African dust: Occurrence, health consequences, and impacts on Texas

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Abstract

The drylands of North Africa (Sahara and Sahel) are the world's largest sources of airborne dust. Clouds of African dust aerosols have been long known to be blown westwards across the Atlantic, and by the 1990s were recognized to be transported across and over Texas. African dust incursions in Texas typically happen several times per year in late spring and summer, manifesting as hazy skies overhead and increased ground-level concentrations of $PM_{2.5}$ (particulate matter fine enough to be inhaled into the human lower respiratory tract). African dust exposure has many reported human health effects in Europe and the Caribbean, including increased all-cause mortality and increased respiratory and cardiovascular disease morbidity and mortality. In Texas, African dust's greatest impacts occur in the Houston metropolitan area where it has been quantitatively shown to increase ambient aerosol concentrations. The potential of African dust increasing concentrations of inhalable particulate matter beyond regulatory limits is of concern. A sequence of investigations filtering particles from the air, measuring their concentrations, and subjecting them to elemental analysis documented far-transported African dust's role in air quality in Houston and Galveston. African dust's contributions to air pollution have been separated from those of local soils and industrial emissions, and Saharan-Sahelian dust has been indicated to sometimes constitute the majority of $PM_{2.5}$ mass in Houston. While studies show the presence of inhalable metals and microorganisms including opportunistic pathogens during Saharan air incursions in Houston, the human health effects of African dust in Texas remain yet unspecified and merit further investigation.

Keywords: aerosols; Africa, Northern; air pollution; dust; particulate matter; public health; Texas

Introduction: North African dust

It has long been recognized that tremendous amounts of airborne dust are generated in North Africa, specifically the Sahara Desert and Sahel regions of West Africa. Modern estimates guided by satellite remote sensing show that over 800 teragrams per year of dust aerosols are emitted into the atmosphere from North Africa, comprising a majority of annual global dust emissions[1] and making it Earth's largest and most active source of dust particles.[1] Large-scale wind patterns transport some of this dust far from its desert sources into Europe, the Middle East, and also westward across the Atlantic Ocean towards the Caribbean basin and the continental United States.

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African dust transport across the Atlantic and to Texas

Charles Darwin's observations during the voyage of the *Beagle* led him to recognize in 1846 that the fine dust falling on vessels in the Atlantic originated in Africa and suggest that the dust could be geologically significant.[2] In the 1950s it was discovered that African dust is transported to the Americas, but the discovery was largely ignored by the scientific world.[3] In 1969, the Saharan Air Layer (SAL) was discovered.[3] The SAL is a large, elevated mass of hot, dry, dust-laden air originating in Africa and capping the moist marine air above the surface of the Tropical Atlantic.[3] This discovery helped cement the understanding that intercontinental transport brought dust to the Western Hemisphere.[3] By 1997, it was established that North African dust was widely and regularly transported into the eastern and south-central United States, especially during the summer.[4] The dust is carried at least as far west as the Guadalupe Mountains in far western Texas.[4] African dust incursions were described as occurring multiple times annually, persisting in the North American atmosphere for over 10 days, and containing far-transported dust particles that could exceed concentrations of locally-generated soil dust.[4]

A 30-year time series (1990-2020) of sky conditions over the Geronimo Creek Atmospheric Monitoring Station (GCAMS) in Central Texas (29.6 N, –97.9 W) shows that significant variations in the transparency of the atmosphere, defined as the aerosol optical depth (AOD), occur between winter and summer.[5] When the AOD is very low (0.0 to 0.1), the sky is extraordinarily blue and clear. As the AOD increases during smoke and dust events, the sky becomes increasingly hazy. The 30-year time series over Central Texas shows episodic increases in AOD caused by Saharan dust during July and August. The African origin of these events is indicated in National Aeronautics and Space Administration (NASA) Atmospheric Composition (2D) Maps and Navy Aerosol Analysis and Prediction System (NAAPS) aerosol forecast models that employ color-coded maps to indicate AOD caused by airborne dust and other aerosols. NASA and NAAPS models clearly show that significant dust originating in North Africa is transported across the Atlantic to North America during summer months (Figure 1). During these events, outdoor observers notice increased haze and a prominent aureole around the sun. Figure 2 shows a faint solar aureole at solar noon during a typical summer day in Central Texas free of Saharan dust, and a prominent solar aureole at solar noon on a day with significant Saharan dust.

