# When the Dust Settles: A Review of the Health Implications of the Dust Component of Air Pollution

Bart Ostro, Yewande Awe, Ernesto Sánchez-Triana

POLLUTION MANAGEMENT & ENVIRONMENTAL HEALTH

WORLD BANK GROUP

**1818 H Street NW**
**Washington DC 20433**
**202-473-1000**
**www.worldbank.org**



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Spaeth Hill

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# Abbreviations

| | |
|---|---|
| **COPD** | chronic obstructive pulmonary disease |
| **CP** | coarse particles (particles between 2.5 and 10 microns in diameter) |
| **EDVs** | emergency department visits |
| **GBD** | Global Burden of Disease |
| **LMICs** | low- and middle-income countries |
| **MISR** | Multi-angle Imaging SpectroRadiometer |
| **$\mu g/m^3$** | micrograms per cubic meter |
| **$PM_{2.5}$** | fine inhalable particles (particles less than or equal to 2.5 microns in diameter) |
| **$PM_{10}$** | inhalable particles (particles less than or equal to 10 microns in diameter) |

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# Preface

A dust storm is an impressive phenomenon to witness. Winds pick up eroded soil, sand, and rock, forming an enormous cloud-like mass that hurtles through the air. A storm can travel for thousands of miles across continents, reaching people far from its origins. But these striking storms contain threats that are tiny in size but significant in impact.

Dust particles are a major source of outdoor air pollution, especially in low- and middle-income countries. Fugitive dust comes primarily from arid and dry regions where high winds can remove and carry the particles over a wide area. Dust particles can be deposited very near their source or, after being carried by the wind, be deposited thousands of miles away. The wind that carries the dust may also carry many other types of particles that may be hazardous to health.

As this report lays out, exposure to dust pollution is harmful to human health. However, difficulty in isolating and measuring exposure to dust particles has led to a limited number of studies on the health effects of natural dust and sparse data on health outcomes of exposure to dust, particularly in low- and middle-income countries. This report takes a vital look at the epidemiological literature to provide a better understanding of the threat to health from short- and long-term exposure to dust and at varying distances from the origin of the dust.

Evidence reviewed in this report shows that in areas directly affected by dust storms, exposure to dust is strongly associated with hospitalization for respiratory outcomes, including worsening of chronic obstructive pulmonary disease and asthma. In areas significantly downwind there is evidence of increased risk of mortality, particularly from cardiovascular disease associated with exposure to dust.

Furthermore, this report's findings suggest, based on the limited number of currently available studies, that a microgram of dust poses a similar health risk to a microgram of most types of particulate matter air pollution. Thus, studies that quantify the health impacts of outdoor air pollution, and measurements of outdoor air pollution, should take into account the contribution of dust.

This report builds on a growing body of evidence that the World Bank is building to better understand the linkages between air pollution and health, strengthen quantification of the global health damage from air pollution, and support improved air quality monitoring and data in low- and middle-income countries.

It is envisaged that the findings of this report will encourage strengthened support, for investments in the establishment of well operated and maintained ground-level air quality monitors, by governments of low- and middle-income countries affected by dust, and institutions such as the World Bank. Data from such monitors would be useful for raising awareness about the health impacts of dust, conducting health studies and for informing the design and implementation of interventions to mitigate dust pollution, including through education, establishment of early warning systems, and land restoration and desertification management programs.

# About This Work

The analytical work in this report builds on a growing body of evidence that the World Bank is building to inform more effective and efficient pollution management interventions and harness the transition to a circular economy in low- and middle-income countries. This growing body of evidence focuses on strengthening the knowledge base that will prompt dedicated action to tackle the forms of pollution that cause the most significant health and social costs in low-and middle-income countries. It also advances inter-disciplinary approaches to assess the linkages between pollution management and circular economy and the World Bank's dual goals of eradicating poverty and promoting shared prosperity. Recent contributions from this body of work include: (i) the monetary valuation of the global cost of mortality and morbidity caused by exposure to ambient fine particulate matter air pollution; (ii) bolstering the case for establishment and strengthening of ground-level air quality monitoring networks in low- and middle-income countries; (iii) the development of a systematic framework to support analysis of health impacts from land-based pollution; and (iv) economic and financial instruments to support the transition to circular economy.

# Acknowledgments

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This report is a product of the Environmental, Natural Resources and Blue Economy Global Practice of the World Bank. This work was conducted under the supervision of **Juergen Voegele** (Vice President, GGSVP), **Karin Kemper** (Global Director, SENDR), **Julia Bucknall** (Global Director, SESD2), **Benoit Bosquet** (Regional Director, SEADR), **Benoit Blarel** (Lead Environment Specialist, SENDR), **Iain Shuker** (Practice Manager, SAEE2), and **Christian Albert Peter** (Practice Manager, SENGL).

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# About the Authors

**Bart Ostro** was the Chief of the Air Pollution Epidemiology Section, California Environmental Protection Agency (CalEPA) for almost 25 years and is now a Research Professor at the University of California at Davis. His primary responsibilities at CalEPA included formulating the Agency's recommendations for state air pollution standards and investigating the health effects of air pollution and climate change. Dr. Ostro was a co-author of the U.S. EPA Regulatory Impact Analysis that was a basis for the federal ban of lead in gasoline. He chaired the U.S. EPA's Science Advisory Board Clean Air Council, and served on the National Academy of Sciences' Committee on Estimating the Benefits of Proposed Air Pollution Regulations. He has published over 100 scientific papers and has consulted for several federal and international institutions and governments. He was honored with Special Achievement Awards from the U.S. EPA and the California Air Resources Board. In 2005 he was given the American Lung Association of California's Clean Air Award, presented to the individual who "has made the most significant contribution to the cause of cleaner air in California."

**Yewande Awe** is a Senior Environmental Engineer at the World Bank where she also holds a leadership position in the Bank's Air Quality Management Community of Practice. She has led and been team member, in the preparation and supervision of policy-based programs, investment projects, technical assistance operations, and analytical activities in several countries. She has worked on projects in Antigua and Barbuda, Argentina, Bolivia, Bosnia and Herzegovina, Kosovo and North Macedonia, Colombia, Dominica, El Salvador, Grenada, Guatemala, Jamaica, Mexico, Nigeria, Peru, Poland, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines, and Yemen. She has authored several publications, in peer reviewed scientific journals, on environmental engineering, environmental health and emerging strategies for environmental quality monitoring in low- and middle-income countries.

She was Scientific Adviser for the First Global Conference on Air Pollution and Health, and a member of the Report Steering Committee for the Lancet Commission on Pollution and Health. She sits on the Board of Directors for Pearson College UWC in Canada, a pre-university school in a movement of 18 global schools dedicated to uniting cultures and countries around the world through education. Awe is involved with Women in Technology International, a global organization dedicated to empowering innovators and building inclusive cultures. Nominated by her colleagues, she serves as Respectful Workplace Advisor at the World Bank. Awe holds a PhD in Environmental Engineering from Imperial College London, United Kingdom.

**Ernesto Sánchez-Triana** is the Global Lead for Pollution Management and Circular Economy for the World Bank. He has worked on projects in numerous countries, including, among others, Afghanistan, Argentina, Bangladesh, Bhutan, Bolivia, Brazil, Ecuador, India, the Lao People's Democratic Republic, Mexico, Pakistan, Panama, Paraguay, and Peru. Before joining the World Bank, he taught at Colombia's National University and worked for the Inter-American Development Bank. He also served as Director of Environmental

Policy at Colombia's National Department of Planning and as President of the Board of Directors of the Cundinamarca Environmental Protection Agency.

Dr. Sánchez-Triana has led the preparation of numerous policy-based programs, investment projects, technical assistance operations, and analytical works. He holds an engineer degree from Universidad de Los Andes (Colombia), and two master of science degrees and a PhD from Stanford University. He has authored numerous publications on air quality management, air quality monitoring, circular economy, cleaner production, climate change, country environmental analyses, energy efficiency, energy policy, environmental economics, environmental sustainability, environmental health, environmental impact assessment, environmental management, industrial sustainable growth, green growth, land-based pollution, organizational learning, policy strategic environmental assessments, sustainable development, and water resources management.

