

Dust Storms, Human Health and a Global Early Warning System

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Abstract Arid regions, the source of most airborne mineral dusts, comprise a third of the Earth's land surface, where some two billion people are exposed daily to the fine particles raised by wind. Crossing political borders and travelling on air currents around the world, these particles not only affect the health of local communities, but also put many other populations extant at risk for cardiovascular and respiratory illnesses and a host of other health problems. Risks of exposure are affected by climatic conditions and their local and regional weather characteristics. And today, because of advancements in science and technology we are at the threshold of significantly reducing these health problems. Examples of meningitis, asthma and Valley fever are used to illustrate how risks may be lowered through a Dust-Health Early Warning System. A little more than a half-century of dedicated measurements of particulate air quality and of environmental science enhanced by Earth-orbiting satellites reveal the truth of airborne dust extent, and much of its variability in time and space. These truths have been essential in advancing numerical, dynamical models of the atmosphere that mimic and predict weather systems that loft the airborne dusts that medical sciences and epidemiology are proving harmful. This union of scientific disciplines and services makes possible today a means to improve public health around the world through a Global Dust-Health Early Warning System.

Keywords Aerosols · Particulates · Airborne dust · Fungi · Mineral dust · Haboob · Dust storm · Dust source · Cardiovascular · Respiratory illness · Valley fever · Cocci · Coccidioidomycosis · Asthma · Human health · Health risks

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S.L. Steinberg and W.A. Sprigg (eds.), *Extreme Weather, Health, and Communities*,
Extreme Weather and Society, DOI 10.1007/978-3-319-30626-1_4

1 A Global Dust-Health Early Warning System (D-HEWS)—The Motive

In late February 2015, a dust storm covering the Arabian Peninsula lasted several days. Child asthma emergency admissions to medical centers in Dubai jumped more than 20 % and asthma related hospital admissions increased more than 25 % in Abu Dhabi, United Arab Emirates (UAE 2015). While the Arabian Peninsula storm was underway, Korean television was alerting the Seoul population of an Asian dust storm bringing health-threatening dust into their area (Arirang 2015). Neither storms such as this nor their health consequences are unexpected. The World Health Organization (WHO) previously alerted all nations of the connection between cardiovascular hospital admissions and mortality to windblown desert dust (WHO 2006, 2013). In Geneva, just a few blocks away from the WHO, Terradellas et al. (2015) raised the human health problem again at the World Meteorological Organization (WMO).

In the Sonoran desert of North America a dust storm of frightening proportions roared through the U.S. city of Phoenix, Arizona on 5 July 2011 (Fig. 1). It was an American haboob, a storm seen rarely in America except for the arid southwest. Produced from thunderstorms that advanced north from Tucson with downdrafts of



Fig. 1 The Phoenix, Arizona haboob of 5 July 2011 around 7 PM local time looking southwest. See also the time lapse movie (<https://vimeo.com/26045314>). Photo and movie courtesy of Mike Olbinski, Phoenix, Arizona

110 km/h pummeling the dry, hot desert floor, outflowing winds gusted to 80 km/h raising a cloud of dirt, sand and dust 1800 m high travelling more than 250 km through city, suburbs, farms and ranches along a 160 km front, 18 km deep (National Weather Service 2011). Mike Olbinski, the Phoenix photographer who took the picture in Fig. 1, says that when the dust overtook him, where he had quickly sought the safety of his truck, visibility dropped to zero (personal communication 2015). It was the first and largest of six such storms that occurred that year in Phoenix (Sprigg et al. 2014). On average, one to three haboob-like storms occur in the region each year according to Raman and Arellano (2013).

Airborne mineral dusts range in size, from sand, a little larger than the width of a 70 μm human hair, to smaller, easily inhalable particles of PM_{10} and $\text{PM}_{2.5}$. The latter refer to particulate matter of aerodynamic diameter 10 μm and less, and 2.5 μm and less. One micrometer (μm), or micron, is one millionth of a meter. These smaller particles maneuver past the fine hairs in one's nose, into the lung. The finer, $\text{PM}_{2.5}$ particles penetrate deep into the lung, and ultrafine particles even enter the blood stream.

Backed by a growing number of studies, arid land mineral dust emissions are shown to contribute to both cardiovascular and respiratory illnesses. Gupta et al. (2012) show that asthma patients experienced significant reduced pulmonary function when exposed to mineral dusts (PM_{10}) that were collected from Rajasthan, the desert state of India. Meng and Lu (2007) statistically analyze respiratory and cardiovascular hospitalizations in Minqin, China, finding that Asia dust events increased both health problems, even reflecting the seasonal characteristics of disease surveillance. Giannadaki et al. (2014) assess global mortality rates from long-term exposure to airborne mineral dusts. More studies include Styer et al. (1995), Ostro et al. (1999, 2000), Lipsett et al. (2006), Cheng et al. (2008), and Goudie (2014). Whether in Kuwait (Thalib and Al-Taiar 2012), Lanzhou (Yan et al. 2012), Seoul (Hong et al. 2010), Sydney (Merrifield et al. 2013), Taipei (Chan and Ng 2011) or El Paso (Grineski et al. 2011), piece-by-piece the harm exacted by windblown dust is being documented.

Yet, more concerns of blowing dust emerge, including eye infections, meningitis, and Valley fever, or coccidioidomycosis: Laniado-Laborin (2007), Sandstrom and Forsberg (2008) and Morman and Plumlee (2013). Stafoggia et al. (2015) are convincing when they link mortality and hospital admissions in Southern Europe with invading Saharan dust. Goudie (2014) chronicles an extensive list of health problems associated with windblown desert dust. And, the U.S. National Research Council (2010) reviewed a Department of Defense effort to understand the health implications of airborne particulates from arid surroundings.

While concerns of public health agencies run the gamut of health complications from windblown dusts, three are elaborated in the following paragraphs: meningitis in Africa, asthma around the world, and Valley fever, or coccidioidomycosis, in the Americas. Addressing these will demonstrate the Conceptual Framework for the global early warning system: global monitoring of dust sources and airborne plumes; forecasts on hemispheric, regional and local geographical scales; and particulate air quality outlooks on climate space and time scales.

