



Minute-scale convective dust events are overlooked in urban air quality monitoring



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Convective dust events pose a health threat as they impact urban air quality, but traditional air quality monitoring methods do not always capture them. Although the impact of these convective dust events is important, they are still poorly understood. Limitations of temporal and spatial observations have an impact on the understanding of their impact on urban air quality. Many urban locations prone to these convective dust events do not have any reference sensors or have a limited number. And these reference sensors are based on hourly measurements, which mask the impact of these convective dust events. This perspective will provide insight into these short-duration convective dust events and their impact on the urban environment, using two locations. Highlighting the uncertainties and the suggestions to solve them using dense networks of low-cost sensors, which will help improve and understand the true impacts of these convective dust events on urban air quality.

Main

Convective dust events pose a threat to urban air quality, but are not always captured by traditional air quality monitoring methods. Here, the measurement and impact of these events on urban settings are examined with reference to two cities in the USA. But before digging into convective dust events and their impact on urban air quality, we need to understand that not all dust events are convective, and not all dust events are defined as dust storms.

Dust events, including blowing dust events (BDE) and dust storms (DS), are common in arid and semi-arid regions^{1,2}. In both, the strong wind lifts dust particles into the air, which reduces horizontal visibility. In BDE, the horizontal visibility can be reduced to ≤ 10 km, but > 1 km, while in DS, visibility decreased to ≤ 1 km³. Two main meteorological disturbances (synoptic and convective) can cause an increase in wind speed, leading to the formation of BDE or DS. Synoptic disturbances are defined as a large-scale process (such as high/low-pressure systems, fronts, or jet streams), impacting a large area over a long period (hours to days), while convective disturbances are a small-scale (localized) process that occur over a small area for a short duration from a few minutes up to a few hours^{4,5}. Observations of dust events caused by a combination of synoptic and convective disturbances have been observed, where the dust events were initiated by a synoptic disturbance but intensified by a convective disturbance. Although they are rare, their impact is still unclear⁶.

Convective dust events are caused by thunderstorms' outflow, boundaries, and downbursts. The melting and evaporating droplets and ice crystals of these thunderstorms create a downdraught (cold pool) that reaches the ground and spreads horizontally¹. These strong winds can lift dust particles forming a wall of dust known as a haboob⁷, even reducing

visibility to near zero, as shown in Fig. 1. Observations of dust with haboob features have been observed even without the formation of thunderstorms, e.g., squall line or cold front^{8,9}, or due to a combination of synoptic and convective¹⁰. But the majority of the haboobs are caused by convective disturbances, almost half of the dust events in the southern Sahara^{11,12}, 40% of those in West Africa¹³, and ~70% of the dust events in Phoenix, Arizona, USA are convective dust events⁵. These convective dust events are common across the world, from Africa^{1,14}, to Asia^{9,15}, Australia¹⁶, the Middle East^{17,18}, and even across the USA^{4,19,20}. Most occur in spring and summer^{14,17,18}. These convective dust events can occur at any hour of the day^{1,17,21}. Majority forms during the late afternoon and early evening hours, when convective storm formation occurs, but observations were also made in the middle of the night and early morning hours^{5,6}.

Although most of these convective dust events last less than an hour, longer events have been recorded^{21,22}. The haboobs front can be tens and hundreds of km wide, travel over a long distance, and reach > 1 km height^{1,4,13}, as shown in Movie 1, in visible light (Movie 1a), and using dust RGB product (Movie 1a), where the haboob is > 300 km wide, passes across Texas and Mexico, and travels over a distance > 500 km.

Many of the convective dust events pass over urban areas, impacting people's lives and well-being. Convective dust events (BDE and DS) and the dust particles that are emitted during these events can impact the Earth's ecosystem, radiation^{10,23}, cloud formation, and precipitation processes^{24,25}, as well as the atmospheric vertical electric field²⁶. These convective dust events pose a safety hazard as they can cause car injuries and fatalities^{27,28}. Although many studies examine the health impact of dust events in general, only a few have examined the impact of convective dust events, also known as "haboob lung syndrome". Panikkath et al.^{29,30} reported on healthy patients who were



Fig. 1 | Haboob in Lubbock, Texas. **a** Haboob from July 4, 2024, photograph by Dr Mary Robinson, used with permission. **b** Haboob images in Lubbock, Texas, from October 17, 2011, show the approaching haboob and visibility at different times.

points, from a camera located on the 12th floor of the Atmospheric Science Group at Texas Tech University, photograph provided by Dr Eric Bruning, used with permission.

hospitalized a few days after exposure to convective dust events. All patients experienced acute lung infiltrates/pneumonia symptoms, and one even passed away^{29,30}.