# I. Executive Summary

- This review of the epidemiological literature on fugitive dust indicates the likelihood of significant public health impacts from both short- and long-term exposure to both fine and coarse dust.[1] These impacts are observed in populations that are both near to and distant from the original dust sources. However, given the difficulties in measuring exposures to fugitive dust and the lack of health and exposure data in low- and middle-income countries (LMICs), additional studies are warranted. This requires careful monitoring of ground-level ambient air quality, as well as high-quality data on both mortality and morbidity.
- Pending further studies, global and local quantification of health impacts of outdoor air pollution should not exclude the contribution of dust from the measurement of particulate-matter concentrations. However, it is reasonable to provide a sensitivity analysis to the impact assessment that excludes the contribution of dust. Unless or until additional evidence is forthcoming, it is reasonable to assume that the health risk per microgram of dust is generally similar to that of other constituents of particulate matter with the exceptions of sulfates and elemental carbon, for which there is fairly good evidence of greater effects than other constituents.
- The existing evidence indicates that countries affected by dust and dust storms should provide appropriate warnings, shelter, and other actions to prevent and treat exposure to fugitive dust. Other actions could include educating and providing medical intervention for those at particular risk including infants, young children, the elderly, and those with pre-existing heart and lung disease, particularly chronic obstructive pulmonary disease (COPD). In addition, there could be a focus on providing proper ventilation, including systems with high-efficiency filters, to schools and other public buildings. Additional proactive measures to mitigate dust storms, such as land restoration or desertification-management programs, could be considered. Decision-making in selecting specific measures or interventions should be informed by the analysis of the economic effectiveness of alternatives.
- Fugitive dust comes primarily from arid and dry regions where high winds can remove and carry the particles over a wide area. In certain countries, blowing dust can be the major component of the particulate matter mixture. Dust particles can be deposited very near their source or, after being carried by the wind, be deposited thousands of miles away. These particles contribute to population exposures in the form of both coarse particles (between 2.5 and 10 microns in diameter) and fine particles ($PM_{2.5}$; particles less than or equal to 2.5 microns in diameter).
- Since dust can be a major source of ambient air pollution, particularly in LMICs, its impacts on public health deserve additional attention. Awareness of its impacts can

1 This report covers literature published through September 2019.

provide important information for government-issued episode alerts and potential mitigation. In addition, determining the health implications of exposure to dust can have significant impacts on the health impact assessment of particulate matter air pollution, such as the Global Burden of Disease (GBD). Further, the dust can result in a high baseline concentration, thereby increasing the impact of additional anthropogenic sources of particulate matter.

- Given the difficulty in isolating and measuring dust particles, there are a limited number of epidemiological studies on its associated health effects. There is a lack of data on health outcomes and exposures, particularly in LMICs, resulting in very few studies near desert areas directly affected by dust storms. Fugitive dust is dominated by coarse particles, which are more difficult to measure accurately from ground-based monitors. In addition, it is often difficult to statistically determine the independent effect of dust in epidemiological studies since it might be correlated with other particulate matter sources.

- The review of studies conducted in areas directly affected by dust storms suggests that exposure to nearby dust, dominated by coarse particles, is strongly associated with hospitalization for respiratory outcomes, including the exacerbation of COPD (chronic obstructive pulmonary disease) and asthma. These observed respiratory morbidity impacts could result in mortality among already compromised individuals, depending on the use of and access to adequate health care facilities. Lack of data in these areas has limited the ability to conduct high-quality mortality studies.

- Several studies on coarse particles found significantly downwind from the original dust source consistently report effects on cardiovascular mortality as well as a weaker association with respiratory mortality. In addition, there is strong evidence for morbidity impacts on asthma and COPD. However, the studies use different methods for defining dust-related particles, and each method will have some uncertainties. Further, the wind may be carrying other pollutants, in addition to the dust, which may contribute to adverse health outcomes. The meteorology related to the wind can also impact local pollutants. There are also several dozen coarse particles studies where dust was not specifically identified but was known to be an important contributor to particulate matter. Taken together, these studies also demonstrate significant associations with both cardiovascular and respiratory mortality.

- Many studies have examined the effect of dust in $PM_{2.5}$ far downwind from its sources, such as the Sahara and Gobi deserts. These studies provide consistent evidence of a mortality effect, particularly for cardiovascular disease. Again, each of the methods for determining the dust component has uncertainties, and the studies use different statistical methods for determining risks. Studies of daily exposures to markers of dust (for example, calcium and silicon) also provide reasonably strong support for an association with both all-cause and cardiovascular mortality and, in some cases, respiratory mortality. Only a few studies provide continuous measures of $PM_{2.5}$ on dusty days, making it difficult to determine their risks relative to non-dusty days. However, based on studies in Madrid, Spain; Barcelona, Spain; and the Canary Islands, Spain; Seoul, Republic of Korea, and several cities in Japan, the risk estimates for $PM_{2.5}$ on dusty days are fairly similar to, and sometimes greater, than the estimates on non-dusty days.

- Studies of long-term exposure to air pollution are particularly important since they generate much higher estimates of mortality risks than do the short-term studies. There is some evidence of an association between long-term exposure to dust (and its markers) and both cardiovascular and respiratory mortality. The association is not as strong as those observed for other components such as sulfate (a marker for coal and other fuel combustion) and elemental carbon (a marker for traffic), and sometimes the hypothesis of no effect of dust cannot be rejected. However, the results are often sensitive to the measurement methods used and the statistical modeling of the risks.
- Dust and desertification have a complex relationship with climate change depending on the dust's composition, size, and location. The presence of dust is likely to cause widespread cooling over the tropical oceans and warming over the major deserts and the Arctic. In addition, there is a feedback loop since climate change can, in turn, affect desertification. Additional research is needed to better elucidate these interactions.

"Global and local quantification of health impacts of outdoor air pollution should not exclude the contribution of dust from the measurement of particulate-matter concentrations...The health risk per microgram of dust is generally similar to that of other constituents of particulate matter with the exceptions of sulfates and elemental carbon, for which there is fairly good evidence of greater effects than other constituents."

# II. Contextual Background

This report was produced as part of a program of analytical work conducted under the framework of the World Bank's multi-donor funded Pollution Management and Environmental Health (PMEH) Program. The overall aim of the analytical work is to develop knowledge and guidance for the improvement of air quality monitoring and the estimation of health risks and effects of ambient air pollution in low- and middle-income countries (LMICs). One component of the analytical work focuses on improving the estimation of health impacts of ambient air pollution in LMICs. In this context, two assessments aim to accumulate new evidence related to health-impact estimation, particularly in LMICs: The first aims to improve the understanding of methodological aspects of health-impact estimation, in particular as developed through the Global Burden of Disease (GBD) studies. The second aims to enhance the understanding of the toxicity and health impacts of particulate-matter pollution ($PM_{2.5}$) from different sources. This report addresses the second aim, focusing on the health implications of exposure to dust particles, specifically crustal material resulting from the erosion of soil, sand, and rock.

# III. Introduction and Objectives

Of the many sources of non-anthropogenic dust in the environment, the most common globally is fugitive dust—the natural erosion of soil, sand, and rock. Fugitive dust (hereafter referred to as "dust") comes primarily from arid and dry regions where high winds can remove and carry the particles over a wide area. In addition, human activity can create more fugitive dust through certain land, water, and farmland management practices. In certain countries, blowing dust can be the major component of the particulate mix. Dust particles can vary greatly in size and can be both visible and invisible. They can be deposited very near their source or, after being carried by the wind, be deposited thousands of miles away. The size of particles is typically characterized as either coarse or fine. Coarse particles (CP; particles between 2.5 and 10 microns in size) and fine particles ($PM_{2.5}$; particles less than or equal to 2.5 microns) originate from different sources and have different properties and potential health effects. CP are generated by resuspended material and mechanical grinding and are dominated by crustal matter (which is the primary source of fugitive dust), road dust, and metals. $PM_{2.5}$ is generally a result of fuel combustion processes (that is, power plants, mobile sources, and biomass burning) or photochemical reactions in the atmosphere and are composed of components such as organic and elemental carbon, sulfate, nitrate, and metals. However, fugitive dust can also be found in the fine-particulate range and expose populations far downwind.

While $PM_{2.5}$ has been associated with mortality in studies conducted around the world (Brook et al. 2010; US EPA 2009), there are far fewer studies of CP, particularly the fugitive-dust component. Since dust can be a major source of ambient air pollution, particularly in low- and middle-income countries, its impacts on public health deserve additional attention. Awareness of its impacts can provide important information for government-issued episode alerts and potential mitigation. In addition, determining the health implications of exposure to dust can have significant impacts on the health-impact assessment of particulate matter air pollution, such as the Global Burden of Disease. Finally, if dust is determined to be a health hazard, it needs to be incorporated into overall abatement strategies for controlling particles in the ambient air. Specifically, while mitigation of fugitive dust may be difficult or even impossible in some locations, it can contribute to a high baseline concentration, thereby increasing the impact of additional anthropogenic sources.