1.1 Meningitis

Africa's Meningitis Belt stretches across the sub-Sahara (Sahel) afflicting many of the least developed countries of the world. The timing of major meningitis outbreaks and dust storms from the Sahara appear highly correlated, and Noinaj et al. (2012) hypothesize that *Neisseria* bacteria, responsible for meningitis, need iron-laden dust to grow and become virulent. Hence, simulating historical events of windblown dust helps to understand whatever role mineral dust may play in meningitis outbreaks across Africa (Pérez et al. 2014; Thomson et al. 2006, 2009; Molesworth et al. 2003). Forecasting near-term Saharan dust storms may lead to reductions in the severity of meningitis outbreaks when the connections between airborne dust and illness are well established and appropriate warning systems are in effect.

Today, the logistics of field research are helped by these forecasts. International organizations including the World Meteorological Organization (WMO), the World Health Organization (WHO) and the Group on Earth Observations (GEO) support research with many African countries in the "Meningitis Environmental Risk Information Technologies" project (MERIT 2012), where the WMO Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) has provided observations, forecasts and simulations of airborne dust and dust storms to assess risks and attribution, cause and effect.

Yaka et al. (2008) and Sultan et al. (2005), examining climate time scales, show that wind is associated with meningitis outbreaks. Sultan even suggests that an "early warning index" for meningitis outbreaks could be developed from wind climate variability. It follows, too, that dust emissions will track climate conditions, as soil is anchored by dampening effects of precipitation and by moisture-invigorated plant roots; fresh foliage is an efficient trap for wind-driven sand and dust. Anticipating Africa's climate may inform agencies of future efforts required to face the risks of meningitis.

A long-term drought across the Sahel that began in the early 1970s was a factor behind calls in the U.S. and elsewhere to increase climate research. The Sahel drought and overgrazing led to drying of Lake Chad and, quite possibly, to observed increases in dust, and whatever hitchhikes with it, transported across the Atlantic Ocean. Caribbean and Western Atlantic dust concentrations correlate with rainfall deficits in North Africa (Prospero and Lamb 2003). Iron- and clay-rich soils found in the Caribbean came from Africa. Prospero and Mayol-Bracero (2013) and Prospero et al. (2014) estimate that every year more than 700 million tons of Africa's dust reach the Americas. In the Pacific basin, Schmidt (2014) and Shinn et al. (2000) find that nutrient-laden dust in Hawaiian rainforests is transported from Asian deserts.

1.2 Asthma

Exposure to desert dust is shown to increase risk of asthma hospitalization for children in Toyama, Japan (Kanatani et al. 2010). In Korea, Yoo et al. (2008, 1) report "... significantly higher frequency of respiratory symptoms" during Asian dust events. Yet, other studies have not found the connection, as in investigation of child asthma and airborne desert dust in Riyadh, Saudi Arabia (Alangari et al. 2015) and in Fukuoka City, Japan (Ueda et al. 2010). Watanabe et al. (2015a) found that Asia dust storms reduced pulmonary function in children, with the degree of impact differing with each dust event. Yet, in a companion study of adults with asthma (Watanabe et al. 2015b), pulmonary function scores were not significantly affected by Asia dust, but storms with larger, inhalable sand particles made lower respiratory tract symptoms worse.

On the other side of the world, under the influence of Africa dust outbreaks, Reyes et al. (2014) found conclusively that Saharan dust transported to Madrid, Spain, increased respiratory-caused hospital admissions. The Caribbean Allergy and Respiratory Association found that asthma has increased 17-fold in Barbados and Trinidad between 1973 and the turn of the Century (Shinn et al. 2000; Prospero and Lamb 2003; Prospero and Mayol-Bracero 2013). And, Molinie (2015) relates Africa dust to pediatric asthma on Guadeloupe. In a conflicting study, the Barbados Public Health Laboratory (Blades 2015) found no relationship between asthma and the 50-year record of Saharan dust measured at Ragged Point on the eastern edge of Barbados (Prospero et al. 2014). A general review of the literature shows that the epidemiology of desert dust and asthma is variable, often conflicting and inconclusive. This is at least partly due to what Wijesinghe et al. (2009, p. 1045) conclude as "... inherently difficult to interpret (trends in asthma mortality) because of the many factors that may change in different countries over time." Asthma in Trinidad has been linked to both Africa dust (Gyan et al. 2003) and climatic conditions (Ivey et al. 2003).

Africa dust makes up about half the airborne particulates in South Florida's air during the summer (Prospero and Lamb 2003; Prospero and Mayol-Bracero 2013). And, Saharan dust does not necessarily stop at Florida and the Caribbean. Further west, local sources of airborne dust are implicated in pediatric asthma and acute bronchitis in El Paso, Texas (Grineski et al. 2011), and Morain et al. (2007, 2009, 2010) engaged several state health agencies (and elementary school nurses) to test the efficacy of dust alerts in reducing respiratory, particularly asthma, risk.

1.3 Valley Fever

Exact locations of *Coccidioides* (*C. immitis* and *C. posadasii*) fungi are poorly known. They thrive in the generally hot, alternately damp and dry soils of the New World. When viable and inhaled, they cause Valley fever (coccidioidomycosis or

cocci). Humans as well as their pet dogs and cats are at risk (Graupmann-Kuzma et al. 2008). This Valley fever, getting its name from San Joaquin Valley, California, not to be confused with Africa's Rift Valley Fever, is believed endemic only in the Americas, generally from California south and east along the U.S./Mexico border, well into Mexico and Central and South America (Hector and Laniado-Laborin 2005; Barker et al. 2012). Yet, as we have seen, dust (and we must assume viable *C. immitis* and *C. posadasii*) is carried over considerable distance. Coccidioides fragments are 3–5 μm in size (Galgiani 2013) and would be included along with other dust particles in PM_{10} . Yin and Sprigg (2010) show that significant amounts of dust cross the border into Texas from Mexico during typical dust events, with dust sources in the U.S. also affecting Mexico's air quality. For Valley fever spores, a question remains as to how long in the free atmosphere *Coccidioides* fungi can stay viable. Pappagianis and Einstein (1978) attributed more than 379 new cases of Valley fever in California to a single 1977 dust storm. Windblown cocci spores from a landslide triggered during the 1994 Northridge, California earthquake caused 203 Valley fever cases in Ventura County, California (Schneider et al. 1997). Litvintseva et al. (2014) found human infection of Valley fever and local *C. immitis* spores in soils further north, well outside the known endemic regions for cocci, in Washington State. While spores may be carried to these regions beyond known endemic regions in ways other than severe weather, organism survival is, indeed, possible over long distances. For example, Prospero et al. (2005) captured viable, Saharan-sourced fungi and bacteria in the Caribbean.

