Dust Under The Radar: Rethinking How to Evaluate the Impacts of Dust Events on Air Quality in the United States

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Abstract

Dust is an important and complex constituent of the atmospheric system, having significant impacts on the environment, climate, air quality, and human health. Although dust events are common across many regions of the United States, their impacts are not often prioritized in air quality mitigation strategies. We argue that there are at least three factors that result in underestimation of the social and environmental impact of dust events, making them receive less attention. These include (1) sparse monitoring stations with irregular spatial distribution in dust-influenced regions, (2) inconsistency with dust sampling methods, and (3) sampling frequency and schedules, which can lead to missed dust events or underestimation of dust particle concentrations. Without addressing these three factors, it is challenging to characterize and understand the full air quality impacts of dust events in the United States. This paper highlights the need for additional monitoring to measure these events so that we can more fully evaluate and understand their impacts, as they are predicted to increase with climate change.

Plain Language Summary

Dust is an important and complex component of the atmospheric system, having significant impacts on the environment, climate, air quality, and human health. Yet, dust events are underestimation and therefore do not receive the level of attention necessary to fully understand their impacts. This is due in part to the fact that monitoring stations are sparse in dust-influenced regions; there is a lack of consistency in dust definitions and sampling methods, and there is a lack of continuous monitoring, which results in missed dust events or underestimations of their particle concentration. This commentary highlights the need for additional monitoring designed to measure dust so that we can more fully understand its impacts, which are particularly important as dust is expected to increase with climate change.

Main Text

Dust particles are emitted and suspended in the atmosphere through entrainment by strong winds across erodible surfaces. This process results in the creation of dust events known as blowing dust events or dust storms; the latter is considered more severe and is defined by conditions resulting in horizontal visibility below 1 km, while blowing dust events are defined by visibility conditions from 1 km to 10 km (WMO, 2019). These dust events have an important effect on the atmospheric system, influencing radiation (Lau et al., 2020), cloud formation (Chen et al., 2019), and the atmospheric vertical electric field (Ardon-Dryer et al., 2022a). Air quality, human well-being, and human health are also affected, mainly negatively (Ardon-Dryer and Kelley, 2022; Tong et al., 2023a,b). Dust in North America is estimated to contribute ~ 2.5% (0.3–0.9 Tg) of the global dust loading for particles with diameters up to 20 μm (PM_{20}) (Kok et al., 2021), yet some studies estimated much higher concentrations as found by Urban et al. (2018), who estimated higher dust emissions just from the Mojave Desert (7-15 Tg $year^{-1}$ for PM_{20}). Further, climate models predict that with increases in aridity, dust events will likely increase in the future (Pu and Ginoux, 2017; Achakulwisut et al., 2018; Brey et al., 2020).

Besides monitoring, other challenges exist when characterizing and managing dust levels in the atmosphere. At the most basic level, a lack of a consistent, or shared, definition of dust amongst scientists, the public, and regulators (Kroepsch and Clifford 2021; Tong et al., 2022) limits the advancement of dust science, in part because of a lack of consensus regarding standard dust measurements. For example, airborne dust is defined in different ways. Some studies define dust based on the concentration of PM_{10} (mass of particles with diameters less than 10 µm; Lei and Wang, 2014; Eagar et al., 2017). Other studies have used coarse mass (PM_{10} - $PM_{2.5}$) (where $PM_{2.5}$ is the mass of particles with diameters less than 2.5 µm; Hand et al., 2017), or the ratio of $PM_{2.5}$ and PM_{10} (Tong et al., 2017) to indicate dust impacts. Fine dust, based on elemental composition, has also been used to characterize dust impacts (e.g., Malm et al., 1994; Chow et al., 2015; Hand et al., 2017; Liu et al., 2022). The definition of the severity of the dust impact is another challenge, as 'blowing dust event' and 'dust storm' are often used interchangeably or broadly, which can cause confusion or limit the interpretation of the impacts of dust events, especially with respect to health applications (Ardon-Dryer et al., 2023). Another challenge is that dust is often dismissed in policy and management decisions (Clifford, 2022). For example, a rule within the Clean Air Act allows dust events to be removed from regulatory datasets when considered an "exceptional" event (Clifford, 2021). Such data exclusions occur in both rural and urban settings, with fine and coarse particles, and while more common in the arid West, are a potential issue across the country. These challenges increase the difficulty of accurately tracking spatial and temporal trends in dust and its impacts on air quality.