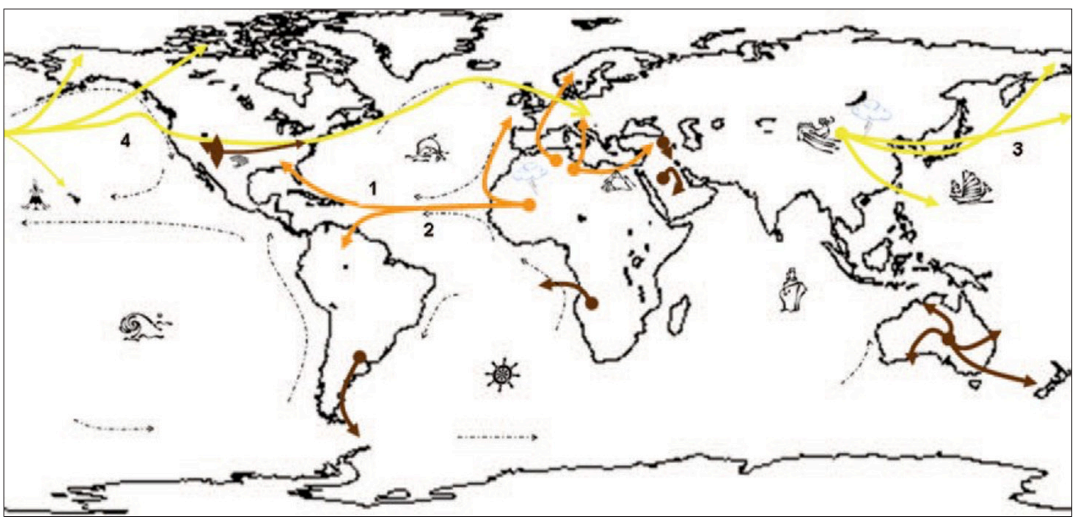
This report provides a review of the published epidemiological studies regarding the public health impacts of exposure to dust from both the coarse and fine modes and at varying distances from the dust's origins. In addition, this report assesses the contribution that exposure to dust may have on the burden of disease associated with outdoor air pollution. This report's focus is fine particles, since that is the pollution metric used in most air pollution burden of disease estimates. This report is not meant as an exhaustive review of the literature, which can be found elsewhere, but more as an indication of the types of studies conducted, their locations, their general findings, and the associated uncertainties. The ultimate objective is to provide policy recommendations for how exposure to dust should be viewed in global or regional health assessments, based on currently available evidence, and research recommendations aimed at developing a better understanding of dust's effects.

"Since dust can be a major source of ambient air pollution, particularly in low and middle income countries, its impacts on public health deserve additional attention"

# IV. Background

Fugitive dust not only affects the areas near the sources of such dust but can be dispersed over thousands of miles. Over 50 percent of global dust emissions come from the Sahara, but significant contributions also come from Central Asia and eastern and western China (20 percent) and the Arabian Peninsula (10 percent) (Tanaka and Chiba 2006). The remainder originates in North America (8 percent), with smaller contributions from South America, Australia, and southern Africa. About 12 percent of the Saharan dust moves north to Europe, 28 percent west to the Americas, and 60 percent south to the Gulf of Guinea (Engelstaedter et al. 2006). A small amount of Saharan dust also moves to the Middle East, although the amount is not specified by this source. Additional details about Saharan dust chemical composition, trajectories, and episodes are available (Karanasiou et al. 2012). Figure 1 displays the origin, pathways, and seasonality of global dust (Griffin 2007).

**FIGURE 1:** Sources, Pathways, and Timing of Desert Dust




**Source:** Adapted from Griffin 2007.

**Note:** Primary sources of desert dust and their atmospheric pathways: (1) During the summer in the Northern Hemisphere (approximately June through October), African desert dust is transported across the Atlantic to the northern Caribbean and North America. (2) During the winter in the Northern Hemisphere (approximately November through May), African desert dust is transported across the Atlantic to the southern Caribbean and South America. (3) The Asian dust season typically lasts from late February to late April. (4) Large Asian dust events can travel significant distances in the Northern Hemisphere. The yellow lines show the atmospheric routes of Asian desert dust, the orange lines show African dust routes, the brown lines show the routes of other sources of desert dust, and the broken black lines depict wind patterns.

Over time and space, the size composition of the dust changes. Local concentrations are dominated by CP but still contain significant amounts of $PM_{2.5}$. For example, data from ground-level monitoring close to the deserts in the Middle East and operating over a year or more show concentrations of $PM_{2.5}$ ranging from 35 to over 100 μg/m³ and concentrations of inhalable particles less than 10 microns in diameter ($PM_{10}$) ranging from 72 to 303 μg/m³ (table 1) (Engelbrecht et al. 2009). In certain countries, dust or blowing sand can make up a majority of the $PM_{2.5}$ and have a significant impact on mortality. For example, source-apportionment studies indicate that 54 percent of the $PM_{2.5}$ in Kuwait City, Kuwait, consisted of sand dust (Alolayan et al. 2013), while Lelieveld et al. (2015) estimated that exposure to dust was responsible for about 90 percent of the $PM_{2.5}$-associated mortality in the Arab Republic of Egypt. The latter study also projected that in 2010, dust was responsible for between 11 percent and 18 percent of global $PM_{2.5}$-associated mortality. The range in this estimate was due to alternative assumptions about the relative toxicity of dust compared to other $PM_{2.5}$ sources.

**TABLE 1:** Annual Concentrations of $PM_{2.5}$ and $PM_{10}$ (μg/m³) in Selected Middle Eastern Locations

| Location | $PM_{10}$ | $PM_{2.5}$ | $PM_{2.5}/PM_{10}$ |
|---|---|---|---|
| Djibouti | 72 | 35 | 0.49 |
| Bagram, Afghanistan | 108 | 38 | 0.35 |
| Khowst, Afghanistan | 127 | 75 | 0.59 |
| Qatar | 165 | 67 | 0.41 |
| United Arab Emirates | 140 | 52 | 0.37 |
| Balad, Iraq | 184 | 56 | 0.30 |
| Baghdad, Iraq | 250 | 103 | 0.41 |
| Tallil, Iraq | 303 | 65 | 0.21 |
| Tikrit, Iraq | 298 | 111 | 0.37 |
| Taji, Iraq | 213 | 81 | 0.38 |
| Al Asad, Iraq | 95 | 37 | 0.39 |
| Northern Kuwait | 211 | 67 | 0.32 |
| Central Kuwait | 298 | 87 | 0.29 |
| Coastal Kuwait | 176 | 60 | 0.34 |
| Southern Kuwait | 199 | 62 | 0.31 |

**Source:** Engelbrecht et al. 2009.

Blowing dust can also contribute significantly to both $PM_{10}$ and $PM_{2.5}$ downwind. Data from 13 southern European cities show that average $PM_{10}$ concentrations from Saharan desert dust (over a four-year-or-longer period ending in either 2009 or 2010) ranged from 20 μg/m$^3$ in Athens, Greece, to 9 μg/m$^3$ in the Emilia Romagna region in Italy, which includes the cities of Parma, Reggio Emilia, and Modena. This is about 25 percent to 40 percent of the total $PM_{10}$ mass (Stafoggia et al. 2016). On days with significant desert dust, total $PM_{2.5}$ concentrations in these cities averaged about 27 μg/m$^3$. For comparison, the current World Health Organization Air Quality Guidelines for annual averages are 10 μg/m$^3$ and 20 μg/m$^3$, respectively, for ambient $PM_{2.5}$ and $PM_{10}$.

Besides the high concentrations of sheer particulate mass, dust storms may pick up and transport biological materials including bacteria, pollen, fungi, and viruses. In addition, dust storms can carry a range of other pollutants, pesticides, heavy metals, dioxins, and radioactive isotopes (Goudie 2014). Goudie's 2014 study also provides evidence of dust's effects including Valley Fever, meningitis, conjunctivitis, dermatological disorders, and deaths resulting from traffic accidents. These dust storm–generated materials are likely to affect both the cardiovascular and pulmonary systems. Sandstrom and Forsberg (2008) commented that the coarse particles in dust, which are mostly deposited in the upper airways, can affect respiratory conditions such as chronic obstructive pulmonary disease (COPD), asthma, and pneumonia. They also indicate that the dust includes a mix of chemicals (iron, copper, and zinc) and endotoxins that are related to oxidative stress and systemic inflammation, both of which are predictors of subsequent cardiovascular disease.

**"Dust storms affect not only the immediate areas but can disperse the associated particles over thousands of miles."**

# V. Uncertainties in Measuring Fugitive Dust

There are several difficulties in measuring the health effects of windblown dust:

First is that on windy, dusty days, people may change their behaviors and reduce their exposures. This is especially likely when these days are a relatively rare occurrence and might explain the lack of an association between windy days carrying coarse particles and mortality in Spokane (Schwartz et al. 1999).

Second, there have not been many studies undertaken in areas directly and immediately affected by dust storms in the Sahara or Asian deserts. This is due to both the lack of ground-level monitors measuring $PM_{2.5}$ or $PM_{10}$ concentrations in these areas as well as the lack of consistent and high-quality health data.

Third, dust is usually dominated by larger coarse particles between 2.5 and 10 microns in diameter (as opposed to particles less than 2.5 microns or $PM_{2.5}$). Coarse particle concentrations tend to vary greatly over a given area and are therefore more difficult (relative to $PM_{2.5}$ which is fairly homogeneous spatially) to measure from a fixed site monitor location. As a result, significant mismeasurement of exposure may exist, which tends to reduce the likelihood of finding an effect, if one exists.