Nguyen et al. (2013) review the state-of-the-science of Valley fever. Most cases are slight and unreported. For thirty to forty percent of cases that are documented, symptoms often mimic pneumonia. Common symptoms include coughing, fever, skin rash, feeling tired and difficulty breathing (Galgiani et al. 2005). Among the U.S. States, Arizona records the greatest number of cases. In 2004 about half of the 6000 cases reported nationwide occurred there (Laniado-Laborin 2007). The fact that cocci was not a reportable disease until 1997, and changes in laboratory tests in 2009 and reporting in 2013, have made construction of a long history of cocci impossible. For example, the 2009 change resulted in cocci numbers more than doubling the next year to 11,888 cases (Tsang et al. 2010; ADHS 2012). Treatment for the infection includes antifungal medication. Concerning vaccines, Galgiani (2008) gave a rather pessimistic prognosis that a vaccine to prevent coccidioidomycosis among infants in endemic regions and immigrants of any age would not be cost-effective.

Costs for cocci treatment are not trivial: 2007 Arizona Hospital Discharge Data show 1735 hospital visits for the disease, which translates to about \$86 million. Galgiani et al. (2005) and Tsang et al. (2010) have analyzed cost and occurrence statistics for Valley fever in Arizona. Hector et al. (2011) report extensively on statistics for both Arizona and California. In neighboring Kern County, California, the CDC (1994) estimated \$45 million for hospital stays and outpatient care between 1991 and 1993. Huang et al. (2015) figure 161 deaths from valley fever occurred on average every year between 1990 and 2008 in the United States. About 30 deaths are attributed to cocci in Arizona each year (Galgiani et al. 2005;

Tsang et al. 2010). According to Flaherman and Rutherford (2007) an average of 70 deaths occurred annually in California between 1997 and 2008.

Yet, it appeared to this author that people were generally unaware of Valley fever, what caused it, and how risks of catching it might be lowered. The value of an early warning system will depend on a community's understanding of the risks if warnings are ignored. Hearing from people who have contracted cocci might reveal clues about populations at risk, and how an early warning *system* might lower that risk.

1.3.1 Interviews with Valley Fever Sufferers

To gain a better understanding of the real impact of Valley fever, this author asked three individuals from Arizona neighborhoods who were under active surveillance or treatment for Valley fever if they would discuss their experiences for readers of this chapter. Two agreed, Mrs. K and Mr. H. Their accounts follow. The third, the youngest and most seriously affected, declined. One clear message from both interviews is that an early warning system must include public education about the disease, mainly because it is not widely publicized and often is misdiagnosed.

Mrs. K, In Her Own Words, June 22, 2015

I now live in Ohio, but early on a Wednesday morning in 2007 I lived in Southern Arizona and awoke with a bad headache and feeling very tired. Taking aspirin I struggled through that day and night. But Thursday morning the headache had worsened and now was accompanied by a terrible pain in my foot. I was listless and had developed a cough. I had no energy to get out of bed. My husband stayed home from work to tend to me. By Friday I had developed a fever and, along with the headache and joint pain, tired and short of breath, a rash appeared on my legs. We went to an Urgent Care where I was prescribed 'Benedril,' and sent home. The diagnosis: allergic reaction to an unknown factor. Benedril was no help. The rash travelled up my legs, all the way to my neck. My husband took me to the hospital emergency room, for I was in no condition to drive. The triage nurse, seeing the rash on my stomach, gasped and said I had 'cocci,' which I learned later was Valley fever. The attending emergency room physician thought differently, agreeing with the allergic reaction diagnosed earlier at Urgent Care. I was given steroids through an IV and treated as 'outpatient.' The weekend went agonizingly slowly and painfully. My listlessness, shortness of breath, joint pain, cough and rash worsened. On Monday I returned to the emergency room where a blood test for cocci returned negative and a chest X-ray revealed a small spot on my lung. Diagnosis: viral pneumonia. The next couple of days I heard nothing from the hospital as to what really might be wrong with me. I did not believe that viral pneumonia was responsible for all these symptoms! I was referred to a pulmonary specialist, and another blood test for cocci, which again came back negative. Someone, I no longer remember who, said I might have lung cancer! Finally, after nearly two weeks of seeing so many doctors I lost count, a third blood test returned positive for Valley fever. Two weeks of watching the disease advance. At least now we knew the problem and it could be treated, as it should, with an anti-fungal medication, fluconazole. I took the antifungal pill for three months. My hair fell out. My pulmonary symptoms continued intermittently and other symptoms became significantly less severe. None of the previously prescribed treatments had helped at all. Along the way through this ordeal I developed fibromyalgia in my legs, which, according to experts, is often associated with Valley fever. This was a new, very painful, experience. Cocci, it seems, wreaks havoc with one's neural

system. For two and a half years after catching Valley fever I periodically developed lesions and the same rash on my stomach, the lingering consequences of Valley fever.

When asked whether she knew when she might have been exposed to the cocci fungus, Mrs. K said that it may have happened perhaps a week or more prior to that Wednesday she awoke with such stress. She had been in her back yard when a strong wind suddenly picked up dirt and dust from all around her. Before she could take cover, the dust enveloped her. She talked also about the family dog, Lady (an alias), who developed Valley fever at the same time, coughing, tired and walking with difficulty. Treated with similar antifungal medication over many months Lady recovered. Clearly, Mrs. K's life had been severely changed by Valley fever and would never return to the quality before that Wednesday in 2007 when she first realized she was so ill.

