia of pregnancy: 5-year analysis. *International Journal of Biometeorology*, *65*(10), 1733–1739. https://doi.org/10.1007/S00484-021-02127-8/TABLES/3

Bouet, C., Labiadh, M. T., Rajot, J. L., Bergametti, G., Marticorena, B., des Tureaux, T. H., et al. (2019). Impact of desert dust on air quality: What is the meaningfulness of daily PM standards in regions close to the sources? The example of southern Tunisia. *Atmosphere*, *10*(8), 452. https://doi.org/10.3390/ATMOS10080452

Brilli, L., Carotenuto, F., Andreini, B. P., Cavaliere, A., Esposito, A., Gioli, B., et al. (2021). Low-cost air quality stations' capability to integrate reference stations in particulate matter dynamics assessment. *Atmosphere*, *12*(8), 1065. https://doi.org/10.3390/atmos12081065

Chen, Q., Yin, Y., Jiang, H., Chu, Z., Xue, L., Shi, R., et al. (2019). The roles of mineral dust as cloud condensation nuclei and ice nuclei during the evolution of a Hail storm. *Journal of Geophysical Research: Atmospheres*, *124*(24), 14262–14284. https://doi.org/10.1029/2019JD031403

Chen, R., Zhao, Z., Sun, Q., Lin, Z., Zhao, A., Wang, C., et al. (2015). Size-fractionated particulate air pollution and circulating biomarkers of inflammation, coagulation, and vasoconstriction in a panel of young adults. *Epidemiology*, *26*(3), 328–336. https://doi.org/10.1097/ede.0000000000000273

Chen, W., & Fryrear, D. W. (2002). Sedimentary characteristics of a haboob dust storm. *Atmospheric Research*, *61*(1), 75–85. https://doi.org/10.1016/S0169-8095(01)00092-8

Cheng, J., Tong, S., Su, H., & Xu, Z. (2021). Hourly air pollution exposure and emergency department visit for acute myocardial infarction: Vulnerable populations and susceptible time window. *Environmental Pollution*, *288*(1), 117806. https://doi.org/10.1016/j.envpol.2021.117806

Clements, A. L., Fraser, M. P., Upadhyay, N., Herckes, P., Sundblom, M., Lantz, J., & Solomon, P. A. (2013). Characterization of summertime coarse particulate matter in the Desert Southwest-Arizona, USA. *Journal of the Air and Waste Management Association*, *63*(7), 764–772. https://doi.org/10.1080/10962247.2013.787955/SUPPL_FILE/UAWM_A_787955_SM2233.PDF

Crooks, J. L., Cascio, W. E., Percy, M. S., Reyes, J., Neas, L. M., & Hilborn, E. D. (2016). The association between dust storms and daily non-accidental mortality in the United States, 1993-2005. *Environmental Health Perspectives*, *124*(11), 1735–1743. https://doi.org/10.1289/EHP216

Crouvi, O., Dayan, U., Amit, R., & Enzel, Y. (2017). An Israeli haboob: Sea breeze activating local anthropogenic dust sources in the Negev loess. *Aeolian Research*, *24*, 39–52. https://doi.org/10.1016/j.aeolia.2016.12.002

Csavina, J., Field, J., Félix, O., Corral-Avitia, A. Y., Sáez, A. E., & Betterton, E. A. (2014). Effect of wind speed and relative humidity on atmospheric dust concentrations in semi-arid climates. *The Science of the Total Environment*, *487*(1), 82–90. https://doi.org/10.1016/J.SCITOTENV.2014.03.138

Dastoorpoor, M., Idani, E., Goudarzi, G., & Khanjani, N. (2018). Acute effects of air pollution on spontaneous abortion, premature delivery, and stillbirth in Ahvaz, Iran: A time-series study. *Environmental Science and Pollution Research*, *25*(6), 5447–5458. https://doi.org/10.1007/S11356-017-0692-9/FIGURES/5

Deary, M. E., & Griffiths, S. D. (2021). A novel approach to the development of 1-hour threshold concentrations for exposure to particulate matter during episodic air pollution events. *Journal of Hazardous Materials*, *418*, 126334. https://doi.org/10.1016/J.JHAZMAT.2021.126334