Fourth, it is often difficult, using current exposure methodologies and statistical methods, to isolate the specific effects of natural dust from the mix of other components (for example, sulfates and metals) that exist in $PM_{10}$ and $PM_{2.5}$. Several studies have utilized sophisticated methods that attempted to do so, but a good deal of uncertainty will continue to exist about both the actual concentration of dust particles (using either direct measurement or source-apportionment techniques) and their independent effects. Some of the health effects will be mitigated by avoidance behavior, which will generate economic but not health effects. The avoidance behavior could result in a lower estimated effect of dust exposure. In addition, very few studies directly compare the effects per $\mu g/m^3$ of dust versus generic $PM_{2.5}$. Finally, in areas such as northern Africa and the Middle East, where windblown natural dust is a primary issue, it is difficult to measure its contribution to $PM_{2.5}$ because of the lack of ground-based monitoring in these areas and the potential difficulties in retrieval by remote-sensing satellites (Van Donkelaar et al. 2016).

Many LMICs lack ground-based monitoring of $PM_{2.5}$ mass and, even more so, the measurement of the different constituents of $PM_{2.5}$ such as dust, elemental carbon, sulfates, and nitrates. In addition, dust is a challenging particulate-matter constituent to quantify for certain satellites because of the complex size-shape-composition (the basis of satellite identification) of minerals and difficulty with aerosol retrievals over arid areas. An exception, however, is the Multi-angle Imaging SpectroRadiometer (MISR) satellite, which can retrieve ambient particulate and surface matter particles and characteristics simultaneously, including bright desert surfaces, and measure dust fairly accurately (Martonchik et al. 2004).

As a result of these uncertainties, global estimates of the health impacts of outdoor air pollution have varied in their treatment and impact of dust. For example, the Global Burden of Disease (GBD) has treated dust toxicity as equal to the toxicity of all other chemical components of $PM_{2.5}$. However, for the GBD 2010 estimates, the separate contribution of dust was about 2 percent of the total global mortality impact, with an acknowledgment that it played a much larger role in North African and Middle Eastern countries (Lim et al. 2012). In their global estimates, Evans et al. (2013) estimated that the global fraction of cardiopulmonary mortality attributed to all $PM_{2.5}$ was 12.1 percent. However, if health effects from dust were excluded, the attributed cardiopulmonary risk decreased to 8 percent. Anenberg et al. (2010) attempted to quantify the impact of the change in $PM_{2.5}$ from preindustrial to current levels and assumed that dust levels had not changed, and, therefore, there was no added health impact of dust. In their global assessment of air pollution health effects, Silva et al. (2016) removed dust from their estimates of $PM_{2.5}$ concentrations. Lelieveld et al. (2015) quantified the global mortality impact of different sources of $PM_{2.5}$ such as dust, power generation, traffic, and biomass combustion. They determined that 18 percent of the global mortality burden was due to naturally generated dust, assuming equal toxicity of dust. In a sensitivity analysis, Lelieveld et al. (2015) determined that if anthropogenic sources were assumed to be five times more toxic per microgram than dust, the global dust burden would drop to 11 percent. Their country-specific results demonstrated the large impact of dust in North Africa, parts of West Africa, the Middle East, and Central Asia. For example, the share of mortality due to dust was very high in Egypt (92 percent), the Islamic Republic of Iran (81 percent), Nigeria (77 percent), and Pakistan (57 percent).

Clearly, a better understanding of the toxicity of dust is necessary to improve the estimates of the health burden of air pollution. The following sections provide an overview of studies examining the immediate and downwind effects of exposure to dust. The review is not exhaustive but does provide a sense of the known impacts. The review begins with the limited studies that were conducted in areas directly and immediately affected by dust storms. Second, given the significance of coarse particles in dust, a subsequent section briefly reviews studies of short-term exposure to coarse particles where dust has been identified as a major factor or has been independently analyzed. Next is a review of studies of acute exposure to $PM_{2.5}$ dust particles or their markers (such as silicon, aluminum, or calcium) where exposure occurs further downwind from the original dust-storm locations. Finally, a review of studies of long-term exposure to $PM_{2.5}$ dust components is presented. The final sections include a summary and conclusions as well as recommendations for future research, especially in low- and middle-income countries, some of which are significantly affected by dust and dust storms.

# VI. Health Effects of Exposure to Dust in Areas Directly Affected by Dust Storms

There are only a few epidemiological studies conducted in areas that are the source of dust storms. Most of the existing studies have been undertaken far downwind from Saharan or Asian dust storms. Abdo et al. (2016) provide a review of studies of environmental factors and respiratory outcomes in the eastern Middle East region. Only a few epidemiological studies have examined the effects of dust storms or very high particulate levels on health. For example, Houssaini et al. (2007) examined school children (average age of 12) in western Morocco to see if there was an association between high pollution and respiratory disease. Total suspended particulates (or TSP, which includes airborne particles of all sizes) were measured in several areas over a four-year period. After controlling for several individual characteristics and indoor environments, the region with the highest levels of TSP was strongly associated with the risk of asthma.

Thalib and Al-Taiar (2012) examined the effect of dust storms (defined as days with $PM_{10}$ > 200 $\mu g/m^3$) on age-specific hospital admissions due to asthma and all respiratory diseases over a period of five years in Kuwait. Statistical methods were used to analyze whether there was an association between the dust storms and same-day or lagged-day admissions. Thalib and Al-Taiar (2012) used a population-based retrospective time-series study of daily emergency asthma admissions and admissions due to respiratory causes in public hospitals. Overall, 34 percent of the days had dust-storm events, and those days were significantly associated with an increased risk of asthma and respiratory admissions, particularly in those under age 15. During the same five-year period, Al-Taiar and Thalib (2014) examined the daily impact of the dust storms on daily mortality in Kuwait. While some positive associations were observed, there were no statistically significant relationships with either all-cause, cardiovascular, or respiratory mortality. However, the study may have lacked the statistical power to detect an effect given that there was an average of 9 deaths per day, including 4.5 for cardiovascular mortality and less than one per day for respiratory mortality.

Meo et al. (2013) selected healthy volunteers in Saudi Arabia to examine the impacts on those exposed to a sandstorm for an average of 24 minutes. They found a significant proportion of the subjects reported cough (48 percent), wheeze (33 percent), and acute asthma (21 percent). Vodonos et al. (2014) analyzed data on 2,100 patients with confirmed COPD living in Be'er Sheva, a southern Israeli town near the Sahara-Arabian dust belt. A time-series analysis was performed to determine if an exacerbation was more likely during high dust-storm days, defined as a day when the $PM_{10}$ concentration was above 71 μg/m$^3$, which is two standard deviations above the background value. In addition, days with $PM_{10}$ > 200 μg/m$^3$ were characterized as intensive dust-storm days. They found a statistically significant association between dust-storm days and hospitalization for COPD, with even greater risks for the intensive dust-storm days.

In one of the few studies examining cardiovascular outcomes, Ebrahimi et al. (2014) examined the association between dust-storm days (based on a definition from the local environmental agency) and emergency visits for cardiovascular and respiratory diseases among residents of Sanandaj, the Islamic Republic of Iran. The average $PM_{10}$ concentration during dust episodes was 187 μg/m$^3$. Using a basic analytic technique, daily concentrations were found to be moderately associated with both cardiovascular and respiratory visits, with correlations of 0.48 and 0.19, respectively.

Ebenstein et al. (2015) examined the effects of sandstorms on hospital admissions for respiratory disease in Jerusalem and Tel Aviv, Israel, from 2007 to 2009. The sandstorms led to an increase of approximately 300 μg/m$^3$ of $PM_{10}$ and had a statistically significant association with hospital admissions, particularly for asthma and COPD.

Other studies of the direct and immediate impact of dust storms have been undertaken outside of the eastern Middle East region. For example, among the first studies of dust storms, Ostro et al. (2000) examined the arid environment of Coachella Valley, California, where frequent dust storms occur. Coarse particles of geologic origin were highly correlated with $PM_{10}$ and accounted for approximately 60 percent of $PM_{10}$, increasing to more than 90 percent during wind events. The time-series analysis of daily exposures found a statistically significant association between coarse particles and cardiovascular mortality.

Johnston et al. (2011) examined the association between both dust and smoke and mortality in Sydney, Australia, from 1997 to 2004. Six dust events were recorded with a mean average daily $PM_{10}$ of 97 μg/m$^3$ and a maximum of 200 μg/m$^3$. Logistic regression was used to examine the association with mortality. The results indicated that dust events were associated with a 15 percent increase in all-cause mortality after a lag of three days.

Tam et al. (2012) also reported the impacts of five dust-storm episodes between 1998 and 2002 in Hong Kong SAR, China. Again, a significant increase in emergency hospitalizations for COPD was reported several days after each of the episodes.

For Guangzhou, China, Liu et al. (2014) examined the effects of heavy dust-haze days, with visibility less than 5 kilometers (4.2 percent of the total days from 2006 to 2011). Statistically significant associations of dust-haze days with all-cause, cardiovascular, and respiratory mortality were observed. However, in both these Chinese studies, the specific contribution of dust to $PM_{2.5}$ or $PM_{10}$ concentrations was not available.