Although much of the dust is overhead at high altitudes, some clearly descends to the surface level, evidenced through wet deposition (rainout)[6] and increased surface concentrations of particulate matter via dry deposition (sedimentation), including $PM_{2.5}$ (airborne particles smaller than 2.5 μm in diameter, a regulated pollutant under the U.S. Clean Air Act). $PM_{2.5}$ is of special interest from the standpoint of health because it is small enough to be inhaled deeply into the human respiratory tract. Figure 3 shows the NAAPS model outputs for the pair of days in Figure 2, indicating essentially no dust on the day with low AOD, and significant dust causing increased AOD and enhanced concentrations of ground-level particulate matter during an African aerosol incursion. NAAPS forecast models often indicate continuing surface dust after the major airborne dust peak is no longer present, which is obvious when the dust occasionally coats windows and cars. In recent years, long-range transport of African dust has been commonly incorporated into television weather reports and news, the Texas

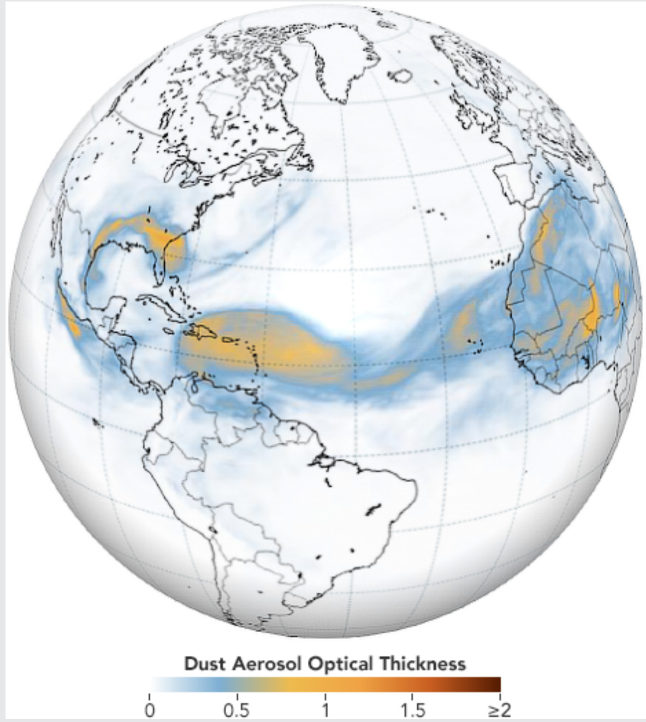

Figure 1. Saharan dust extends from Texas and the southeastern USA to Africa on 27 June, 2020. Visualization based on data from NASA's Goddard Earth Observing System (GEOS) modeling system. Image from NASA Earth Observatory at https://earthobservatory.nasa.gov/images/146913/a-dust-plume-to-remember.