Recollections of Mr. H

Sometimes the case for Valley fever is not as clear. Take, for example, Mr. H (Personal communication, May 18–28, 2015). In 2002, just before moving to the American Southwest, Mr. H had a regular health exam in New Jersey, including a chest X-ray that had revealed no problem. In 2003, just months after arriving in his new home in the Sonoran desert, he “experienced a rash on my arms and legs, and flu like symptoms, including headache, joint pain and a general feeling of fatigue over a ten to fourteen day period.” He does not recall having a fever or feeling nauseous. Since the time between infection and emergence of symptoms may be as long as four weeks (Galgiani 2012) he may not even recall when or where he was exposed to the cocci mold spore. He did not seek medical treatment. Being a newcomer to the region he had heard nothing about Valley fever or its symptoms.

He is a smoker and his Arizona internist ordered a chest X-ray in his 2004 annual physical. “Results suggested lung abnormalities, and comparison to the 2002 films evidenced a pronounced difference. Examination by a pulmonary specialist and a full C-T scan preceded a lung biopsy in January 2005. With seven nodules identified clearly by the C-T, the presumptive ingoing position was that I had lung cancer. They were all benign.”

“The biopsy was not the closing chapter in my book,” says Mr. H. “Although characterized as ‘damage or abnormality consistent with Valley fever exposure,’ further examination and blood tests did not provide confirmation. The exact cause of my lung nodules is indeterminate. I have an annual lung scan, results of which are compared to all prior records to ascertain if the nodules have changed in size or shape. I have been ‘stable’ since 2005.”

So, is Mr. H “stable” from a case of cocci ... or something else? He has definitely suffered from something that negatively impacted his breathing and lung function. One fact is clear. Newcomers to cocci endemic regions are usually unaware of the disease, the symptoms or cause. Sometimes this applies to attending clinicians as well. An early warning system that includes public alerts, first of climatic pre-conditions for Valley fever and then, forecasted dust storms, will educate visitors and all new residents, physicians and clinicians included, of the dangers and ways to lower risks. As of right now however, no such system exists.

Yet, as we shall see in the following pages, one could be operational today by making use of current technology.

1.3.2 Acquired Insights for a Valley Fever Early Warning System

A 2012 NASA-sponsored workshop and consequent study (Sprigg et al. 2012, 2014) makes several recommendations for reducing risk of contracting valley fever. Many of these risks may be lowered through increased cocci surveillance, stabilization of reporting methods, availability of satellite-based remote sensing and advances in dust storm modeling and prediction. New optimism about low cost, effective means of detecting *C. immitis* and *C. posadasii* in the soil (Sheff et al. 2010; Litvintseva et al. 2014; Hasan et al. 2014) opens the way to better define the geographical regions where cocci risks are higher, and where education, storm warnings and mitigation efforts may be most valuable. Too, *C. immitis* and *C. posadasii* thrive only in rather narrow climatic ranges (Kolivras and Comrie 2003a, b; Zender and Talamantes 2005; Comrie 2012), which informs us where potential changes in endemic areas may occur under conditions of climate variability and change. Enhanced cocci surveillance along with routine airborne dust forecasting will improve disease epidemiology and risk avoidance.

2 This Chapter's Focus on Airborne Dust and Human Health

There are, of course, other health effects of wind blown dust, one or two steps removed from this chapter's focus. They would include risks to aviation and highway safety, loss of arable soil and risks to food supplies, and to changes in fresh water storage and availability because dust accelerates melt of mountain snow and ice. Only aspects related to inhalation of airborne dust (and whatever hitchhikes with it) are addressed here.

In a world community of environmental and health scientists, health practitioners and service providers, we are far behind following through on the problem of airborne dirt from nature's back yard. Common wisdom says that inhalation of particulates of any kind is unhealthy, but the focus of research, engineering and service has rested on man-made particles, principally those emissions from industry, energy and transportation. Outdoor natural environmental conditions are difficult to deconstruct. The problem has appeared intractable, as we shall see in 2.1. In addition to the anthropogenic source pollutants, spores, bacteria, viruses, pollens and other organic particles are carried along with mineral dust (Prospero et al. 2005; Smith et al. 2011). They complicate the epidemiologists' world (Watanabe et al. 2011). So, to help those epidemiologists, the mechanisms for cause and effect, from inhalation of dust to negative health outcome, are under medical science scrutiny as well: Ghio et al. (2014), for example, show that human respiratory epithelial cells

respond biologically to desert mineral dust, an effect further confirmed in respiratory tract injuries in mice following dust inhalation. And Ichinose et al. (2008) show that mice, exposed intratracheally to mineral dust, particularly silicon dioxide (SiO_2), react with allergic inflammation in the lung— SiO_2 is common in Earth's crust, common in Arizona deserts, and commonly associated with sandstone and silica sand throughout the world.

2.1 *The Dust-Health Challenge*

Today, with negative health implications better understood, what can be done to stop emissions or avoid breathing this dust *from a third of the Earth's land surface*? These questions are rather intimidating. At first blush it appears the answer is “nothing,” because such huge scales are involved. Recall that Prospero et al. (2014) estimate more than 700 million tons of Africa's dust are transported annually across the Atlantic to the Caribbean and Central and South America—about half of the world's annual airborne desert dust. We think of most of the other half also coming from such vast, uncontrollable sources as the Taklimakan, Gobi, Atacama, Simpson and Mohave deserts. These questions, and the usual hesitations that follow, often justify low priority for this research. Nonetheless, after the last decade or two of investigation into these dust sources, development of observation tools and networks, and atmospheric models that mimic pick-up, entrainment and dispersion of dust, the answers are right before us. The once parallel lines of airborne-dust-focused health and environmental sciences may now be aimed to intersect in a global dust-health early warning system. With it, comes a wealth of information for the epidemiology, diagnosis and prevention of all airborne particulate-based illnesses around the world.