Deary, M. E., & Griffiths, S. D. (2024). The impact of air pollution from industrial fires in urban settings: Monitoring, modelling, health, and environmental justice perspectives. *Environments*, *11*(7), 157. https://doi.org/10.3390/environments11070157

Díaz, J., Linares, C., Carmona, R., Russo, A., Ortiz, C., Salvador, P., & Trigo, R. M. (2017). Saharan dust intrusions in Spain: Health impacts and associated synoptic conditions. *Environmental Research*, *156*, 455–467. https://doi.org/10.1016/J.ENVRES.2017.03.047

Domínguez-Rodríguez, A., Báez-Ferrer, N., Abreu-González, P., Rodríguez, S., Díaz, R., Avanzas, P., & Hernández-Vaquero, D. (2021). Impact of desert dust events on the cardiovascular disease: A systematic review and meta-analysis. *Journal of Clinical Medicine*, *12*(4), 727. https://doi.org/10.3390/jcm10040727

Eagar, J. D., Herckes, P., & Hartnett, H. E. (2017). The characterization of haboobs and the deposition of dust in Tempe, AZ from 2005 to 2014. *Aeolian Research*, *24*, 81–91. https://doi.org/10.1016/j.aeolia.2016.11.004

Elmassry, M. M., Ray, N., Sorge, S., Webster, J., Merry, K., Caserio, A., et al. (2021). Investigating the culturable atmospheric fungal and bacterial microbiome in West Texas: Implication of dust storms and origins of the air parcels. *FEMS Microbes*, *1*(1). https://doi.org/10.1093/FEMSMC/XTAA009

EPA. (2011). *Exposure factors handbook 2011 edition*. (Final Report). U.S. Environmental Protection Agency. EPA/600/R-09/052F, 2011. Retrieved from https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=236252

EPA. (2017). Quality assurance handbook for air pollution measurement systems volume II ambient air quality monitoring program. Retrieved from https://www.epa.gov/sites/default/files/2020-10/documents/final_handbook_document_1_17.pdf

EPA. (2022). Pre-generated data files. Retrieved from https://aqs.epa.gov/aqsweb/airdata/download_files.html#Raw

EPA. (2023). National ambient air quality standards (NAAQS) for PM. Retrieved from https://www.epa.gov/pm-pollution/national-ambient-air-quality-standards-naaqs-pm

EPA. (2024a). 40 CFR Part 58- Ambient air quality surveillance. Retrieved from https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-58#Appendix-A-to-Part-58

EPA. (2024b). Acute exposure guideline levels. Retrieved from https://www.epa.gov/aegl/about-acute-exposure-guideline-levels-aegls

Evan, A., Walkowiak, B., & Frouin, R. (2022). On the misclassification of dust as cloud at an AERONET site in the Sonoran desert. *Journal of Atmospheric and Oceanic Technology*, *39*(2), 181–191. https://doi.org/10.1175/JTECH-D-21-0114.1

Evan, A. T., Porter, W., Clemesha, R., Kuwano, A., & Frouin, R. (2022). Measurements of a dusty density current in the western Sonoran desert. *Journal of Geophysical Research: Atmospheres*, *127*(8), e2021JD035830. https://doi.org/10.1029/2021JD035830

Firouzabadi, M., Mirzaei, M., & Mohebalhojeh, A. R. (2019). The climatology of severe convective storms in Tehran. *Atmospheric Research*, *221*(6), 34–45. https://doi.org/10.1016/j.atmosres.2019.01.026

Foroutan, H., & Pleim, J. E. (2017). Improving the simulation of convective dust storms in regional-to-global models. *Journal of Advances in Modeling Earth Systems*, *9*(5), 2060. https://doi.org/10.1002/2017MS000953

Gorris, M. E., Ardon-Dryer, K., Campuzano, A., Castañón-Olivares, L. R., Gill, T. E., Greene, A., et al. (2023). Advocating for coccidioidomycosis to Be a reportable disease nationwide in the United States and encouraging disease surveillance across north and South America. *Journal of Fungi*, *9*(1), 83. https://doi.org/10.3390/JOF9010083