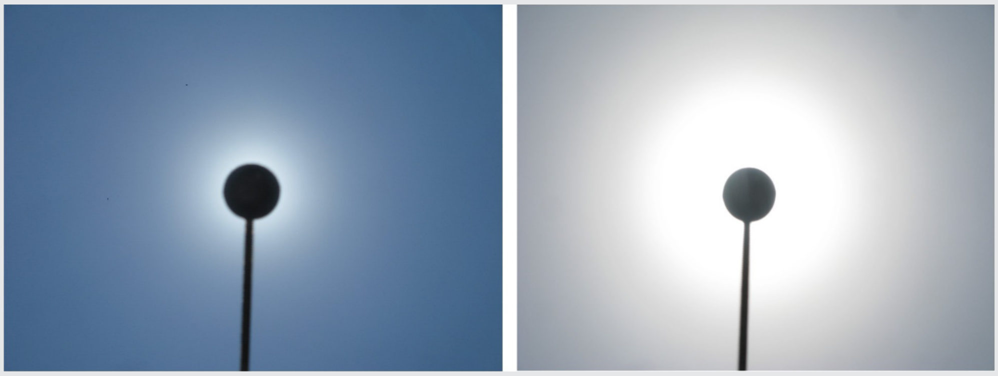

Figure 2. (Left) Solar aureole over GCAMS on July 11, 2020 (AOD = 0.175 at 816 nm), a day with no African dust over or on the surface of Central Texas. (Right) Solar aureole over GCAMS on July 2, 2020 (AOD = 0.401), a day with significant African dust both over and on the surface of Central Texas.

Commission on Environmental Quality's daily air quality forecast, and other internet media sites in Texas, resulting in the general public increasingly recognizing African influence on local air quality in the Lone Star State.

Health effects and air quality impacts

The adverse human health impacts of exposure to African dust have been recognized and studied in many receptor locations. In the Sahel, dust and wind levels are predictive factors for the seasonal onset and spread of bacterial meningitis.[7,8] Within North Africa, windblown dust has been shown to be associated with infant mortality,[9] there are anecdotal reports of its association with cardiovascular disease,[10] and it may be associated with respiratory disease,[11] although quantitative studies are lacking.[12,13] In Europe, African dust intrusions have been associated with increased daily all-cause mortality,[14,15] cardiac mortality,[15] respiratory mortality in susceptible populations,[16] increased hospital admissions[17] and emergency room visits for respiratory disease[18] including COPD,[19] as well as increased asthma susceptibility in children.[20] In the Americas, African dust has been associated with preterm births in Guadeloupe,[21] COPD in Miami, Florida,[22] and bronchial inflammation in Puerto Rico.[23] Saharan dust has been suggested to have a role in pediatric asthma outbreaks on some Caribbean islands,[24,25] although findings on other islands are conflicting[26] and dust's role in disease in the Caribbean may be subtle and hard to deconvolute from other environmental factors.[25,26] The Saharan Air Layer is known to carry, along with the dust, biota including bacteria[27] and fungi,[28] potentially including pathogenic species.[29] Even insects, including locusts[30] and butterflies,[31] have been transported alive from Africa to the Western Hemisphere in this dusty air layer.

It was recognized as early as 1998 that dust transported from Africa was a component of ground-level $PM_{2.5}$ concentrations in Texas.[32] Coupled with rising concerns in Houston beginning in the late 1990s about its $PM_{2.5}$ levels potentially exceeding Clean Air Act standards, it was realized that Saharan dust could be contributing to ground-level $PM_{2.5}$ concentrations that might push Houston over the regulatory compliance threshold. Quantitatively distinguishing between locally emitted versus long-range transported PM is vitally important for regulatory purposes. It enables states to exclude "exceptional events," such as dust transported across international borders or oceans that subsequently impact local air quality. Such events are beyond regulatory control.[33]

Case study: detecting and quantifying African dust in greater Houston

A 2013 publication that identified a major Saharan dust event in 2008 which raised both $PM_{2.5}$ and PM_{10} (particles smaller than 10 μm, also regulated under the Clean Air Act) levels in Houston[33] highlighted the potential role of long-range-transported dust originating outside the United States in maintaining compliance with air quality regulations. Chellam and colleagues have been regularly monitoring African dust intrusions and their effects on ambient airborne particulate matter in greater Houston ever since then.[33–39] In these studies,