We highlight three major factors that interfere with accurately estimating the impacts of dust events on air quality. These issues likely lead to an underestimation of the actual dust concentrations, which limits our understanding of the air quality impacts and the many issues associated with and caused by dust across the United States. These three factors are described below:

Large spatial gaps in data result in unmonitored events

Dust data are often based on the impact of dust on particulate matter (PM) measurements of $PM_{2.5}$ and PM_{10} gravimetric mass, which also include contributions from other aerosol species. $PM_{2.5}$ and PM_{10} are routinely monitored by the United States Environmental Protection Agency (EPA) as part of large-scale monitoring networks in mostly urban settings in support of the National Ambient Air Quality Standards (NAAQS). In addition, the EPA operates the large-scale Chemical Speciation Network (CSN) for health exposure studies (Solomon et al., 2014), with sites mainly in urban and suburban settings. Aerosol speciation measurements also occur at remote and rural sites by the Interagency Monitoring of Protected Visual Environments (IMPROVE) aerosol speciation network for the purpose of monitoring visibility (Malm et al., 1994; see Figure 1a for map of network site locations). While the networks often have similar measurement strategies and sampling schedules, they were not initially designed as dust monitoring networks. However, combining data from several hundred sites across the networks has led to a better understanding of large-scale spatial patterns and seasonality of dust across the United States (Hand et al., 2017; 2019; Tong et al., 2017; Aryal and Evans, 2022). Nevertheless, it is clear from these studies that the spatial gaps between and within monitoring networks are limiting our knowledge of dust impacts on air quality.

In particular, regions influenced by dust events, as observed from satellites, often do not have PM monitors. For example, only 21% of counties in the United States have $PM_{2.5}$ monitors (Sullivan and Krupnick, 2018), and most of the PM monitoring that supports NAAQS and other health exposure studies are in areas with high population density, resulting in spatial gaps in many rural areas that often experience dust events (see examples of dust events in Figure 1b and

1c). In recent years, commercially available, low-cost air quality sensors have become common, and regulatory agencies started using them to obtain more granular information on air quality spatial and temporal distribution (Jaffe et al., 2023). However, the accuracy and precision of these sensors need to be characterized (Zheng et al., 2018), the sensors require calibrations (Ardon-Dryer et al., 2020) and recent work suggests they are unable to accurately characterize coarse particles (> 2.5 µm) (Jaffe et al., 2023; Kaur and Kelly, 2023; Rueda et al., 2023) and they still contain spatial gaps. These spatial gaps limit our ability to fully quantify the number of dust events and their subsequent impacts. While satellite observations provide useful spatial and temporal information regarding large dust events, as well as identify affected regions void of monitors, satellites cannot replace ground-based monitoring to adequately characterize dust impacts on surface air quality, and satellites may miss dust events depending on the timing of satellite coverage.