- Dust storms, their three dimensional plumes and downwind dust concentrations can be predicted, an opportunity to avoid harmful exposure
- Dust storms and their downwind concentrations can be simulated, an opportunity for epidemiological studies of health consequences when looking into the past ... or into the future under changing environmental conditions
- Satellite-based instruments identify, measure and follow dust plumes around the world, a means to warn of approaching trans-continental, global dust movement
- Surface-based remote sensing, a valuable complement to satellite instruments, identify and measure dust plume characteristics, a means to verify model forecasts and health consequences of exposure
- Atmospheric models calculate the back-trajectories of known hazardous plumes to identify their origins, an opportunity to control emissions
- Since dust emissions, even from the major deserts, are characteristically “point” sources, a few particularly hazardous ones may be controlled
- Global, regional and local infrastructures are available to warn of oncoming windblown dust, including weather services, broadcast media, and social networks paced by smartphone technology

- Global, regional and local health infrastructures are in place to respond to alerts and warnings, including the World Health Organization, the International Federation of Red Cross and Red Crescent Societies (IFRC 2013, 2014a, b), the Pan-America Health Organization, the Caribbean Public Health Agency, and public health service offices around the world.

3 Dust-Health Early Warning System—The Means

The underpinning for a Dust Health Early Warning System is available: in the medical, health, biological, and environmental sciences that currently demonstrate why airborne dust is a health hazard and how health risks may be reduced; in the current remote sensing and in situ environmental monitoring technology that reveal the truth of exposure; in the current skill of model forecasts and simulations; and in the infrastructure of current weather, health and information services that international, national and local missions provide. While nonexistent today, a D-HEWS could be assembled quickly from these components to serve global public health and medical communities.

3.1 Atmospheric Dust Modeling

Contemporary airborne dust forecast models can identify the time and place when blowing dust, or dirt, will cause air quality standards to be violated or will be a problem because of its content.

Zavisa Janjic (personal communication, Janjic 2013), in a lecture after receiving the prestigious International Meteorological Organization Prize for 2012, stated "... 10 km resolution medium range global forecasts and high resolution climate studies (are) possible with the NMMB (Nonhydrostatic Multiscale Model on B Grid)." This aim and thrust of research is another cause for optimism. We may relatively soon be able to go beyond the future-climate scenario-building of the Intergovernmental Panel on Climate Change (IPCC) and anticipate, in higher time and space resolution, local and regional dust-related health problems in future climates, not just for current climate conditions, as we do today. *Current* capabilities based on the Nickovic et al. (2001) dust regional model, DREAM, replicate all significant processes of dust mobilization, entrainment, dispersion and downwind wet and dry deposition (Nickovic 2002). In a forecast and simulation system in the U.S. Southwest that depends on state-of-the-science weather forecast models, such as the NMMB (Janjic and Gall 2012), and remote sensing technology and computer power, DREAM has demonstrated 24 to 36-h warnings of respirable dust concentrations on fine grid scales of under 4 km spatial resolution (Sprigg et al. 2014). This includes one

remarkable forecast of the American haboob (Fig. 1) that struck the U.S. city of Phoenix on 5 July 2011 (Vukovic et al. 2014). Epidemiologists, public health experts and dust modelers have participated in tests of dust model systems for application in public health (Morain et al. 2007, 2009, 2010; Sprigg et al. 2014). The field of study has progressed such that within the framework of the World Meteorological Organization (WMO) Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS), dust models are now being compared with each other, to see which model structures and their internal components and treatments prove best under different circumstances and conditions (Huneus et al. 2015).

Recall the potential health risks of very fine (SiO_2) Silica dust (Ichinose et al. 2008) mentioned in Sect. 2. The digitized global database of soil classification is improving (Nickovic et al. 2012) and, when used in model boundary conditions for dust forecasts or simulations, adds a critical parameter for estimating health risk. Harris and Roffers (2012) show how existing geologic and soils data can be used to estimate risk potential for Valley fever. While Fisher et al. (2000, 2012) describe optimum soil environment conditions for *Coccidioides* (*C. immitis* and *C. posadasii*), the soil-dwelling spores responsible for Valley fever (coccidioidomycosis, or cocci), Sprigg et al. (2014) demonstrate how this information can be used in forecast models to assess downwind valley fever risks. As a first-order estimate of cocci high-risk areas, following techniques described, for example, in Steinberg and Steinberg (2015), these and other spatially mapped data locate high-risk, current hot spots for potential cocci spores, which would then form the model boundary condition for *Coccidioides*-laden dust emissions.

3.1.1 Model Forecast and Simulation Verification

Model objective verification is essential for the credibility of every operational forecasting system. Well-defined and conducted verification helps in several ways: An informed user needs to understand the quality of the product; verification guides model development and forecast improvement strategies; and the statistics of verification allow comparison of models with other systems and different forecast methodologies. The latter is of much practical value when selecting the most appropriate forecast system for a given application; the “best” performer in one season or region of the world may not be the best in another season or region. Typically, one wants to know forecast scores, bias (mean error), mean absolute error, root mean square error, and correlation coefficient of surface dust concentration (PM_{10} and $\text{PM}_{2.5}$) and aerosol optical depth (AOD).

Verification of a dust forecast is challenging since surface observations of dust concentrations or low visibilities are not always located where the dust is occurring. Satellite observations over land also face problems such as high (and similar) reflectance for both dust aloft and soil below. The two vantage points for dust observations, space-based and surface-based, or in situ, are discussed next.

3.2 *Satellite-Based Remote Sensing*

Remote sensing from space-based platforms can identify and monitor dust sources and identify and track dust plumes as they drift around the world. Prospero et al. (2002) used satellite technology to identify preferential sources of dust. Morain et al. (2007, 2009) and Sprigg et al. (2008) applied NASA's Moderate Resolution Imaging Spectroradiometer (MODIS), which sees every part of the earth every one to two days, to monitor dust sources in the NASA projects, PHAiRS (Public Health Applications in Remote Sensing) and ENPHASYS (ENvironmental Public Health Application SYStems). The Short-term Prediction Research and Transition (SPoRT) Center at NASA Marshall Space Flight Center uses a MODIS Normalized Difference Vegetation Index (NDVI) to produce a high-resolution, real-time, daily map of areas covered (and not) by vegetation. It has been shown to improve model surface characteristics (Case et al. 2014).