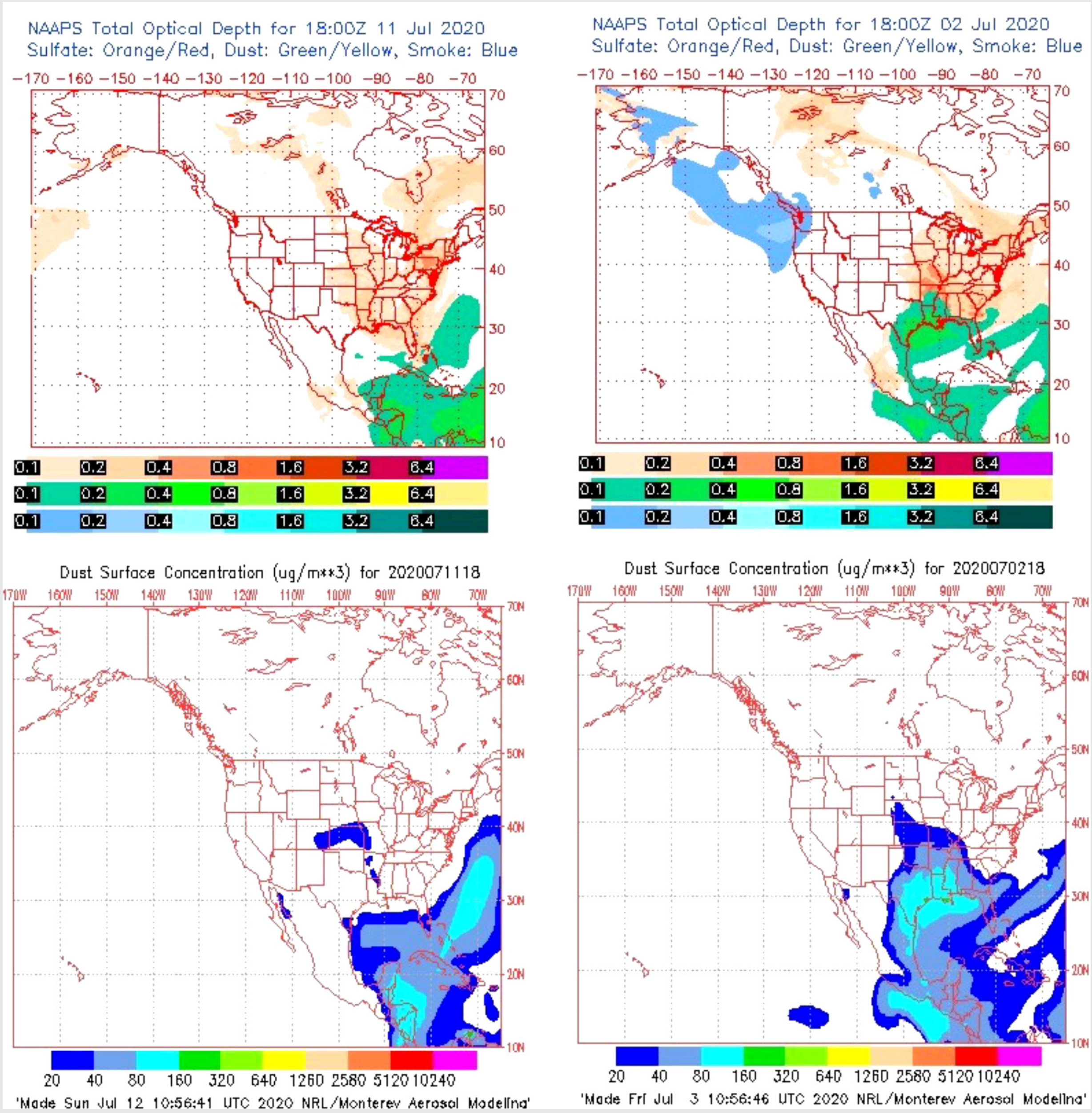

Figure 3. NAAPS model outputs. The two panels on the left-hand side indicate the presence of aerosols including dust on July 11, 2020. The top left panel shows the total optical depth (green color indicates dust, depicting values approx. <0.8) and the bottom left panel depicts dust concentrations at the surface (in blue color for values approx. <160 μg/m^3). Note that areas above Texas are clear indicating that dust is largely absent over land on this date. In contrast, the two panels on the right-hand side depict significant amounts of dust over Texas on July 2, 2020. This is indicated by the total optical depth (in green color depicting values due to dust approx. <0.8) covering southeast Texas (top right panel). Dust concentrations at the surface are shown in the bottom right figure, in blue color depicting modeled values up to ~160 μg/m^3 over almost the entire state of Texas and beyond. Satellite images, back trajectories, and other modeling tools have demonstrated that the source of this dust is northern Africa (i.e., the Sahara Desert).