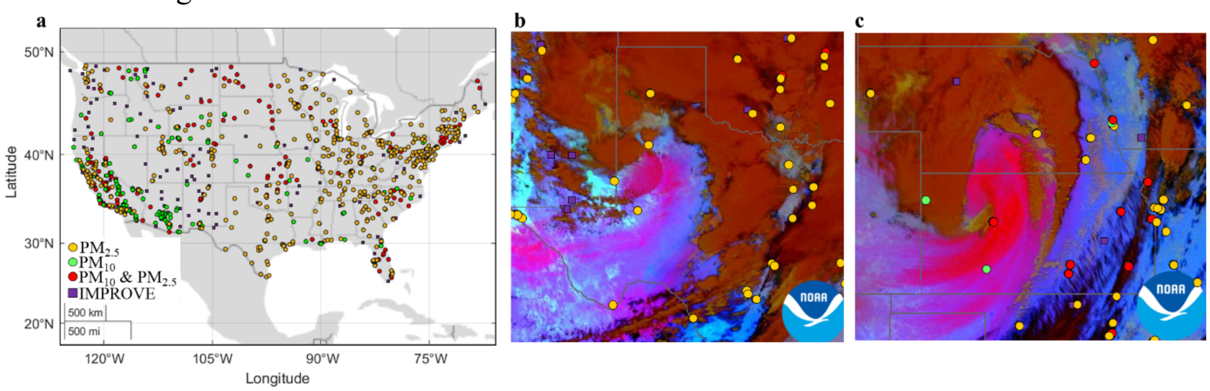

Figure 1. (a) Large-scale monitoring networks, including EPA's Federal Reference Method (FRM) networks for only $PM_{2.5}$ (orange), only PM_{10} (green), collocated $PM_{2.5}$ and PM_{10} (red), as well as IMPROVE sites ($PM_{2.5}$ and PM_{10}, purple) that were active in 2020. (b) Examples of dust events (in pink) captured by the GOES-16 satellite over Texas (22 March 2021), and (c) over Kansas (15 December 2021), highlighting areas void of sensors, with $PM_{2.5}$ (orange), PM_{10} (green), $PM_{2.5}$ with PM_{10} (red), and IMPROVE sites (purple). Satellite images retrieved from AerosolWatch (https://www.star.nesdis.noaa.gov/smcd/spb/aq/AerosolWatch/, accessed on 11 February 2023).

Monitors may miss dust events due to particle size

Dust particle size can range across several orders of magnitude (~100 nm to 100 µm, Scheuvens and Kandler, 2014; Ardon-Dryer and Kelley, 2022; Ardon-Dryer et al., 2022b). Some of these inhalable particles have serious health effects (Martinelli et al., 2013; Tobias et al., 2019). Measurements of $PM_{2.5}$ or dust concentrations derived from $PM_{2.5}$ elemental speciation measurements could lead to underestimates of dust impacts on air quality as they miss the fraction of dust particles which are often associated with the coarse aerosol mode (PM_{10}-$PM_{2.5}$), or even giant mode dust (van der Does et al., 2018). Differences in spatial and seasonal variability of reconstructed fine dust and coarse mass suggest that knowledge of dust size distribution and coarse mass composition may be critical for understanding and reconciling $PM_{2.5}$ and PM_{10} data that are influenced by dust events (Hand et al., 2023). Annual mean fine dust concentrations from 2016 through 2019 at sites from the IMPROVE network are shown in Figure 2a, compared to the annual mean coarse mass at the same sites (Figure 2b). Differences in spatial patterns, especially at sites in the central United States, may be due to dust size distribution, or different sources and composition of coarse mass (Malm et al., 2007; Bondy et al., 2018). Without these additional measurements, we can only speculate regarding the sources and transport of dust. In addition, biases in fine dust concentrations derived from measurements using collocated but different samplers from the CSN and IMPROVE networks are likely due to the sharpness of the cut point of the sampler that allows varying amounts of coarse mode dust to be collected on the $PM_{2.5}$ filter (Solomon et al., 2014; Gorham et al., 2020; Hand et al., 2012; 2023).

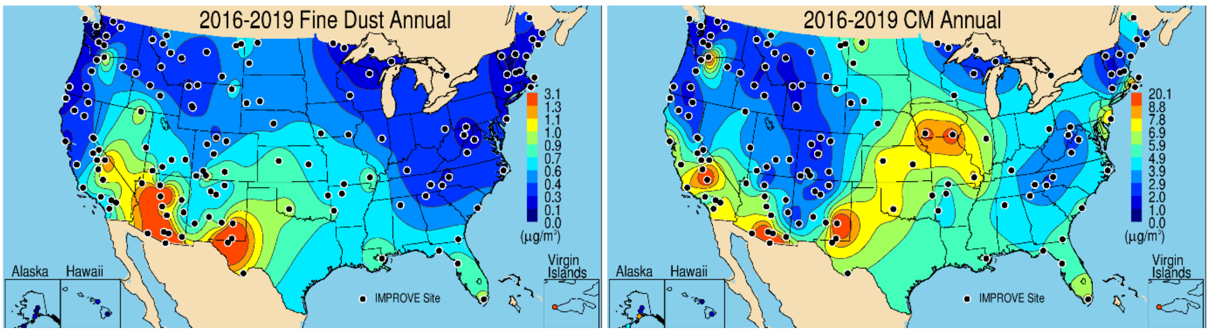

Figure 2. 2016-2019 IMPROVE annual mean (a) reconstructed fine ($PM_{2.5}$) dust (µg m^{-3}) and (b) gravimetric coarse mass (PM_{10}-$PM_{2.5}$, µg m^{-3}), adapted from Hand et al., 2023.