However, when dust becomes airborne over the land from which it originates it is hard to see. Technology improved quickly (Walker et al. 2009; Ginoux et al. 2010) from earlier attempts (Mahler et al. 2006) in the American southwest desert to distinguish airborne dust from the sand and dust of the same colour as the surface below. These new data and analysis methods help identify "point" emission sources from sites that appear to prefer releasing soil to the wind, while areas surrounding them are less apt to do so. Certain of these preferential point sources may be small enough to control.

Aiming to develop satellite tools for public health, Estes et al. (2009) use space-based remote sensing to identify dust storms. Prasad et al. (2010) used satellite observations to study implications of Sahara dust transported into the Nile Delta. Researchers all over the world are using satellite sensors to detect and distinguish airborne smoke, anthropogenic aerosols, dust and other airborne particles. For example, with critical use of satellite observations, El-Askary et al. (2003, 2009) and Fetouh et al. (2013) shed light on the complex nature of windblown dust and anthropogenic pollution over Egypt and the Nile delta region.

Remote sensing technology continues to offer new tools for researchers as well as practitioners to see further, faster and more completely than ever before. Details of particle composition and distribution with altitude are now possible, for example, from instruments that depict a virtual slice or cross-section of the atmosphere as the satellite flies overhead. The CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) satellite, a French–American collaboration, provides such atmospheric profiles (Winker et al. 2004; McGill et al. 2007). Although it is relatively rare to catch a short-term event like an haboob, El-Askary was lucky! A CALIPSO flyby collected data which he analyzed for the date and time of the American haboob as it struck Phoenix on 5 July 2011 (Vukovic et al. 2014).

Satellites provide remotely sensed data from a maze of acronymned instruments useful in detecting and monitoring airborne dust, including the aforementioned MODIS twin sensors aboard NASA's Terra and Aqua satellites, the Visible Infrared Imaging Radiometer Suite (VIIRS) aboard the Suomi NPP (National Polar-orbiting

Partnership) satellite operated by the National Oceanic and Atmospheric Administration (NOAA), the Multi-angle Imaging Spectro-radiometer (MISR) instrument on Terra, the Ozone Monitoring Instrument (OMI) on the NASA Aura satellite, the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) sensor on CALIPSO.

Detecting bare soil, potential dust emission sites, is but one part of the solution to monitoring dust sources. When the ground is wet, sand and dust are not likely to become airborne. Dust forecasts depend on knowing when this may happen. While some numerical dust forecast systems (e.g. Nickovic et al. 2001) include damping of sources in the model forecast scheme, it is best to have verification, and perhaps even some reliance, on an observation. So, precipitation over potential dust emitting sources is important. Rainfall is measured from space in a collaboration of aerospace agencies from Japan, India, Europe and the U.S. One result is the Global Precipitation Measurement (GPM) Core Observatory satellite operated jointly by JAXA (Japan Aerospace eXploration Agency) and NASA. If you are still counting acronyms, here are three more: the GPM Imager (GMI), which maps precipitation across the land surface, the Dual-Frequency Precipitation Radar (DPR), which detects the intensity of snow and rain at Earth's surface, and NASA's Soil Moisture Active Passive (SMAP) mission, which maps soil moisture and whether the surface is frozen or thawed.

Technically sophisticated resources are globally available to forecast dust emissions and plumes. Most, if not all, dust researchers and forecasters take advantage of them, for example Liu et al. (2011) and Wang et al. (2011) for dust events over China and environs, and El-Askary et al. (2006) and Prasad and Singh (2007) who consider both space-based (MODIS) and surface-based (AERONET) remote sensing for insight on dust storm impacts over India. AERONET is discussed in following sections.

3.3 Surface-Based Remote Sensing and in Situ Observations

While space-based instruments, looking down, provide essential global coverage of Earth's environmental dust conditions, similar technologies, looking up, anchored on the surface, are critical as well. Weather radar and instruments that measure meteorological conditions from points around the world are operated by national weather services linked to global data networks coordinated through the WMO. They are invaluable in verifying weather and dust model forecasts. The WHO monitors air quality to assess risks to human health; data are provided from national networks that serve various purposes, including epidemiology and development and enforcement of air quality standards.

3.3.1 Upward Looking Remote Sensing

A number of short-term, even multi-year research projects use upward-looking remote sensing instruments such as ceilometers (used to measure cloud heights and aerosol concentration), hand held sun-photometers (instruments for measuring direct Solar radiance) and Lidars (Light Detection And Ranging) to measure vertical column characteristics of dust and other aerosols. Data from many of these projects are not immediately available and are generally unannounced and unknown until completion of the project and publication of the results. A Dust-Health Early Warning System cannot depend on these disparate projects for routine model forecast verification. On the other hand, governments have established surface-based remote sensing networks that are dependable, tested, and data-rich, with data easily accessed and widely used.

The Aerosol Robotic Network (AERONET) is a federation of cooperative observing sites around the world using sun-photometers, direct-beam solar measurements that provide daytime AOD (Aerosol Optical Depth) measurements on average every 15-min (Holben et al. 1998, 2001; Dubovik et al. 2000). Established by NASA and the *Centre National de la Recherche Scientifique* (CNRS), AERONET provides information on the optical, physical and radiative properties of dust and other aerosols in the atmosphere. The network is used extensively today as a complement to AOD measurements from space and in airborne dust model verification (WMO 2015). With approximately 400 sites in 50 countries on all seven continents, it is the world's largest ground-based network of sensors for aerosols.

The NASA Micro-Pulse Lidar Network (MPLNET) federated network of NASA and partners around the world measures aerosol (including dust) vertical structure continuously, day *and* night (Campbell et al. 2012). Lidar technology illuminates a target (e.g., a cloud of dust particles) with a laser, measures the distance to it, and analyzes the reflected light. Most MPLNET sites are co-located with AERONET sites. The networks provide vertical profiles of dust (and other aerosol) properties such as optical depth and particle size distribution (Campbell et al. 2010). MPLNET data are used to calibrate space-based lidars such as CALIOP/CALIPSO and to validate and help interpret measurements from NASA satellite sensors such as MISR (Misra et al. 2012). There were 17 active MPLNET sites reported in 2000 (Welton et al. 2001).