Another way to examine the impact of these convective dust events is to look at their impact on air quality. Observations of air quality are based on the concentrations of PM_{10} and $PM_{2.5}$ (defined as particulate matter with an aerodynamic diameter of up to 10 and 2.5 μm , respectively). These PM sensors are, in most cases, reference sensors defined as official regulatory PM sensors operated by the EPA and provide hourly PM values. Many studies from across the world presented an increase in dust particle concentrations at the time of the convective dust events^{20,31–33}. Yet, the traditional way to examine their impact on air quality is based on the recommended daily threshold for exposure. For example, the World Health Organization (WHO) recommends a daily threshold of 45 and 15 $\mu\text{g m}^{-3}$ for PM_{10} and $PM_{2.5}$, respectively³⁴, while the U.S. Environmental Protection Agency (EPA) recommends a daily threshold of 150 and 35 $\mu\text{g m}^{-3}$ for PM_{10} and $PM_{2.5}$, respectively³⁵. Although many dust events (BDE & DS) can exceed these daily thresholds^{2,4,36–38}, measurements from around the world of convective dust events show that the PM concentrations do not exceed these daily thresholds^{5,21,31,33,39,40}. It should be noted that these recommendations of daily thresholds were developed based on epidemiological studies that estimate chronic exposure to anthropogenic pollution⁴¹, while convective dust events represent acute exposure to natural particles. Previous studies demonstrated that short-term (acute) exposures to high anthropogenic emissions can lead to degradation of human health^{42–44}. Highlighting the fact that sub-daily exposure should be considered, as the peak PM concentration may capture the health effects of ambient PM better than daily averages^{43,44}. Yet, the health consequences of short exposure to dust particles (e.g., from convective dust events) are unclear, and there are no guidelines to evaluate these short-term exposures⁴⁵. It is possible to assume that since most observations of dust events, in general, were based on daily and hourly PM values, the impact of convective dust events on PM concentrations and hence on human health is underestimated.

Two urban locations prone to convective events in the USA (Lubbock, Texas, and Phoenix, Arizona) will be used to highlight the impact of convective dust events on air quality. Lubbock, located in West Texas, is an urban city (~250,000 people) surrounded by a rural agricultural area. This area experienced an average of 29 ± 16 dust events per year⁶. Some claim it is the dustiest place in the Great Plains or even across the USA^{46,47}. Convective dust events represent ~33% of the dust events in this region, mainly in late spring to early summer⁶. Several studies examine the impact of these convective dust events on air quality^{21,40}. Kelley and Ardon-Dryer²¹ examined convective dust events from 2000 to 2019 and found that none of these convective dust events exceeded the EPA $PM_{2.5}$ recommended daily threshold. Ardon-Dryer and Kelley³⁹ measured two convective dust events and found similar findings where the daily PM_{10} and $PM_{2.5}$ did not exceed the EPA daily threshold. Yet, observations based on hourly PM_{10} and $PM_{2.5}$ values were 6 to 9 times higher (respectively) than the daily values, and concentrations based on 10-min averages were ~4 times higher than those measured based on hourly averages and 24–47 times higher compared to daily concentrations. Even the concentrations of PM_1 (particulate matter with an aerodynamic diameter of up to 1 μm) and the number concentrations of particles in the range of 0.3–1 μm increased during these convective dust events, highlighting the importance of these small particles as they can impact people's health³⁹.

The October 17, 2011, haboob shown in Fig. 1b in Lubbock, Texas, highlights the severity of these intense convective dust events. During this event, the wind speed and gust reached 21.6 ms^{-1} and 28.3 ms^{-1} (respectively). This specific dust event was defined as DS as visibility by the local meteorological station reported visibility $<1 \text{ km}$. Visibility as low as 0.4 km was reported for ~20 min, shown by the complete blackness in Fig. 1 (17:40 local time-LT). The $PM_{2.5}$ daily average during this day was $23.5 \mu\text{g m}^{-3}$, below the EPA daily $PM_{2.5}$ threshold, while hourly $PM_{2.5}$ concentration at the peak of the dust was $167 \mu\text{g m}^{-3}$. While observations only based on daily average values would make us think this day was fine and did not have any reason for concern, the high hourly values and Fig. 1b highlight the severity of this DS. This also supports the suggestions by Ardon-Dryer et al.⁴⁰ who

stated that averaging PM concentration over the entire day will mask the severity and true impact of these convective dust events.