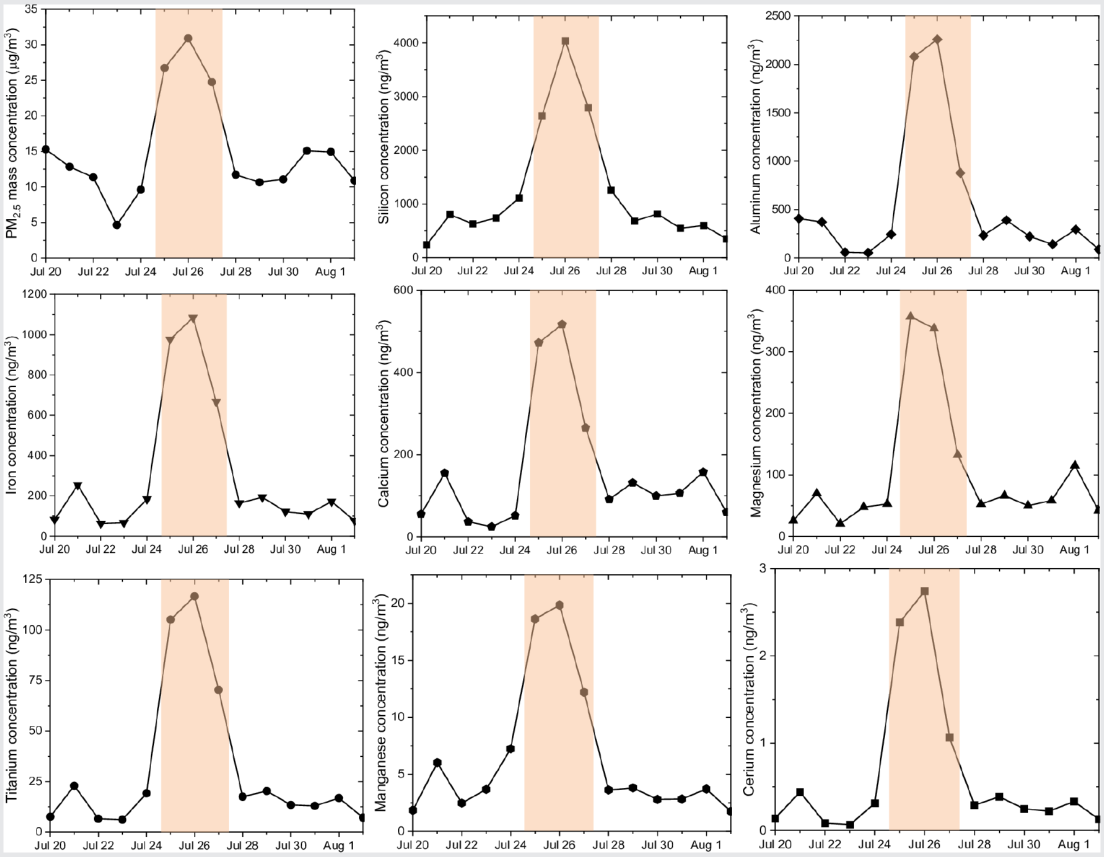

Figure 4. Time series of $PM_{2.5}$ mass and concentrations of selected elements covering a North African dust episode in the Channelview suburb of Houston (Latitude: 29° 48′ 10″ North (29.8027231°), Longitude: −95° 7′ 32″ West (−95.1254893°)) in late July 2008 (adapted from Bozlaker et al.[33]). Top row left to right shows concentrations of aerosol mass, silicon, and aluminum. The second row left to right shows iron, calcium, and magnesium concentrations. Third row shows titanium, manganese, and cerium. These elements (Si, Al, Fe, Ca, Mg, Ti, Mn, and Ce) were selected because they represent major and trace components of the Earth's crust. The major dust peak passed through greater Houston during July 25, 26, and 27 and is shown as the light brown shaded rectangular area.