Yang et al. (2016) conducted a time-series analysis of “dust-haze” days (defined as having daily visibility of less than 10 kilometers, no rainfall, and relative humidity of less than 80 percent) in ten Chinese provincial capitals. An analysis of each city—controlling for seasonality, day of the week, and weather—was first conducted and then combined in a meta-analysis. The pooled relative risks had statistically significant (p [probability value][2] $< 0.05$) effects on all-cause and diabetes-related mortality and near significance ($p < 0.10$) for respiratory and cardiovascular mortality.

Crooks et al. (2016) examined the mortality association with 209 dust storms in the United States (dominated by storms in California and Arizona) from 1993 through 2005. In this case, dust storms were broadly defined by the US National Weather Service and based on a variety of sources including emergency management officials, law enforcement, media reports, and the insurance industry. All-cause mortality increased by 7.4 percent (95 percent CI: 1.6, 13.5) two days after the dust-storm effect, with associations also observed for cardiovascular but not respiratory mortality.

Possible biologic mechanisms for the observed effects of exposure to dust storms are provided by a Nigerian cardiologist who has directly observed the impacts during the Harmattan season (Okeahialam 2016). The Harmattan season usually occurs between December and March and is characterized by colder temperatures and dry dusty winds that bring Saharan dust to the West African region. An increase in visits (about a 10 percent increase over baseline) to the hospital for cardiovascular problems is observed during this period; the increased visits are thought to result from a combination of the dust and the colder temperatures. The author suggests that the relative cold dries the mucus, which reduces the normal body defense mechanisms and increases the amount of inhaled particles. This results in increased airway inflammation and the subsequent oxygen-stress burden, which is a risk factor for cardiovascular disease.

**Summary:** The review of studies conducted in places directly affected by dust storms suggests that exposure to nearby dust storms, dominated by coarse particles, is strongly associated with hospitalization for respiratory outcomes including exacerbation of COPD and asthma. These observed respiratory morbidity impacts could result in mortality among already compromised individuals, depending on the use of and access to adequate health care facilities. Additional studies of immediate exposure to dust storms report a significant association with cardiovascular and sometimes all-cause mortality, although there does not appear to be an association with respiratory mortality. However, it is possible that the deaths from respiratory causes were often diagnosed ultimately as cardiovascular.

**2** The probability value is the likelihood of incorrectly rejecting the null hypothesis that no effect exists.

# VII. Health Effects of Exposure to Coarse Particles Downwind from Dust Origins

The examination of dust-specific coarse particles can enhance the understanding of the impacts of their exposures downwind and provide insight into the potential consequences of direct and immediate exposure to dust.

Several Saharan coarse particle (CP) dust studies have been conducted in Barcelona, Spain. Perez et al. (2012) utilized a methodology that identified the concentration of coarse particles on dusty days in Barcelona between 2003 and 2007. Separate analyses were run for dusty and non-dusty days. On dusty days (about 10 percent of the total), CP concentrations increased by an average of 14 $\mu g/m^3$, with a single-day maximum of 43 $\mu g/m^3$. The results indicated that CP was significantly associated with both cardiovascular and respiratory mortality on non-dusty days, while it was associated with cardiovascular but not respiratory mortality on dusty days. An earlier paper (Perez et al. 2008) reported a statistically significant association between coarse particles on dusty days and all-cause mortality. No association was observed for CP on non-Saharan dust days. Crustal material made up 65 percent of the CP. In addition, associations have been reported between daily CP and/or $PM_{10}$ from Saharan dust and mortality in Madrid, Spain; Rome, Italy; and Cyprus (Tobias et al. 2011; Mallone et al. 2011; Neophytou et al. 2013).

De Longueville et al. (2013) provide a comprehensive review of 50 studies conducted from 1999 to 2011 that focus on health effects downwind from dust storms originating in the Saharan or Asian regions. A majority of the studies (32) examined the impact of dust originating from Asian deserts on other Asian countries. Thirteen studies examined the impact of dust of Saharan origin on either Europe (8 studies), the Caribbean (3 studies), or other areas (2 studies). An additional five studies focused on other source areas. The studies used many different metrics to define the dust event such as high $PM_{10}$ levels, low visibility, and a binary variable for a dust episode and back-trajectory analysis. In addition, several different statistical approaches were used. Thirty of the studies report statistically significant associations of dust events with either respiratory or cardiovascular mortality or morbidity. A majority of the papers reported effects on asthma and COPD hospital admissions and emergency room visits. Eight of the ten studies that examined cardiovascular mortality reported statistically significant associations with dust, and six of the seven that examined respiratory mortality reported statistically significant associations. Associations with respiratory or cardiovascular mortality were also reported in Sydney, Australia; Seoul, Korea; the Canary Islands, Spain; Emilia-Romagna, Italy; and Taipei, China—but not in Athens, Greece; Nagasaki, Japan; or Spokane, Washington in the United States.

In a study of the effects of short-term exposure to CP (not specific to only dust episodes per se), Adar et al. (2014) conducted a meta-analysis of available studies that analyzed daily associations with mortality and hospitalization using a random-effects model. The studies were primarily from the United States and Western Europe but included evidence from one study in Chile and one from China. Ultimately, there were 23 studies available for mortality (19, 11, and 14 for all-cause, respiratory, and cardiovascular, respectively) and 10 available for hospitalization (9 for respiratory and 7 for cardiovascular). In general, the associations between CP and the health outcomes were statistically significant. The greatest risk from CP exposure was related to respiratory mortality and hospitalization. Specifically, for mortality, the risks per 10 μg/m$^3$ were 0.6 percent (95 percent CI = 0.3, 0.8), 1.4 percent (95 percent CI = 0.5, 2.4), and 0.75 (95 percent CI = 0.2, 1.2) for all-cause, respiratory, and cardiovascular, respectively. For hospitalization, the risks were 1.0 percent (95 percent = 0.1, 1.8) for respiratory and 0.5 percent (95 percent Ci = 0.3, 0.7) for cardiovascular. Additional analyses indicated that the respiratory effects were fairly robust, and especially important, continued to be present when there was a low correlation between CP and $PM_{2.5}$. This reduced the likelihood that the CP effects could be attributed to $PM_{2.5}$. All-cause and cardiovascular mortality were more affected (larger confidence interval and reduction in statistical significance) when correlations with $PM_{2.5}$ were examined, although the associations remained positive. The meta-analysis also indicated an association between CP and hospitalizations for both cardiovascular and respiratory diseases.

Lee et al. (2013) examined the impact of Asian dust storms in seven major cities in Korea. Dust-storm identification was based on data observance of dust episodes in China and Mongolia, consultation with weather maps and satellites, and visual observation from $PM_{10}$ monitors. Time-series analysis was performed to first determine the acute effects on mortality from dust days for each of the cities. The results were then pooled in a meta-analysis. The results indicated a significant association between cardiovascular mortality and $PM_{10}$ on days with significant dust, with an increased mortality risk of 2.9 percent (95 percent CI = 0.1, 5.8) on those days.

A recent study by Stafoggia et al. (2016) was aimed explicitly at determining the acute effects of desert-dust outbreaks on mortality and hospitalization in 13 southern European cities. The study period was generally from 2007 to 2010. Desert-related $PM_{10}$ was distinguished from non-desert $PM_{10}$ by using several sophisticated tools including meteorological studies and software, aerosol maps, atmospheric models of air mass back-trajectories, and satellite images (Pey et al. 2013). After a dust-outbreak day was officially determined, the $PM_{10}$ concentrations above local background levels were quantified. Separate regression models were run for each city and separately from desert-dust versus non–desert-dust days. The city-specific results were then pooled in the meta-analysis. On average, 15 percent of the days were affected by desert dust concentrations with an average increase in $PM_{10}$ of 14 µg/m³. The study found associations between desert $PM_{10}$ and both all-cause and cardiovascular mortality, but not with respiratory mortality. Is it important to note that non-desert $PM_{10}$ had a similar effect on the estimate of all-cause mortality and was not associated with cardiovascular mortality but was associated with respiratory mortality. Specifically, for cardiovascular mortality, the risk estimate for desert-$PM_{10}$ was 1.1 percent (95 percent CI = 0.16, 2.06) versus a risk estimate for non-desert $PM_{10}$ of 0.49 (95 percent CI = -0.31, 1.29). If these results are taken at face value, it suggests that desert $PM_{10}$ has an equal or greater effect on all-cause and cardiovascular mortality but a lesser effect on respiratory mortality. However, it is also possible that the results were due to measurement issues and/or statistical modeling. Regarding hospital admissions, desert $PM_{10}$ was associated with respiratory diseases for those under age 15 but not with older individuals or with cardiovascular diseases. Non-desert $PM_{10}$ was associated with both younger and older respiratory disease admissions but, like desert $PM_{10}$, not cardiovascular disease admissions.