Similar findings were found for Phoenix, Arizona, which is a large urban area with several million people who experience many convective dust events. About 70% of the total dust events in this area are convective dust events⁵. Several convective dust events in Phoenix exceeded the WHO and EPA daily guidelines. For example, the 5 July 2011 dust had a PM₁₀ daily value of 225 $\mu\text{g m}^{-3}$, hourly PM₁₀ and PM_{2.5} concentrations during this day reached 1974 $\mu\text{g m}^{-3}$ and 907 $\mu\text{g m}^{-3}$ respectively⁴. Not far from Phoenix, PM₁₀ hourly concentrations reached 2316 $\mu\text{g m}^{-3}$ ⁴⁸. Ardon-Dryer and Aziz⁴⁹ examined 93 convective dust events in Phoenix between 2015 and 2021 and found that many of these convective dust events did not exceed the EPA and WHO PM₁₀ daily thresholds. They indicated that even if the convective dust events were below the EPA and WHO thresholds, they still had very high PM₁₀ concentrations. For example, the dust event of August 16, 2021, had daily PM₁₀ concentrations of $40 \pm 86 \mu\text{g m}^{-3}$, hourly concentrations of 434 $\mu\text{g m}^{-3}$ at 23:00 LT, and 10-min PM₁₀ concentrations of 1814 $\mu\text{g m}^{-3}$ at 23:00 LT. The 10-min PM₁₀ concentrations were 4 times higher than the hourly values and 45 times higher than the daily values. The convective dust event that took place on July 8, 2018, had daily PM₁₀ concentrations above the EPA and WHO thresholds ($385 \pm 1068 \mu\text{g m}^{-3}$). The hourly PM₁₀ concentration at the peak of the dust was 4288 $\mu\text{g m}^{-3}$ (at 23:00 LT), while 10-min PM₁₀ concentrations at the peak of the dust reached 8129 $\mu\text{g m}^{-3}$ (at 23:20 LT), which were double the hourly value and 20 times higher than the daily values. These high short-duration (10-min) PM₁₀ concentrations have been observed regardless of whether the convective dust events were above or below the EPA and WHO daily thresholds or where they were defined as BDE or DS⁴⁹.

Observations from multiple PM sensors allow for monitoring the temporal and spatial movement of these convective dust events as they impact the urban air quality. Lubbock has only one reference sensor that monitors PM_{2.5} concentration, while Phoenix has several reference sensors with PM₁₀ and PM_{2.5} stations. Figure 2 provides examples of several convective dust events from the greater Phoenix area as they pass the urban area. It should be noted that these examples were taken from Ardon-Dryer and Aziz⁴⁹ study, who used hourly and 10-min PM₁₀ values from multiple local reference sensors.

The convective dust event of August 27, 2015 (Fig. 2a) had a large increase in PM₁₀ concentrations at only one station (4-13-4010), hourly PM₁₀ concentrations reached 1784 $\mu\text{g m}^{-3}$ at 15:00 LT. The other sensors, who were active at that time, only reached a maximum hourly PM₁₀ concentration of 162 $\mu\text{g m}^{-3}$ (measured by station 4-13-4016, the closest one to

4-13-4010). This impact can also be seen with the short-term observations, which showed that 10-min PM₁₀ concentrations reached 5401 $\mu\text{g m}^{-3}$ (sensor 4-13-4010 at 15:20 LT); the nearest sensors (station 4-13-4016) reported at the same time 10-min PM₁₀ concentrations reached 499 $\mu\text{g m}^{-3}$. It took another 30 min for the other sensors across Phoenix to detect this dust, and the increase in these sensors did not exceed 10-min PM₁₀ concentrations of 350 $\mu\text{g m}^{-3}$.