daily particulate matter samples are collected on filters at various receptor sites. The aerosol mass concentrations are measured along with the concentrations of approximately 50 chemical elements in the aerosols. Statistical techniques are then used to quantify the impact of various sources based on the unique elemental "fingerprint" of specific sources (e.g., local soils, combustion processes, refinery emissions in Houston and Galveston, etc.), which are distinctly different from those of African dust.[40,41]

Figure 4 illustrates the 2008 North African dust episode that raised awareness of its role in increasing particulate matter levels in greater Houston.[33] The light brown rectangle in the middle of each panel depicts the major dust peak as it passed through the city on July 25–27, 2008. As shown in the top left panel, $PM_{2.5}$ mass concentrations fluctuated from around 5–15 μg/m^3 just before and after the peak and reached a maximum of ~32 μg/m^3 during the dust episode. Elements such as silicon, aluminum, iron, calcium, magnesium, titanium, manganese as well as the rare earth cerium (shown in the top, second, and third rows) were in-phase with the dust mass, which is consistent with aerosols largely composed of material from geological sources. Importantly, the relative abundance of these elements

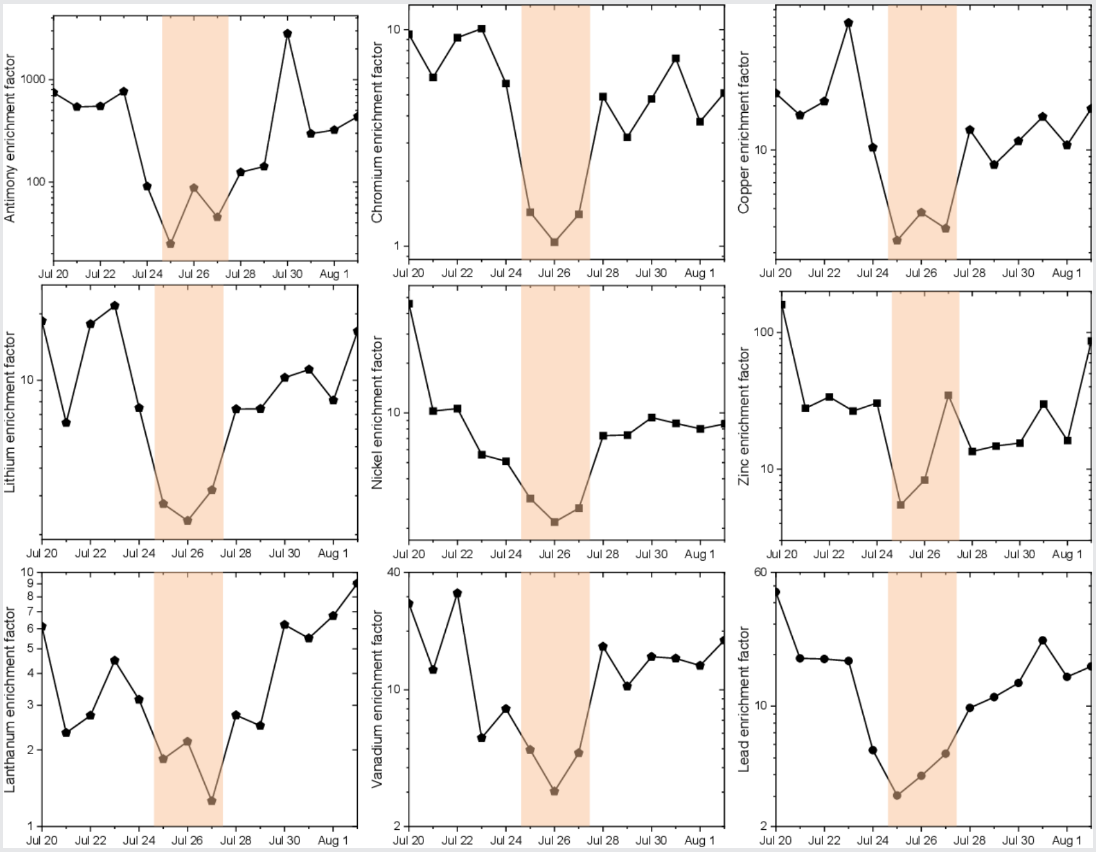

Figure 5. Enrichment factors for aerosols are shown in Figure 4. Top row left to right shows enrichment factors for antimony, chromium, and copper. The second row left to right shows enrichment factors for lithium, nickel, and zinc. The third row depicts enrichment factors for lanthanum, vanadium, and lead. These trace metals (Sb, Cr, Cu, Li, Ni, Zn, La, V, and Pb) represent anthropogenic activities (industrial sources). Enrichment factors are shown as semi-logarithmic plots because they cover variations over one or two orders of magnitude. The major dust peak passed through greater Houston during July 25, 26, and 27 and encompasses the light brown shaded rectangular area.

in Earth's crust (Si > Al > Fe > Ca > Mg > Ti > Mn > Ce)[42] was identical to the sequence in peak aerosol concentrations during the African intrusion, providing qualitative evidence for the presence of large quantities of aerosolized crustal material (i.e., dust) in Houston's atmosphere. The elemental composition[33] and isotopic signature[37,38] of aerosols also confirmed the continuing presence of African dust at ground level after the main peak had passed.

Additional evidence for the origins of the dust were obtained by analyzing enrichment factors, a method by which the patterns of relative concentrations of different elements in a sample are matched to that characteristic of a particular material or location, in this case, crustal materials. Enrichment factors for all elements depicted in Figure 4 were close to unity throughout the two-week study confirming that they largely originated from materials from the Earth's crust, such