Another recent study examined $PM_{10}$ on dusty days throughout Spain (Diaz et al. 2017). Analysis of its impact on natural mortality was conducted for a representative province in each of Spain's nine major regions. Dusty days were identified based on daily interpretation of back trajectories, synoptic meteorological charts, satellite imagery, and consultation with daily dust forecast models. Ultimately, regressions were run to compare the acute effect of days that had $PM_{10}$ with Saharan dust advections versus days without the Saharan advections. Four of the regions had statistically significant associations between mortality and $PM_{10}$ with Saharan dust. Two of those regions did not have an association with non-dust $PM_{10}$. Of the two that did have an association, their risk estimates were generally similar to the days with Saharan dust.

Taken together, these meta-analyses based on studies conducted in Korea, the United States, and Western Europe provide compelling evidence of an effect of dust particles in the coarse size.

There are many factors that may contribute to the toxicity of the downwind coarse particles:

First, the wind may be carrying both the mass of coarse (and fine) particles and also carry other pollutants in addition to the dust that may contribute to the health impacts (Rodríguez et al. 2001; Sajani et al. 2012). This is especially possible when the back trajectory of the dust storm includes other major sources such as fuel combustion from power plants or traffic-related pollutants.

Second, dust may contain microbes and other toxic compounds. For example, samples of Saharan dust contain several times the number of microbes and fungi relative to non-dust samples (Griffin 2007). The bacteria in the dust have been linked to several diseases, including pneumonia. In addition, samples of the dust have been found to include soluble metals that are associated with the production of reactive oxygen species, a known risk factor for cardiovascular disease.

Third, the dust provides a core for subsequent chemical attachment of local sulfur and nitrogen dioxide, which can create secondary particulate pollutants such as nitrates and sulfates (Alastuey et al. 2005).

Finally, there is evidence that the meteorological conditions associated with dust storms may affect (lower) the height of the mixing layer downwind. The mixing layer is the layer of air, usually below a stable layer, within which pollutants are mixed by turbulence and diffusion. It has been inversely correlated with particle concentrations, and reductions in the mixing layer have been associated with increases in the health effects of particulate matter (Pandolfi et al. 2014). Therefore, the impacts of the dust may be confounded by an increase in local pollutants.

**Summary:** Effects on cardiovascular mortality as well as a weaker association with respiratory mortality have been consistently reported by several studies on CP or $PM_{10}$ significantly downwind from the original dust source that have specifically isolated the impact of the dust component. In addition, there is strong evidence for morbidity impacts on asthma and COPD. However, the studies use different methods for defining dust-related particles, and each method will have some uncertainties. Further, the wind may be carrying other pollutants in addition to the dust, which may contribute to the health impacts and affect local pollutants.

In addition to the CP and $PM_{10}$ studies that specifically identify a dust component, there exist several dozen coarse-particles studies where dust was not specifically identified but known to be an important constituent. Taken together, these studies also demonstrate statistically significant associations with both cardiovascular and respiratory mortality.

# VIII. Health Effects of Dust in $PM_{2.5}$ or Its Markers

Evidence exists that there is a significant amount of $PM_{2.5}$ in the Saharan dust. For example, Sajani et al. (2012) examined Saharan dust events over an eight-year period at the Mount Cimone observatory located in the mountains between Florence and Bologna, Italy. This rural area is unaffected by normal urban pollution. Their results showed that on average, approximately 35 percent of the particulate mass is below 2.5 microns. Given the likely $PM_{2.5}$ in dust-storm events, the studies of the effects of $PM_{2.5}$ during dust events are noteworthy.

Several studies that reported effects of coarse particles or $PM_{10}$ on Saharan dust days did not find associations for $PM_{2.5}$ on dust days (or non-dust days) in Rome, Italy, and Madrid, Spain (Mallone et al. 2011; Tobias et al. 2011). However, in the Madrid $PM_{2.5}$, non-Saharan dust days were statistically significant with a risk of 2.7 percent (95 percent CI = 1.4, 4.1) for cardiovascular mortality, and there was a similar risk of 2.6 percent (95 percent CI = 0, 5.8) and near significance for Saharan dust days.

Perez (2012) collected daily $PM_{2.5}$ data from 2003 to 2007 in Barcelona, Spain. Saharan dust days were identified based on both back-trajectory analysis and observation of high $PM_{10}$ at a background, rural monitoring site. A time-series model was used to determine the effects of $PM_{2.5}$ with and without a contribution from Saharan dust. Associations with cardiovascular mortality were observed for both non-Saharan dust days with a 5.5 percent increase in risk (95 percent CI = 2.3, 8.9), and Saharan dust days with a risk of 9.3 percent (95 percent CI = 1.8, 17.3) for their associated interquartile range (the difference between the 75 percent and 25 percent of the distribution). Converting both the risk from dust and non-dust days to effects per 10 $\mu g/m^3$, the risks for dust days are 13.3 percent versus 10.3 percent for non-dust days.

Kim et al. (2012) examined the impacts of $PM_{2.5}$ from Asian dust storms in Seoul, Korea, from 2003 to 2006. Asian Dust (AD) events were officially determined by the Korean Meteorological Administration. For AD events, statistically significant associations were reported with natural mortality with a risk of 0.3 percent (95 percent CI = 0.1, 0.5) per 10 $\mu g/m^3$ and for cardiovascular mortality for those above age 75 with a risk of 0.5 percent (95 percent CI = 0, 1.1). These risk estimates were generally higher than on days without smog or AD episodes, a finding that also held true for the general (all-age) population.

The previously discussed study of Spain by Díaz et al. (2017) reported an association between all-cause mortality and $PM_{2.5}$ on dusty days in the Canary Islands—supporting an earlier study by López-Villanueva et al. (2012)—without an association on non-dusty days. Finally, over a six-year period, Kashima et al. (2012) measured particles below 8 microns ($PM_8$) on days without and with incursions from AD. The latter was defined as days above 100 μg/m$^3$, whereas the overall mean concentration during the study was 25 μg/m$^3$. The analysis indicated that days with AD had higher risk estimates per μg/m$^3$ and stronger associations for cardiovascular diseases (such as heart attacks and arrhythmia), all respiratory diseases, and specifically pneumonia.

Thus, five of the six studies that looked at $PM_{2.5}$ dust days reported statistically significant associations (or near significance in the case of Madrid) with either natural or cardiovascular mortality. Of the remaining study, conducted in Rome, Italy, there were no associations reported with $PM_{2.5}$ on either dust or non-dust days.

In another mortality study, Owili et al. (2017) used satellite data over Africa to determine the annual average concentrations of components of $PM_{2.5}$, including dust. The continent was divided into five geographic regions, and annual data on infant (age < 5) and maternal mortality were utilized for the years 2000 to 2015. Using two alternative ecologic regression models (that is, no individual data were available), the researchers examined the association between the dust component and infant and maternal mortality. The results are difficult to interpret but are broadly suggestive of a possible effect on both infant and maternal mortality. Specifically, both models reported statistically significant effects in northern Africa between dust exposure and infant mortality, while in southern Africa there was an association from one model and near association in the other. For the western, eastern, and central regions of Africa, the models were either conflicting (one positive and one significant) or both non-significant. No positive associations were observed between dust and maternal mortality in any of the regions.

There are also two morbidity studies of $PM_{2.5}$ on dust days. Li et al. (2015) examined the effects of components of $PM_{2.5}$ and all-cause, cardiovascular, and respiratory mortality in Beijing, China, using daily data from 2005 through 2009. One of the components studied, calcium, is considered to be a good tracer for soil and crustal material. In their cold-season analyses, the researchers reported associations between calcium and both all-cause and respiratory mortality, but not with cardiovascular mortality. The authors concluded that "Combustion-related products, traffic sources, vegetative burning, and crustal component and resuspended road dust may play a key role in the associations between air pollution and public health in Beijing."

Liu et al. (2017) tracked the effects of dust storms from northern China on emergency room visits in Taiwan from 2006 to 2008. Dust-storm episodes were defined as days where the visibility was below 1 km and levels of $PM_{10}$ exceeded 150 μg/m$^3$ for three consecutive days. Logistic regression was used to determine the effects of dust days versus non-dust days. The authors found associations between dust days and emergency room visits for both cardiovascular and respiratory diseases.

Other studies, mostly from the United States, have examined the effects of crustal material, soil, or their tracer chemicals such as silicon and calcium rather than $PM_{2.5}$ directly. For example, Ostro et al. (2011) used daily data from 2000 to 2003 in eight California metropolitan areas. The study examined the relationship between mortality and $PM_{2.5}$ mass and components including elemental and organic carbon, nitrates, sulfates, and various metals and several other elements. An association was reported between all-cause mortality and two markers of soil, calcium, and silicon during the winter months. It should be noted for this and the other studies reviewed that the silicon marker may include road dust, which includes many other potential toxicants such as transition metals.