Another example that highlight the spatial impact of these events, is the convective dust events of July 23, 2017 (Fig. 2b). In this case the convective dust event first impacted two PM₁₀ stations (sensors 4-13-4006 and 4-13-4004), but the impact was very small, at 18:00 LT hourly PM₁₀ concentration by these two sensors reached 184 and 142 $\mu\text{g m}^{-3}$ (4-13-4006 and 4-13-4004, respectively). By 19:00, the dust reached station 4-13-4009, and hourly PM₁₀ concentrations maxed at 1230 $\mu\text{g m}^{-3}$. The two sensors in the west part of the area (station 4-13-4016 and 4-13-4010) did not have a strong increase in hourly PM₁₀ concentration remained below 35 $\mu\text{g m}^{-3}$. Observations based on 10-min PM₁₀ concentrations allow us to observe how these dust particles pass through the urban area. Sensor 4-13-4006 was the first to detect the increase of PM₁₀ concentrations (367 $\mu\text{g m}^{-3}$ at 18:20 LT). Ten minutes later, at 18:30 LT, sensor 4-13-4004 detected the first increase of PM₁₀ concentrations (238 $\mu\text{g m}^{-3}$). Sensor 4-13-3003 was the next to detect the dust at 18:50 LT (232 $\mu\text{g m}^{-3}$), just 20 min later, an increase in PM₁₀ concentrations was observed by sensor 4-13-3002. At 19:20, sensor 4-13-4009 detected the dust where 10-min PM₁₀ concentrations were 2948 $\mu\text{g m}^{-3}$, 10 min later the PM₁₀ concentrations reached 3269 $\mu\text{g m}^{-3}$ (at 19:30 LT), by 20:00 LT the concentrations reported by this sensor went back to the background onrtrations measured before the dust. Senors 4-13-4010 and 4-13-4016 had a very small increase in PM₁₀ concentrations around 19:50 LT (10-min PM₁₀ concentrations reached 62 and 101 $\mu\text{g m}^{-3}$, respectively).

While these two examples highlight that the impact of convective dust events can be on some part of the urban area, some convective dust events may impact the entire urban area, as the one presented in Fig. 2c. Figure 2c presents a convective dust event from August 23, 2017. Almost all of the eight PM₁₀ stations observed an increase in PM₁₀ concentrations. An increase in PM₁₀ concentrations was first observed by stations 4-13-4006 and 4-13-4004, then by stations 4-13-4009, 4-13-3002, and 4-13-3003, and later by 4-13-4010 and 4-13-4016. The maximum hourly PM₁₀ concentrations reported by all these stations ranged from 492 $\mu\text{g m}^{-3}$ (by 4-13-4016) up to 1517 $\mu\text{g m}^{-3}$ (by 4-13-3003). While 10-min PM₁₀ concentrations ranged from 861 $\mu\text{g m}^{-3}$ (by 4-13-4016) to 2601 $\mu\text{g m}^{-3}$ (by 4-13-3003). Although high PM₁₀ concentrations were

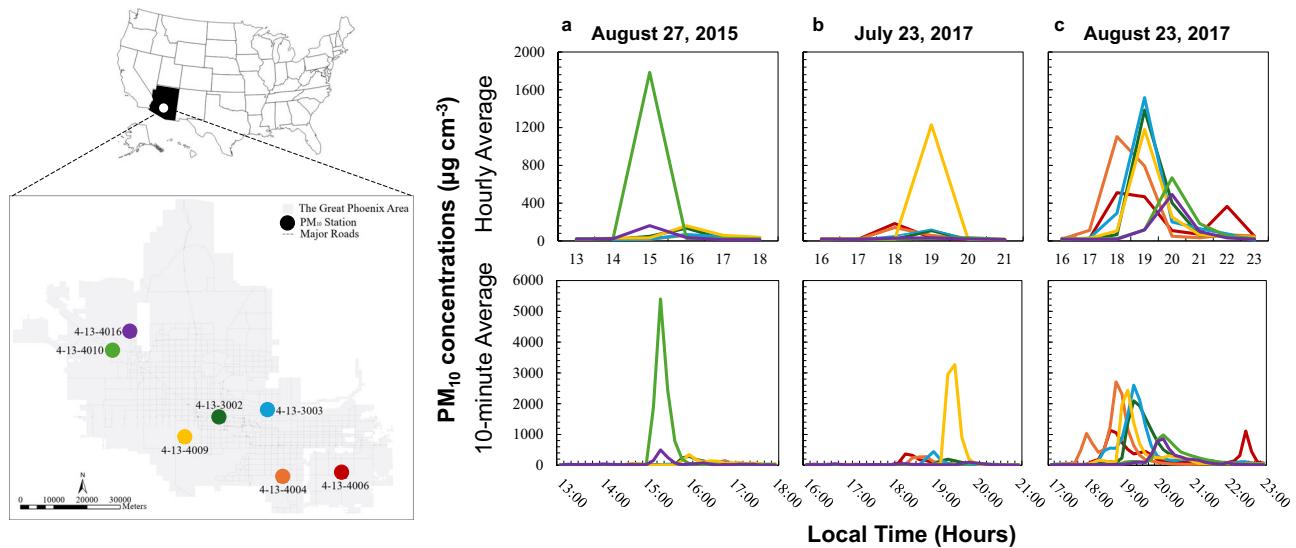


Fig. 2 | Examples of the special impact of convective dust events on the greater Phoenix area air quality. Convective dust event impacts a small area of the urban area (a, b), as well as convective dust events that impact on air quality across many neighborhoods of the urban area (c). Data retrieved from Ardon-Dryer and Aziz⁴⁹ with modification.

observed during this dust event, none of the stations had daily PM₁₀ values that exceeded the EPA daily threshold (150 $\mu\text{g m}^{-3}$).