Goudie, A. S. (2014). Desert dust and human health disorders. *Environment International*, *63*, 101–113. https://doi.org/10.1016/J.ENVINT.2013.10.011

Goudie, A. S., & Middleton, N. J. (2006). Desert dust in the global system. In A. S. Goudie & N. J. Middleton (Eds.), *Desert dust in the global System* (1st ed.). Springer Berlin Heidelberg. https://doi.org/10.1007/3-540-32355-4/COVER

Greven, F. E., Krop, E. J., Spithoven, J. J., Burger, N., Rooyackers, J. M., Kerstjens, H. A., et al. (2012). Acute respiratory effects in firefighters. *American Journal of Industrial Medicine*, *55*(1), 54–62. https://doi.org/10.1002/ajim.21012

Griffiths, S. D., Chappell, P., Entwistle, J. A., Kelly, F. J., & Deary, M. E. (2018). A study of particulate emissions during 23 major industrial fires: Implications for human health. *Environment International*, *112*, 310–323. https://doi.org/10.1016/j.envint.2017.12.018

Grineski, S. E., Staniswalis, J. G., Bulathsinhala, P., Peng, Y., & Gill, T. E. (2011). Hospital admissions for asthma and acute bronchitis in El Paso, Texas: Do age, sex, and insurance status modify the effects of dust and low wind events? *Environmental Research*, *111*(8), 1148–1155. https://doi.org/10.1016/j.envres.2011.06.007

Hahnenberger, M., & Nicoll, K. (2012). Meteorological characteristics of dust storm events in the eastern Great Basin of Utah, U.S.A. *Atmospheric Environment*, *60*, 601–612. https://doi.org/10.1016/J.ATMOSENV.2012.06.029

Hahnenberger, M., & Nicoll, K. (2014). Geomorphic and land cover identification of dust sources in the eastern Great Basin of Utah, USA. *Geomorphology*, *204*, 657–672. https://doi.org/10.1016/j.geomorph.2013.09.013

Hamza, W. (2021). Dust Storms and Its Benefits to the Marine Life of the Arabian Gulf. In L. A. Jawad (Ed.), *The Arabian Seas: Biodiversity, environmental challenges and conservation measures* (pp. 141–160). Springer. https://doi.org/10.1007/978-3-030-51506-5_7

Hefflin, B. J., Jalaludin, B., McClure, E., Cobb, N., Johnson, C. A., Jecha, L., & Etzel, R. A. (1994). Surveillance for dust storms and respiratory diseases in Washington State, 1991. *Archives of Environmental Health*, *49*(3), 170–174. https://doi.org/10.1080/00039896.1994.9940378

Herrera-Molina, E., Gill, T. E., Ibarra-Mejia, G., & Jeon, S. (2021). Associations between dust exposure and hospitalizations in El Paso, Texas, USA. *Atmosphere*, *12*(11), 1413. https://doi.org/10.3390/atmos12111413

Herrera-Molina, E., Gill, T. E., Ibarra-Mejia, G., Jeon, S., & Ardon-Dryer, K. (2024). Associations between dust exposure and hospitalizations in a dust-prone city, Lubbock, TX, USA. *Air Quality, Atmosphere & Health*, *17*(5), 1091–1105. https://doi.org/10.1007/s11869-023-01489-9

Huang, M., Tong, D., Lee, P., Pan, L., Tang, Y., Stajner, I., et al. (2015). Toward enhanced capability for detecting and predicting dust events in the western United States: The Arizona case study. *Atmospheric Chemistry and Physics*, *15*(21), 12595–12610. https://doi.org/10.5194/acp-15-12595-2015

Hyde, P., Mahalov, A., & Li, J. (2018). Simulating the meteorology and PM10 concentrations in Arizona dust storms using the Weather Research and Forecasting model with Chemistry (Wrf-Chem). *Journal of the Air & Waste Management Association*, *68*(3), 177–195. https://doi.org/10.1080/10962247.2017.1357662