Sampling frequency and duration limit the ability to detect the impact of dust events on air quality

While some of the EPA FRM $PM_{2.5}$ and PM_{10} sensors provide hourly values (EPA, 2020), most networks collect aerosol on filters for 24 hours every third, sixth, or twelfth day, depending on the site. Given these schedules, dust events are often missed. Dust events can happen on time scales of hours or less, and some may exceed EPA daily thresholds, EPA daily thresholds are 35 µg m^{-3} for $PM_{2.5}$ and 150 µg m^{-3} for PM_{10} (Figure 3a). Integrated samples or 24-hour averages of hourly data may mask the severity and true impact of these events, leading to a low daily threshold (Figure 3b). In a recent study, Ardon-Dryer and Kelley (2022) showed that even hourly PM measurements may mask the contribution of PM concentrations during short-duration (sub-hourly) dust events, leading to underestimation of the PM concentrations during these short and intense events. While overlooked, these short-duration dust events still carry important impacts; studies found that exposure to high PM concentrations (of fine and coarse PM) causes health issues (Pérez et al., 2008; Malig and Ostro, 2009; Martinelli et al., 2013; Tobias et al., 2019). Yet, it is still unclear what the health consequences are of such intense but relatively short exposure to dust particles (e.g., acute exposure). This raises questions about whether we might need different air quality standards that account for such short-duration dust emissions (Bouet et al., 2019), especially as it is speculated these are more common across the United States compared to dust events around the world.

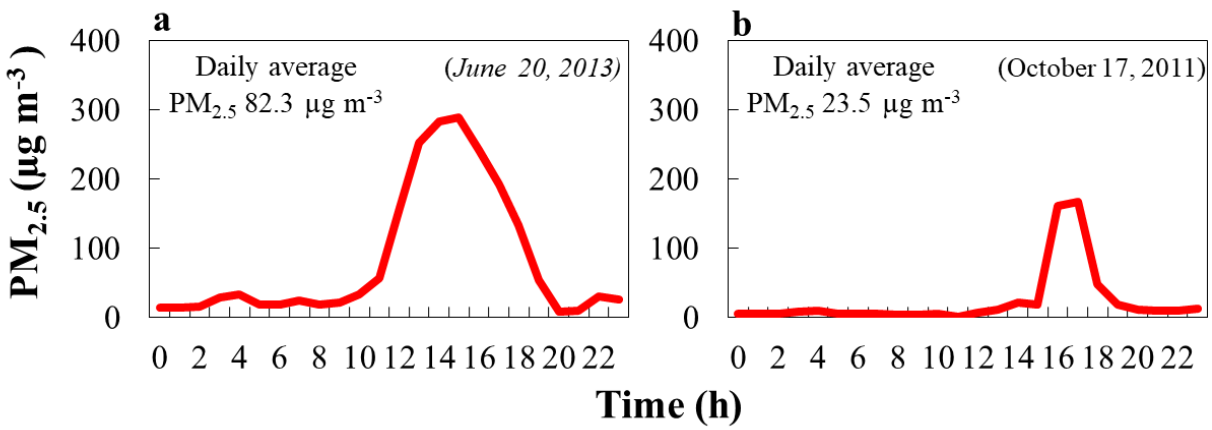

Figure 3. Hourly gravimetric $PM_{2.5}$ measurements of dust events measured by TCEQ from Lubbock, Texas with daily values (a) Example of the hourly values during longer-term dust events show high daily $PM_{2.5}$ values. (b) Example of short-term dust events that do not exceed the daily $PM_{2.5}$ threshold.

Moving Forward

Dust can contribute significantly to particulate matter in the United States, especially on a seasonal basis. Current estimates suggest that half of the $PM_{2.5}$ mass during spring in the Southwest is fine dust, and coarse mass can contribute more than 70% to PM_{10} across the West on an annual basis (Hand et al., 2017; 2019, 2023). However, without consistent, more frequent measurements in dust-influenced regions, these are likely underestimates. Recent studies suggest that dust loading will increase due to climate change (Pu and Ginoux, 2017; Achakulwisut et al., 2018) but without additional data, we are limited in our ability to fully characterize its impacts on air quality and therefore on health. Even designing appropriate mitigation strategies to reduce its future impacts will require accurate characterizations of dust events. The first step is to enhance the monitoring network with additional monitors that sample more frequently, especially in dust-influenced regions. Consistent measurements of particle size and composition would also help characterize the environmental, climate, and human health impacts of dust events. Because these additions are likely cost prohibitive, the development and deployment of low-cost sensors that can accurately measure coarse PM concentrations during dust events may be a path forward to help understand the true impacts of dust on air quality in the United States.

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