Although the impact of these convective dust events is important, they are still poorly understood for both their dynamics and the amount of dust particles they may lift into the atmosphere^{23,50,51}. The main issues when looking at the impact of these convective dust events on air quality can be temporal and spatial. Only a few urban locations impacted by convective dust events have multiple reference PM sensors that spread across the urban environment to monitor these convective dust events on air quality. As shown in Fig. 2, some of these convective dust events may affect the entire city, while others can only affect several neighborhoods. Observation of the spatial aspect of these convective dust events depends on the spread of air quality sensors across the city. Unfortunately, many locations prone to convective dust events do not have any air quality sensors or have only one, which may or may not be impacted by these convective dust events^{40,52}. Hence, the true impact of these convective dust events on the local air quality is still limited.

As shown in the examples presented another aspect that should be considered is the duration of most of these convective dust events which is fast (less than 1-h), meaning traditional air quality observation and methods (e.g., reference sensors), which are based on hourly values, may mask the impact of these convective dust events, miss them completely, or not report their true impact on air quality⁴⁰. Therefore, short-duration measurements (ideally those that can be reported every 5 or 10 min) will allow us to capture these convective dust events and the dust particle concentrations, and allow document and understand their impact on air quality.

One way to overcome these spatial and temporal issues is with the use of low-cost sensors that will be spread across the urban area and provide short-duration PM measurements. Yet many of these commercially low-cost sensors cannot detect coarse dust particles or accurately measure PM concentrations^{53,54}. Recent studies found that some higher-grade low-cost sensors (e.g., the optical sensor Alphasense OPC-N3) could be efficient in detecting dust particles during dust events^{54–56}, which is in use in one of the commercially low-cost sensor companies. The efficiency of many of these commercially low-cost sensors is still questionable, mainly for their accuracy in detecting coarse dust particles, and therefore, they require additional investigation, mainly in dust-prone regions and those with convective dust events. Dense networks of these low-cost sensors (with appropriate calibration, and with the ability to take short-term measurements, each minute) may help improve the ability to capture these short convective dust events, allowing to understand the true impacts of these convective dust events on air quality.

Another issue that should be mentioned is the inability to accurately report atmospheric PM concentrations during extreme high-dust events. Some convective dust events may have very high PM concentrations that will exceed the upper limit threshold of some of the air quality sensors used as regulatory reference sensors, as presented in Rodríguez and López-Darias⁵⁷. Although none of the dust events presented in this work⁵⁷ were convective dust events, it is possible that some convective DS could have very high PM concentrations, above the upper limit of the reference sensors, not allowing the detection of the true atmospheric particle concentrations. To overcome this issue, it is recommended that sensors with a higher upper limit threshold be used in areas prone to dust.

In addition to the limitation of measuring the air quality impact of these convective dust events, many models cannot accurately simulate or predict these convective dust events, and cannot capture the correct particle sizes or concentrations emitted during these convective dust events^{2,13,14,23,50,51,58,59}. Improving modeling for convective dust events requires simulating the strong winds and cold pools generated. Studies suggest that improvement of the prediction of convective dust events requires parametrization that uses downdraft mass flux⁶⁰, use of lightning assimilation¹³, and a non-hydrostatic model with high resolution². Reliable predictions of convective dust events are necessary to help determine their effects on air quality, but also their impact on visibility and the radiation budget, which can help predict how these convective dust events will change in the future^{10,59}. Evaluation of the

impact of these convective dust events on air quality and human health is needed to quantify their risk. Such knowledge will help to develop better mitigation practices and allow the creation of prediction and warning systems that could be used to alert the public, mainly in regions prone to these convective dust events.

Data availability

Data presented in this study can be found in Kelley and Ardon-Dryer²¹, in Ardon-Dryer and Kelley³⁹, and in Ardon-Dryer and Aziz⁴⁹.

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Competing interests

The author declares no competing interests.

Additional information

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