Iowa State University. (2021). Iowa Environmental Mesonet, ASOS-AWOS-METAR Data. Retrieved from https://www.mesonet.agron.iastate.edu/request/download.phtml?network

Ishii, M., Seki, T., Sakamoto, K., Kaikita, K., Miyamoto, Y., Tsujita, K., et al. (2020). Association of short term exposure to Asian dust with increased blood pressure. *Scientific Reports*, *10*(1), 17630. https://doi.org/10.1038/s41598-020-74713-6

Jiang, D., Liu, Z., & Cao, C. (2003). Desertification and Ecological Restoration of Keerqin Sandy Land. Retrieved from https://www.amazon.com/Desertification-Ecological-Restoration-Keerqin-Sandy/dp/7801635701

Jones, B. A. (2020). After the dust settles: The infant health impacts of dust storms. *Journal of the Association of Environmental and Resource Economists*, *7*(6), 1005–1032. https://doi.org/10.1086/710242

Kaly, F., Marticorena, B., Chatenet, B., Rajot, J. L., Janicot, S., Niang, A., et al. (2015). Variability of mineral dust concentrations over West Africa monitored by the Sahelian Dust Transect. *Atmospheric Research*, *164–165*, 226–241. https://doi.org/10.1016/j.atmosres.2015.05.0

Karami, S., Ranjbar, A., Mohebalhojeh, A. R., & Moradi, M. (2017). A rare case of haboob in Tehran: Observational and numerical study. *Atmospheric Research*, *185*, 169–185. https://doi.org/10.1016/j.atmosres.2016.10.010

Kasey, B., Mark, S., & Steven, F. (2019). Meteorological catalysts of dust events and particle source dynamics of affected soils during the 1930s Dust Bowl drought, Southern High Plains, USA. *Anthropocene*, *27*, 100216. https://doi.org/10.1016/j.ancene.2019.100216

Kok, J. F., Parteli, E. J. R., Michaels, T. I., & Karam, D. B. (2012). The physics of wind-blown sand and dust. *Reports on Progress in Physics*, *75*(10), 106901. https://doi.org/10.1088/0034-4885/75/10/106901

Lau, W. K. M., Kim, K., Zhao, C., Leung, L. R., & Park, S. H. (2020). Impact of Dust-Cloud-Radiation-Precipitation Dynamical Feedback on Subseasonal-to-Seasonal Variability of the Asian Summer Monsoon in Global Variable-Resolution Simulations With MPAS-CAM5. *Frontiers in Earth Science*, *8*, 226. https://doi.org/10.3389/FEART.2020.00226/BIBTEX

Lei, H., & Wang, J. X. L. (2014). Observed characteristics of dust storm events over the Western United States using meteorological, satellite, and air quality measurements. *Atmospheric Chemistry and Physics*, *14*(15), 7847–7857. https://doi.org/10.5194/acp-14-7847-2014

Lin, H., Liu, T., Xiao, J., Zeng, W., Guo, L., Li, X., et al. (2017). Hourly peak $PM_{2.5}$ concentration associated with increased cardiovascular mortality in Guangzhou, China. *Journal of Exposure Science and Environmental Epidemiology*, *27*(3), 333–338. https://doi.org/10.1038/jes.2016.63

Maricopa County. (2022). Climate Summary Report South Mountain Park Weather Station. Retrieved from http://alert.fcd.maricopa.gov/alert/Rain/FOPR/68500_FOPR.xlsx

Marticorena, B., Chatenet, B., Rajot, J. L., Traoré, S., Coulibaly, M., Diallo, A., et al. (2010). Temporal variability of mineral dust concentrations over West Africa: Analyses of a pluriannual monitoring from the AMMA Sahelian Dust Transect. *Atmospheric Chemistry and Physics*, *10*(18), 8899–8915. https://doi.org/10.5194/acp-10-8899-2010

Middleton, N. (2019). Variability and trends in dust storm frequency on decadal timescales: Climatic drivers and human impacts. *Geosciences*, *9*(6), 261. https://doi.org/10.3390/geosciences9060261