Cakmak et al. (2009) evaluated the association between several elements of $PM_{2.5}$ and mortality in the general population of Santiago, Chile, between 1998 and 2006. The strongest individual constituent effect was seen for elemental carbon. Using factor analysis, a group of elements consistent with a mobile combustion source (carbon monoxide, nitrogen dioxide, and elemental and organic carbon) was significantly associated with total mortality. Soil-sourced particles had a weaker but statistically significant mortality association.

Sacks et al. (2012) applied various regression models developed in previous multicity time-series studies of air pollution and mortality to data from Philadelphia, Pennsylvania (May 1992–September 1995). Single-pollutant analyses used daily cardiovascular mortality, $PM_{2.5}$, speciated $PM_{2.5}$, and gaseous pollutant data, while multipollutant analyses used source factors identified through principal component analysis. A principal component analysis yielded factors with species associated with traffic, crustal material, residual oil, and coal. Mortality risk estimates examined using a source-oriented approach yielded more stable and precise risk estimates, compared with single-pollutant analyses. Factors associated with traffic and crustal material showed consistently positive associations in the warm season, while the coal-combustion factor showed consistently positive associations in the cold season.

Krall et al. (2013) estimated short-term associations between daily mortality and $PM_{2.5}$ constituents across 72 urban US communities from 2000 to 2005. Using US Environmental Protection Agency (EPA) Chemical Speciation Network data, they analyzed seven constituents that, together, composed 79–85 percent of $PM_{2.5}$ mass: organic carbon matter, elemental carbon silicon, sodium ion, nitrate, ammonium, and sulfate. The results indicated that several of the components including silicon were associated with increases in mortality.

Dai et al. (2014) estimated the effects of $PM_{2.5}$ species on mortality using data from 75 mostly eastern and midwestern US cities from 2000 to 2006. Silicon and sulfur were associated with both all-cause and CVD mortality, whereas sulfur was related to more respiratory deaths. Indeed, the authors observed that "the effect of $PM_{2.5}$ mass on all-cause and respiratory mortality was modified by sulfur."

Ostro et al. (2016) used city-specific $PM_{2.5}$ mass source apportionment in eight major metropolitan areas in California during 2005–2009 to examine the associations of source-specific $PM_{2.5}$ exposures from vehicular emissions, biomass burning, soil, and secondary nitrate and sulfate sources with emergency department visits (EDVs) for cardiovascular and respiratory diseases. Among the results using a case-crossover analysis, they observed an association between soil-sources respiratory EDVs and EDVs for asthma. The soil source, which includes resuspended road dust, generated the highest risk estimate for asthma of all the sources.

**Summary:** Based on studies conducted in Barcelona, Madrid, the Canary Islands, and Seoul that examined the effects of dust included in the $PM_{2.5}$ size range, there is consistent evidence of a mortality effect, particularly for cardiovascular disease. Again, each of the methods for determining the dust component has uncertainties and the studies use different statistical methods for determining risks. The studies of daily exposures to dust or dust-like particles or tracers (including soil, crustal material, calcium, and silicon) from Chile and the United States also provide reasonably strong support for an association with both all-cause and cardiovascular mortality and in some cases, respiratory mortality. Taken together, there appear to be mortality risks associated with $PM_{2.5}$ dust days, and based on the studies in Madrid and Barcelona, the risk estimates for the dusty days are fairly similar to those of the non-dusty days.

# IX. Health Effects of Long-term Exposure to Dust

Since the Global Burden of Disease and other global estimates rely on long-term studies for determining the mortality effects of outdoor air pollution, the long-term studies that include dust or other constituents of particulate matter are particularly important, but unfortunately, there are few of them. This section includes the studies of long-term exposure to dust or its markers (for example, silicon) and provides context by also including the findings for the other constituents.

The first published effort to examine the association between long-term exposure to $PM_{2.5}$ constituents and mortality was a cross-sectional study of 1980 mortality rates in 98 US metropolitan areas (Ozkaynak and Thurston 1987). Rather than using individual-level data, this study analyzed the association between metropolitan area-wide mortality rates and area-wide concentrations of annual average $PM_{2.5}$. An additional analysis was conducted of the association of mortality with source-specific $PM_{2.5}$ including soil, auto emissions, residual oil combustion, metals, and coal combustion (Thurston et al. 1984). Of these sources, coal combustion had the most significant impact on mortality, and no association was observed for soil (Ozkaynak and Thurston 1987).

Ostro et al. (2011) examined long-term exposure to $PM_{2.5}$ components among 102,000 California women teachers and administrators from the California Teachers Study who were followed from 2001 through 2007. To reduce exposure misclassification, the sample was restricted to those living within 30 km of a ground-level monitor, resulting in a study population of just under 45,000 women. A Cox proportional hazards model was used to estimate the mortality risks. For cardiopulmonary mortality, among the major constituents of $PM_{2.5}$, significant associations were observed for nitrate, sulfate, and silicon, along with $PM_{2.5}$ mass. No association was observed between these constituents and respiratory mortality.

Vedal et al. (2013) used data from the Women's Health Initiative–Observational Study, a cohort of about 90,000 women from 45 US cities across the nation, to investigate the effects of constituents and sources on total cardiovascular mortality and several subclasses. Besides $PM_{2.5}$, data on elemental carbon, organic carbon, sulfur, and silicon were examined in the model. The components were measured as city-wide averages and assigned to each participant's residence. The authors' source-apportionment analysis indicated that these components were, respectively, markers of local combustion including traffic, primary gasoline and biomass combustion and secondary organic carbon formation, secondary sulfate formation, and crustal/soil. In the basic analysis across metropolitan areas, organic carbon was most consistently associated ($p < 0.05$) with cardiovascular death and many of its subclasses including atherosclerotic and cerebrovascular deaths. However, silicon was associated ($p < 0.05$) with deaths diagnosed as resulting from possible coronary heart disease—that is, from the buildup of plaque in the heart's arteries.

Another recent study examined the effect of $PM_{2.5}$ components and sources using a subset of the national American Cancer Society's Cancer Prevention Study-II cohort (Thurston et al. 2013). A total of 446,000 adults in 100 US metropolitan areas were followed from 1982 to 2004. In this case, the average of available US EPA speciation monitors in each city were used as a measure of metropolitan area-wide concentrations of the pollutants. Sixteen constituents (including calcium and silicon, the tracers for soil) and eight sources (including soil) were examined. Standard Cox regression was used to estimate the risks of mortality. Among the models that were examined was one that considered the data on the components and another based on a source-apportioned data set in which $PM_{2.5}$ mass is apportioned among all the potential sources.

In the components model, calcium was associated with ischemic heart disease mortality, which includes heart attacks, and both calcium and silicon were associated with respiratory mortality. The soil source was associated with all-cause mortality, ischemic heart disease mortality, and, most consistently, with respiratory mortality. The quantitative results suggest that soil or its markers had a lower risk than traffic and coal combustion sources, but a risk generally similar to many of the other $PM_{2.5}$ sources. The results, however, were sensitive to the statistical methods and model specification, and in the follow-up study (Thurston et al. 2016) elemental carbon and sulfur (a tracer for combustion from coal and residual oil) were significant in most models of ischemic heart disease mortality, while organic carbon and silicon were not.

Finally, Crouse et al. (2016) utilized data from the Canadian Census Health and Environment Cohort of approximately 2.4 million subjects at baseline living throughout the country, with about 60 percent of subjects from the urbanized airshed that includes southern Ontario and Quebec. The cohort data cover 1991 through 2006; $PM_{2.5}$ components were estimated from satellite and chemical transport models starting in 1990 and assigned to each participant's residence. Ultimately, the $PM_{2.5}$ concentration was apportioned to six components: sulfate, nitrate, ammonium, organic mass, black carbon, and crustal dust. Risks from Cox regression models were examined for all-cause mortality and cardio-metabolic (cardiovascular plus diabetes) mortality. Except for mineral dust, all the constituents were highly correlated with each other and with $PM_{2.5}$. For both all-cause mortality and cardio-metabolic mortality, statistically significant associations ($p < 0.05$) were observed for all the factors, except mineral dust. However, for cardio-metabolic mortality, a modest association ($p < 0.10$) was observed for mineral dust.

**Summary:** There is some evidence of an association between long-term exposure to dust (and its tracers calcium and silicon) and both cardiovascular and respiratory mortality. The association is not as strong as those observed for other components such as sulfate (a tracer for coal and other fuel combustion) and elemental carbon (a tracer for traffic); in certain studies, no association is observed for dust. However, the results are often sensitive to the measurement methods used and the statistical modeling of the risks.

# X. Dust and Climate Change

Dust has a complicated impact on climate change depending on the composition, size, and location of the dust (Albani and Mahowald 2018). The presence of dust is likely to cause widespread cooling over the tropical oceans and warming over the major deserts and the Arctic. Thus, more dust in the air could result in less incoming solar radiation, but its coverage of surfaces that reflect and reduce the heat could mean more warming. Simply put, dust particles in the air may reflect light but in certain areas such as those covered by glacial ice, the dust particles will absorb heat and increase melting. The direct and indirect effects of dust on climate are described in Choobari et al. (2014). In addition, there is a feedback loop, since climate change can increase desertification (land degradation in arid, semi-arid, and dry low-humidity regions). However, as discussed in a report by the United Nations (IPCC 2019): "Despite numerous relevant studies, consistent indicators for attributing desertification to climatic and/or human causes are still lacking due to methodological shortcomings."