The European Lidar Network (EARLINET) provides ground-based information on the vertical distribution of aerosols over Europe. This included 27 stations in 16 countries in 2013 (Pappalardo et al. 2014; Biniotoglou et al. 2015). The network was initially a research project established in 2000 to build a multi-year, statistically significant, database of a three dimensional, temporal distribution of aerosols on a continental scale.

3.3.2 In Situ Dust Measurements and Monitoring

Near surface observations of dust concentrations reveal the quality of the air we breathe. How well these observations contribute to health surveillance, epidemiology and dust modelling depends upon their length of record, their continuity, and the extent to which they are part of a coordinated network with high standards of measurement. Dust forecasts and simulations are compared with these observations for quantitative assessment of model skill. However, particulate air quality networks vary across the globe. To address this issue, the United Nations Environment Programme, with the WHO, World Bank, WMO and other international partners are part of a Global Platform on Air Quality and Health, now in the process of developing tools and information for monitoring and assessing air quality and health consequences around the world (WHO 2008; UNEP 2015). For the purpose of this chapter's discussion, air quality networks of the United States, and the way in which the State of Arizona apply them, may serve as a model for the Dust-Health Early Warning System.

The U.S. Example of the Arizona Department of Environmental Quality (ADEQ) operates a network of ambient air quality instruments in order to meet Federal and State air quality requirements. The network exists, fundamentally, to answer the question: is Arizona in compliance with the National Ambient Air Quality Standards (Federal Register 2013) to protect public health and the environment? ADEQ's six PM_{2.5} and fifteen PM₁₀ monitoring sites include both filter-based samplers and continuous monitors located across the state. Filtered samples are analyzed for particle metal and chemical composition. The data from them become part of the US Environmental Protection Agency's Air Quality database (AIRNow, http://www2.epa.gov/aqs#_). Individual counties in Arizona also maintain measurement sites that become part of the State and Federal cooperative network. All conform to data management and quality assurance according to national standards.

These data become part of the Center for Disease Control and Prevention (CDC) Environmental Public Health Tracking Network (Meyer et al. 2006; Charleston et al. 2008). Not all U.S. States participate directly in the EPHTN. Arizona does not, for example. Sprigg et al. (2012, 2014) make a case for expanding the CDC network, at least to all western states, where epidemiological studies of windblown dust health impacts are starved for a longer and a more geographically dense record of PM measurements and disease surveillance.

The EPHTN aims for the ongoing assembly, integration, analysis, interpretation, and dissemination of environmental hazard, human exposure and health surveillance data (Meyer et al. 2006; Charleston et al. 2008). The CDC funds 26 state and local health departments to develop local tracking networks that contribute to the national network. English and Balmes (2004) and Wilhelm et al. (2008) give the example of California.

The ADEQ partners with more PM networks, increasing data access for all: the Chemical Speciation Network (CSN), the National Air Toxics Trends Stations

(NATTS), and the Interagency Monitoring of Protected Visual Environments (IMPROVE). The NATTS network is nationwide. The CSN is designed to determine trends in concentration of selected ions, metals, carbon species, and organic compounds in the PM_{2.5} samples. The CSN has about 200 sites nationwide. In 2002 there were 160 sites associated with IMPROVE, most located in the west (UC Davis 2002). The whole is, indeed, other than the sum of the parts.

Furthermore, it is common to cast a broad net for more data on particulate air quality. One example comes from the ADEQ Urban Haze Network, with high-resolution cameras, transmissometers and nephelometers that monitor visibility (ADEQ, Visibility Index Oversight Committee 2003). Vukovic et al. (2014) used Doppler RADAR images to define the three-dimensions of an American haboob. The RADAR's radio waves bounced off the dust particles to reveal a picture of the storm that verified the model forecast.

4 Global Partners in Public Health Applications: Dust-Health Early Warning System—The Opportunity

Epidemiology, medical science and clinical evidence confirm that airborne dust is a health risk. Science and engineering have developed the tools to avoid much of that risk. And, the infrastructure to apply these tools for a healthier world is embedded in the missions of international, national, and local agencies and nongovernmental organizations.

4.1 A Conceptual Framework

The globally successful (Famine Early Warning System) begun in 1985 by the U.S. Agency for International Development, is a model for risk reduction and avoidance (Brown 2008). Research based analyses over an international federation of partners, delivers early warnings of environmental hazards and risks to agriculture and food production. A D-HEWS (Dust-Health Early Warning System) for health services can begin where dust forecast and simulation models are quasi-operational today and where they can be implemented with the earliest and greatest gain. A case in point: the African Sahel and wherever the dust and sand from the Sahara may travel, including to neighbors around the Mediterranean and the distant Caribbean and Americas. On the other side of the world, Asian dust events are a consequence as far eastward as the U.S., and routinely affect nearby Japan, Korea and Taiwan.

4.1.1 Global Dust Movement

The WMO Sand and Dust Storm Warning Advisory and Assessment System (WMO 2015) is operational today with forecasts and simulations of dust plumes on the hemispheric scale, generally depicting the 3-D presence of dust, in varying degrees of optical depth (AOD) or particle concentration, around 50 km spatial resolution. The global networks of observation systems, both satellite- and surface-based, monitor dust sources and plumes in real-time, and provide real-world data for model verification.

4.1.2 Regional and Local Dust Exposure

The synoptic scale forecast of near surface $PM_{2.5}$ or PM_{10} concentrations is ready for validation in routine health and safety service operations (Sprigg et al. 2014). These forecasts, covering, for example, the entire SW United States, have spatial resolutions less than 4 km, fine enough to resolve thunderstorm dynamics and haboob-forming processes (Vukovic et al. 2014). Forecast skills will continue to improve from scientific advances, perhaps, for example, by Janjic's 10 km global forecast model, by an expansion of the lidar system MPLNET, or by faster computers.