Middleton, N., & Kang, U. (2017). Sand and dust storms: Impact mitigation. *Sustainability*, *9*(6), 1–22. https://doi.org/10.3390/su9061053

Middleton, N., Yiallouros, P., Kleanthous, S., Kolokotroni, O., Schwartz, J., Dockery, D. W., et al. (2008). A 10-year time-series analysis of respiratory and cardiovascular morbidity in Nicosia, Cyprus: The effect of short-term changes in air pollution and dust storms. *Environmental Health*, *7*(1), 39. https://doi.org/10.1186/1476-069x-7-39

Miller, S. D., Kuciauskas, A. P., Liu, M., Ji, Q., Reid, J. S., Breed, D. W., et al. (2008). Haboob dust storms of the southern Arabian peninsula. *Journal of Geophysical Research*, *113*(D1), D01202. https://doi.org/10.1029/2007JD008550

Mohebbi, A., Green, G. T., Akbariyeh, S., Yu, F., Russo, B. J., & Smaglik, E. J. (2019). Development of Dust Storm Modeling for Use in Freeway Safety and Operations Management: An Arizona Case Study. *Transportation Research Record*, *2673*(5), 175–187. https://doi.org/10.1177/0361198119839978

Moreira, I., Linares, C., Follos, F., Sácnhez-Martínez, G., Vellón, J. M., & Díaz, J. (2020). Short-term effects of Saharan dust intrusions and biomass combustion on birth outcomes in Spain. *Science of the Total Environment*, *701*, 134755. https://doi.org/10.1016/j.scitotenv.2019.134755

Moreno-Rodríguez, V., Del Rio-Salas, R., Adams, D. K., Ochoa-Landin, L., Zepeda, J., Gómez-Alvarez, A., et al. (2015). Historical trends and sources of TSP in a Sonoran desert city: Can the North America Monsoon enhance dust emissions? *Atmospheric Environment*, *110*, 111–121. https://doi.org/10.1016/J.ATMOSENV.2015.03.049

Nguyen, A., Ebisu, K., Basu, R., Schulte, N., Epstein, S. A., & Wu, X. (2024). Subdaily $PM_{2.5}$ exposure and cardiorespiratory risks: Data and findings from Southern California, 2018–2020. *Air Quality, Atmosphere & Health*, *17*(11), 2431–2444. https://doi.org/10.1007/s11869-024-01583-6

Nhung, N. T. T., Amini, H., Schindler, C., Kutlar Joss, M., Dien, T. M., Probst-Hensch, N., et al. (2017). Short-term association between ambient air pollution and pneumonia in children: A systematic review and meta-analysis of time-series and case-crossover studies. *Environmental Pollution (Barking, Essex : 1987)*, *230*, 1000–1008. https://doi.org/10.1016/J.ENVPOL.2017.07.063

Nickling, W. G., & Brazel, A. J. (1984). Temporal and spatial characteristics of Arizona dust storms (1965–1980). *Journal of Climatology*, *4*(6), 645–660. https://doi.org/10.1002/joc.3370040608

Occupational Safety and Health Administration. (2024). Chemical Hazards and Toxic Substances. Retrieved from https://www.osha.gov/chemical-hazards

Okin, G. S. (2022). Where and How Often Does Rain Prevent Dust Emission? *Geophysical Research Letters*, *49*(4), e2021GL095501. https://doi.org/10.1029/2021GL095501

Pantillon, F., Knippertz, P., Marsham, J. H., & Birch, C. E. (2015). A Parameterization of Convective Dust Storms for Models with Mass-Flux Convection Schemes. *Journal of Atmospheric Science*, *72*(6), 2545–2561. https://doi.org/10.1175/JAS-D-14-0341.1

Raman, A., Arellano, A. F., & Brost, J. J. (2014). Revisiting haboobs in the southwestern United States: An observational case study of the 5 July 2011 Phoenix dust storm. *Atmospheric Environment*, *89*, 179–188. https://doi.org/10.1016/J.ATMOSENV.2014.02.026