# XI. Summary and Conclusions

This review of the epidemiological literature on fugitive dust indicates the likelihood of significant public health impacts from short- or long-term exposure to dust. These impacts are observed in populations that are both near to and distant from the original dust sources. Dust storms affect not only the immediate areas but can disperse the associated particles over thousands of miles. Over 50 percent of global dust emissions come from the Sahara, but significant contributions also come from Central Asia and eastern and western China (20 percent) and the Arabian Peninsula (10 percent). Over time and space, the size composition of the dust changes. Local concentrations are dominated by coarse particles (2.5 to 10 microns in diameter) but still contain significant amounts of fine particles (particles less than 2.5 microns in diameter or $PM_{2.5}$). Further downwind, the dust is dominated by $PM_{2.5}$.

Besides the high concentrations of particulate mass, dust storms may pick up $PM_{2.5}$ originated from sources over its trajectory as well as biological materials including bacteria, pollen, fungi, and viruses. Dust storms can carry a range of other pollutants, pesticides, heavy metals, and dioxins. There are other factors that may affect the toxicity of the natural dust. The natural dust particles may provide a core for the attachment of gases that ultimately become fine particles such as nitrates and sulfates. In addition, the meteorological conditions associated with dust storms might lower the height of the downwind mixing layer, resulting in less pollution dispersion and higher pollutant concentrations.

There are many difficulties in assessing the health impact of immediate as well as downwind exposures to natural dust. First, the areas directly affected often have no ground-level monitoring to measure exposures and/or limited systematic, high-quality health data to record potential impacts. Second, existing studies have used a variety of methods, sometimes fairly crude, to measure the dust-related contribution to particulate matter. Third, the studies often involve different statistical methods, exposed populations, and co-pollutants. All of these factors add to the uncertainty of determining the independent effect of dust.

Nevertheless, there is sufficient literature to provide reasonable evidence of the public health impacts of exposure to dust. Epidemiological studies of coarse particles have been conducted in areas directly affected by dust and dust storms. In addition, there are studies of dust found in both fine and coarse particulate matter in areas downwind from their sources.

Unfortunately, there are few studies from areas where populations are directly and immediately affected, such as countries in northern and western Africa and the eastern Mediterranean because of limited health and exposure data. However, the existing studies of morbidity indicate that exposure is associated with exacerbation of COPD and asthma. Analysis of cities or regions outside of the large desert regions (that is, the Sahara, Arabian, and Gobi deserts) but clearly subject to blowing dust in California and Arizona in the United States, as well as in Australia and China, show fairly consistent and statistically significant association with cardiovascular, and occasionally, all-cause mortality. There are fewer associations observed with respiratory mortality, but this may be due to these deaths often being diagnosed as cardiovascular.

Several studies of coarse particles or $PM_{10}$ downwind from the original dust source have specifically isolated the impact of the dust component and provide consistent evidence of effects on cardiovascular mortality as well as a weaker association with respiratory mortality. Taken together, these meta-analyses based on studies in Korea, the United States, and Western Europe provide compelling evidence of an effect of dust particles in the coarse-size range. The available coarse particle studies also provide strong evidence for morbidity impacts on asthma and COPD. However, the studies use different methods for defining dust-related particles, and each method will have some uncertainties. Further, the dust-storm winds may be carrying other pollutants in addition to the dust, which may contribute to the health impacts.

In addition to these studies, there are epidemiological studies in areas where the dust component has not been isolated but where coarse particles tend to be dominated by crustal material and dust re-entrained by road traffic. Some of the studies provide separate control for the independent effects of $PM_{2.5}$ so the CP effect is not confounded. Taken together, these studies also demonstrate statistically significant associations of coarse particles with both cardiovascular and respiratory mortality. However, there are studies of CP that do not find an independent effect. It is not clear whether this is due to a true lack of an association or difficulties in measuring CP, since these particles vary spatially and are less evenly dispersed than $PM_{2.5}$.

Given that $PM_{2.5}$ becomes more significant in the composition of dust downwind from the original dust locations, it is important to assess the epidemiological studies that measure sources of dust or crustal material in fine particles. Epidemiological studies have also examined the effects of components of particulate matter that are considered good markers of these sources, such as calcium and silicon. Unfortunately, there are only a few studies that isolate the dust component in $PM_{2.5}$ and provide risk estimates when $PM_{2.5}$ concentrations are measured continuously on dust days. However, based on the studies in Madrid, the Canary Islands, and Barcelona, and from Japan and Korea, the mortality risks for dust days were significantly associated with cardiovascular (and sometimes respiratory) mortality with risk estimates similar to, and sometimes greater than, the days without dust. The more consistent findings for cardiovascular versus respiratory mortality may be due to coding issues since many people with chronic respiratory disease may ultimately die from heart attacks or heart failure.

Finally, there is also evidence of health effects from long-term (that is, a year or more) exposure to the part of $PM_{2.5}$ identified as crustal material, soil, or its markers. These studies are particularly important because global studies of the burden of air pollution tend to rely on the long-term studies of $PM_{2.5}$, since they provide the clearest evidence of significant reductions in life expectancy. Again, the study results are somewhat mixed, but often show associations between soil, or its chemical markers such as silicon, and cardiovascular mortality.

Taken together, the epidemiological evidence provides a reasonable evidence base for including the effects of dust on mortality (and morbidity) in the quantitative estimates of the global burden of disease from air pollution. In addition, the evidence to date supports risk estimates (that is, percent change in the mortality or morbidity outcome per microgram per cubic meter) for dust that are generally similar to that of $PM_{2.5}$ in general.

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# XII. Future Needs and Recommendations

1. There is a need for high-quality and reliable ambient $PM_{2.5}$ and $PM_{10}$ ground-level monitors to be located particularly in low- and middle-income countries directly affected by dust and dust storms and where air quality measurements are scarce or nonexistent. To advance the study of the health effects of dust, some of these monitors should be placed in areas where there is significant population exposure to the dust source origins. The use of universally accepted ground-level monitors, including the measurement of both mass and specific components, in countries with limited or no monitors would represent a significant enhancement to current knowledge. Not only would this information help to identify the magnitude of the air pollution problem and the components, including dust, that are the most important to control, but such information would help in calibrating estimates from remote-sensing satellites, thereby improving the accuracy of future exposure model projections.

2. Development and quality control of health data are crucial for improving understanding of the effects of dust exposure. This could include vital statistics data on mortality records including day, diagnosis, and residence. In addition, high-quality morbidity data could be collected, such as emergency room or hospitalization data from major hospitals in the study area. When possible, these data should include respiratory outcomes such as asthma and COPD, which appear to be the most likely outcomes of exposure to dust. An additional alternative could be the establishment of health clinics with trained staff that could collect prespecified data on visits for certain acute outcomes such as asthma or respiratory disease in general. These data could then be used in subsequent epidemiological studies. Again, there is a substantial lack of high-quality, publicly available health data in LMICs where dust sources may be a dominant source of particulate matter.

3. There should be more epidemiologic research on the health impacts of components of $PM_{2.5}$ and $PM_{10}$, including dust. This research could help determine and document the extent of the health effects related to exposure to dust and provide comparisons with other sources of particulate matter. An understanding of the concentration levels of dust necessary to elicit specific outcomes, the populations at risk, and the severity of that risk could help in the formulation of population mitigation strategies, in which the adverse effects of dust could be reduced. The epidemiologic studies would provide important information for the design and implementation of policies to reduce air pollution and improve public health.

4. Although further study is needed, the existing evidence indicates that countries affected by dust and dust storms should provide appropriate warnings, shelter, and other actions to prevent and treat exposure to fugitive dust. Other actions could include educating and providing medical intervention for those at particular risk including infants, young children, the elderly, and those with preexisting heart and lung disease, particularly COPD. Additionally, there could be a focus on providing proper ventilation, including systems with high-efficiency filters to schools and other public buildings. Additional proactive measures to mitigate dust storms, such as land restoration or desertification management programs, could be considered. Decision making for the selection of specific measures or interventions should be informed by the analysis of the economic effectiveness of alternatives.

5. Pending further studies, global and local quantification of health impacts of outdoor air pollution should not exclude the contribution of dust from the measurement of particulate matter concentrations. However, it is reasonable to provide a sensitivity analysis to the impact assessment that excludes the contribution of dust. Until or unless additional evidence is forthcoming, it is reasonable to assume that the mortality and morbidity risk per microgram of dust is generally similar to that of other constituents of particulate matter, with the exception of sulfates and elemental carbon for which there is fairly good evidence of effects greater than the effects of other constituents. For some outcomes, such as asthma and COPD, the effects of coarse dust particles may be particularly significant.

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