Rudiments of the synoptic scale warning system have been tested through the NASA sponsored projects mentioned earlier in Sect. 3.2, PHAiRS and ENPHASYS. Both focused on dust storm emissions of particulates ($PM_{2.5}$ and PM_{10}), their public health and safety consequences in the Southwest United States, how such conditions and their downwind plume concentrations may be predicted, and how to communicate results and find community solutions engaging science, service and the public (Morain et al. 2007, 2009; Sprigg et al. 2008, 2012).

4.1.3 Transdisciplinary Information Exchange (TIE)

The D-HEWS is an opportunity to "go global" with an international version of the CDC's National Public Health Tracking Network (www.cdc.gov/nceh/tracking and www.ephtracking.cdc.gov). The NPHTN attracts the necessary talent in scientists, data managers and practitioners because it addresses a problem that everyone recognizes is important, each participant takes an essential role in a consensus plan, and accomplishments are documented and clear. The TIE for D-HEWS, adapted from the NPHTN structure, is envisioned a catalyst for assembling and distributing information on the sources and makeup of airborne dust, the observed and modeled airborne dust concentrations, and a clearinghouse for the scientific literature documenting potential human health risks.

4.2 Implementation

The WMO Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS), launched in 2007, responding to a request from more than forty countries to help address the health and safety issues surrounding windblown desert dust. From the system's implementation plan (WMO 2015), its purpose is to "... develop, refine and provide a basis for distributing to the global community products that are useful in reducing the adverse impacts of SDS and to assess impacts of the SDS process on society and nature." The WMO confidence in following through is undoubtedly based on many factors, including much improved, worldwide extent of environmental observations and dust measurements, advanced weather models, and the growing number of researchers attacking the problem.

A significant increase in airborne dust-related research publications (Stout et al. 2009), from 150 publications per year to 250 per year, roughly corresponds to greater access to in situ particulate air quality monitoring in the mid-1960s. The number of publications increased steadily to more than 500 per year in 1990, to approximately 900 per year in 1995. By 2012 the number jumped to some 7000 per year, as found in a *Google Scholar* search (WMO 2015) for "atmospheric dust Sahara" alone! Airborne dust forecast and simulation research from this author's team (e.g., Mahler et al. 2006; Yin and Sprigg 2010; Sprigg et al. 2008, 2012, 2014; Vukovic et al. 2014) and that of his contemporaries (e.g., Park and In 2003; Zhou et al. 2008; Grell and Baklanov 2011; Knippertz and Todd 2011; Pérez et al. 2006; Pérez García-Pando et al. 2014; Huang et al. 2015) has been stimulated in the 21st century by greater availability of in situ and space-based observations, computing power and advances in weather forecast modeling (e.g. Tanaka and Chiba 2005; Janjic et al. 2001, 2010; Janjic and Gall 2012; Adachi et al. 2013; Müller and Janjic 2015).

The goals and mission for the SDS-WAS welcome a D-HEWS: (a) delivery of information and technology along with local capability in their use, (b) receipt of information on local dust characteristics and health consequences, and (c) assessment of priorities for research and services. Its mission: enhance WMO Members' ability to deliver timely, quality sand and dust storm forecasts, observations, information and knowledge to users through an international partnership of research and operational communities (WMO 2015). In 2008, two SDS-WAS regional centres were established in China and Spain. A third node of cooperation that will complete global coverage for the System is under consideration for Pan America. Countries participating now in SDS-WAS number more than fifty (WMO 2015).

The WMO has integrated the SDS-WAS into other global, international infrastructure to add resources and greater assurance of long-term operational stability. The WMO World Weather Research Programme and the Global Atmosphere Watch coordinate the System jointly. In 2014, the World Health Organization (WHO) and the WMO formed a joint office to improve application of research, observations and knowledge of weather and climate in matters of global

environmental health. Thus, the mechanism exists for WMO and WHO collaboration in SDS-WAS to understand airborne dust contributions to air quality and human health for today and for future climates. From this collaboration, further ties to public health communities are virtually assured and include the International Federation of Red Cross and Red Crescent Societies the regional Pan-America Health Organization and the Caribbean Public Health Agency, and national and local public health service offices around the world. The charter of the International Federation of Red Cross and Red Crescent Societies (IFRC 2014a) is particularly apt, with a mission to build local capacity within high-risk and vulnerable communities (IFRC 2013) and support national societies to develop the “processes, systems and teams” for acting locally and linking globally (IFRC 2014b).

5 Conclusions: Best Practices in Technology Transfer, Capacity Building, Training and Education

Meiyan et al. (2015, p. 1) state intentions, or best practices, quite nicely for early warning weather systems in general:

Increased media coverage and a perception of an acceleration in the occurrence of disasters has led to a public outcry for better information that will permit individuals to act in time to save their lives, property and livelihoods from damage. Thus, over the last 50 years, governments and the public have shifted from wanting to know *what the weather will be* to wanting to know *what the weather will do* (to socio-economic systems). Both want to mitigate and reduce disaster risks.

Dust forecasts through the WMO SDS-WAS will, of course, help in real-time risk avoidance. And model simulations of past dust conditions add to the air quality period of record, to building the capacity for epidemiological studies and to a deeper understanding of weather related health issues. Satellite pictures and forecast displays are important for education and raising public awareness of potential risks. Mobile apps and other public media allow rapid transfer of information to and from the public, researchers and forecast operations. Information and technology transfer, training for product production and use, and measures for assessing progress in “capacity building” would be done through “cooperation projects” that have the big picture in mind, integrated within the SDS-WAS, and leveraging health NGOs, local and regional resources, the WHO, PAHO and other intergovernmental agencies. And, research will keep feeding the system with new ideas and improvements.

All the necessary resources to launch a global, coordinated Dust-Health Early Warning System are available. Organizing them into an operational, federated system will require participation of the agencies and institutions that fund and manage them—and a plan. The quickest path to launch is through the agencies and organizations with a global mandate, but all who are integral to the system should be present, at least figuratively, from the beginning. So, local, regional and

international health and environmental services will participate, as will medical, health and environmental sciences, without prejudice for either top-down or bottom-up guidance.

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