Ray, A. E., & Vaughn, D. L. (2009). Standard Operating Procedure for the Continuous Measurement of Particulate Matter. Retrieved from https://www.epa.gov/sites/default/files/2021-03/documents/905505_teom_sop_draft_final_sept09.pdf

Roberts, A. J., & Knippertz, P. (2014). The formation of a large summer-time Saharan dust plume: Convec-tive and synoptic-scale analysis. *Journal of Geophysical Research: Atmospheres*, *119*(4), 1766–1785. https://doi.org/10.1002/2013JD020667

Robinson, M. C., & Ardon-Dryer, K. (2024). Characterization of 21 Years of Dust Events Across Four West Texas Regions. *Aeolian Research*, *67–69*, 67–69. https://doi.org/10.1016/j.aeolia.2024.100930

Robinson, M. C., Schueth, K., & Ardon-Dryer, K. (2024). The Spatial and Temporal Impact of the February 26, 2023, Dust Storm on the Meteorological Conditions and Particulate Matter Concentrations Across New Mexico and West Texas. *Atmospheric Chemistry and Physics*, *24*(23), 13733–13750. https://doi.org/10.5194/acp-24-13733-2024

Rublee, C., Sorensen, C., Lemery, J., Wade, T., Sams, E., Hilborn, E., & Crooks, J. (2020). Associations between dust storms and intensive care unit admissions in the United States, 2000–2015. *GeoHealth*, *4*(8), e2020GH000260. https://doi.org/10.1029/2020GH000260

Samoli, E., Nastos, P. T., Paliatsos, A. G., Katsouyanni, K., & Priftis, K. N. (2011). Acute effects of air pollution on pediatric asthma exacerbation: Evidence of association and effect modification. *Environmental Research*, *111*(3), 418–424. https://doi.org/10.1016/j.envres.2011.01.014

Sandhu, T., Kelley, M., Rawlins, E., & Ardon-Dryer, K. (2024). Identification of dust events in the greater Phoenix area. *Atmospheric Pollution Research*, *15*(11), 102275. https://doi.org/10.1016/j.apr.2024.102275

Seihei, N., Farhadi, M., Takdastan, A., Asban, P., Kiani, F., & Mohammadi, M. J. (2024). Short-term and long-term effects of exposure to PM10. *Clinical Epidemiology and Global Health*, *27*, 101611. https://doi.org/10.1016/j.cegh.2024.101611

Shahsavani, A., Naddafi, K., Jafarzade Haghighifard, N., Mesdaghinia, A., Yunesian, M., Nabizadeh, R., et al. (2012). The evaluation of PM10, PM2.5, and PM1 concentrations during the Middle Eastern Dust (MED) events in Ahvaz, Iran, from april through september 2010. *Journal of Arid Environments*, *77*(1), 72–83. https://doi.org/10.1016/J.JARIDENV.2011.09.007

Shahsavani, A., Tobías, A., Querol, X., Stafoggia, M., Abdolshahnejad, M., Mayvaneh, F., et al. (2020). Short-term effects of particulate matter during desert and non-desert dust days on mortality in Iran. *Environment International*, *134*, 105299. https://doi.org/10.1016/j.envint.2019.105299

Sissakian, V. K., Al-Ansari, N., & Knutsson, S. (2013). Sand and dust storm events in Iraq. *Natural Science*, *05*(10), 1084–1094. https://doi.org/10.4236/ns.2013.510133

Stafoggia, M., Zauli-Sajani, S., Pey, J., Samoli, E., Alessandrini, E., Basagaña, X., et al. (2016). Desert Dust Outbreaks in Southern Europe: Contribution to Daily PM_{10} Concentrations and Short-Term Associations with Mortality and Hospital Admissions. *Environmental Health Perspectives*, *124*(4), 413–419. https://doi.org/10.1289/ehp.1409164

Staniswalis, J. G., Parks, N. J., Bader, J. O., & Maldonado, Y. M. (2005). Temporal Analysis of Airborne Particulate Matter Reveals a Dose-Rate Effect on Mortality in El Paso: Indications of Differential Toxicity for Different Particle Mixtures. *Journal of the Air & Waste Management Association*, *55*(7), 893–902. https://doi.org/10.1080/10473289.2005.10464696