as desert dust. However, the elements shown in Figure 5, which are metals emitted into the air by industrial processes, showed substantially enriched concentrations in aerosols before and after the major dust event while declining by approximately an order of magnitude during the three days of dust intrusion. The highly elevated enrichment values (⩾1) in the particulate matter during the absence of African dust demonstrated the anthropogenic nature and industrial origins of inhalable aerosols present in Houston during most periods. However, during July 25–27, 2008, marked reductions in enrichment factors for these anthropogenic metals are consistent with their "dilution" by large quantities of crustal aerosols (from the Sahara-Sahel region in this case). Elemental concentrations were also used as inputs to source apportionment receptor models, a class of statistical models, to quantify African contributions. These calculations estimated that Saharan aerosols accounted for ~54% of $PM_{2.5}$ mass during July 25–27.

In summary, detailed analysis of major and trace elements that assisted in tracking dust-laden African air masses that reached Southeast Texas, along with satellite imagery and numerical model results, provided strong evidence for the mixing of Saharan-Sahelian aerosols with local emissions. These findings demonstrated that the African dust had a major impact on air quality, even at times overwhelming local emissions in Houston.

Another line of inquiry being pursued by the Chellam group is to identify the microorganisms associated with long-range dust transport to Texas.[36] Their initial investigation revealed numerous opportunistic human, plant, or animal pathogenic bacteria and fungi concurrent with a Saharan episode in Houston.[36] Additionally, the four most prominent fungal genera responsible for human allergies were detected in all samples.[43] Although we could not prove that the bacteria and fungi were transported from North Africa to the Houston receptor site, the pilot study provides a foundation for more detailed measurements which will be undertaken in the near future.

Conclusions

We now know that clouds of North African dust are transported every summer to Texas skies. To our knowledge, other than detailed measurements of inhalable metals[33,36,38,40] and preliminary characterization of microbes[36] reaching the Houston area, no other research has yet been carried out on the dust's potential human health effects in Texas. Since the health impacts of far-reaching African dust have been documented in multiple other locations, and since locally generated dusts are known to have multiple adverse effects on the health of Texas residents,[44,45] a research gap to bridge exposure and health effects clearly exists. We hope that this report will spur investigations of whether African dust is a health hazard here in Texas, more than 8,000 kilometers downwind of its source.

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