Strong, C. L., Parsons, K., McTainsh, G. H., & Sheehan, A. (2011). Dust transporting wind systems in the lower Lake Eyre Basin, Australia: A preliminary study. *Aeolian Research*, *2*(4), 205–214. https://doi.org/10.1016/j.aeolia.2010.11.001

Swiston, J. R., Davidson, W., Attridge, S., Li, G. T., Brauer, M., & van Eeden, S. F. (2008). Wood smoke exposure induces a pulmonary and systemic inflammatory response in firefighters. *European Respiratory Journal*, *32*(1), 129–138. https://doi.org/10.1183/09031936.00097707

Takemi, T. (1999). Structure and Evolution of a Severe Squall Line over the Arid Region in Northwest China. *Monthly Weather Review*, *127*(6), 1301–1309. https://doi.org/10.1175/1520-0493(1999)127<1301:SAEOAS>2.0.CO;2

Thermo Scientific. (2009). Thermo Scientific Ambient Particulate Monitor, TEOM® 1400ab. Retrieved from www.thermo.com/air

Thermo Scientific. (2019). 1405-DF TEOM^{TM} Continuous Dichotomous Ambient Air Monitor. Retrieved from https://www.thermofisher.com/order/catalog/product/TEOM1405DF?SID=srch-srp-TEOM1405DF

Tong, D., Gorris, M., Gill, T. E., Ardon-Dryer, K., Wang, J., & Ren, L. (2022). Dust Storms, Valley Fever, and Public Awareness. *GeoHealth*, *6*(8), e2022GH000642. https://doi.org/10.1029/2022GH000642

Toure, N. O., Gueye, N. R. D., Mbow-Diokhane, A., Jenkins, G. S., Li, M., Drame, M. S., et al. (2019). Observed and Modeled Seasonal Air Quality and Respiratory Health in Senegal During 2015 and 2016. *GeoHealth*, *3*(12), 423–442. https://doi.org/10.1029/2019GH000214

Trianti, S. M., Samoli, E., Rodopoulou, S., Katsouyanni, K., Papiris, S. A., & Karakatsani, A. (2017). Desert dust outbreaks and respiratory morbidity in Athens, Greece. *Environmental Health: A Global Access Science Source*, *16*(1), 1–9. https://doi.org/10.1186/S12940-017-0281-X/FIGURES/1

US Census Bureau. (2022). Phoenix metro area population 2021. Retrieved from https://www.statista.com/statistics/815239/phoenix-metro-area-population/

Vukovic, A., Vujadinovic, M., Pejanovic, G., Andric, J., Kumjian, M. R., Djurdjevic, V., et al. (2014). Numerical simulation of "an American haboob". *Atmospheric Chemistry and Physics*, *14*(7), 3211–3230. https://doi.org/10.5194/acp-14-3211-2014

Wang, C., Jeong, G. R., & Mahowald, N. (2009). Particulate absorption of solar radiation: Anthropogenic aerosols vs. dust. *Atmospheric Chemistry and Physics*, *9*(12), 3935–3945. https://doi.org/10.5194/ACP-9-3935-2009

Wang, Q., Gu, J., & Wang, X. (2020). The impact of Sahara dust on air quality and public health in European countries. *Atmospheric Environment*, *241*, 117771. https://doi.org/10.1016/J.ATMOSENV.2020.117771

World Health Organization. (2022). Ambient (outdoor) air pollution. Retrieved from https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health

World Meteorological Organization. (2019). *Manual on codes - Regional codes and national coding practices* (Volume II: Vol. I) (Updated in 2021, Issue 306). WMO. Retrieved from http://epic.awi.de/29966/1/WMO2011h.pdf

Zhang, X., Zhao, L., Tong, D. Q., Wu, G., Dan, M., & Teng, B. (2016). A Systematic Review of Global Desert Dust and Associated Human Health Effects. *Atmosphere*, *7*(12), 158. https://doi.org/10.3390/ATMOS7120158