Dust in the wind:

Long range transport of dust in the atmosphere and its implications for global public and ecosystem health

Movement of soil particles in atmospheres is a normal planetary process. Images of Martian dust devils (wind-spouts) and dust storms captured by NASA's Pathfinder have demonstrated the significant role that storm activity plays in creating the red atmospheric haze of Mars. On Earth, desert soils moving in the atmosphere are responsible for the orange hues in brilliant sunrises and sunsets. In severe dust storm events, millions of tons of soil may be moved across great expanses of land and ocean. An emerging scientific interest in the process of soil transport in the Earth's atmosphere is in the field of public and ecosystem health. This article will address the benefits and the potential hazards associated with exposure to particle fallout as clouds of desert dust traverse the globe.

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Alexander von Humboldt, who Darwin referred to as "*the greatest scientific traveler who ever lived*", explained in "Ansichten der Natur" (1807), how dust particles could be taken up into the atmosphere after viewing wind-spout activity in the Orinoco basin of South America[1]. Darwin himself, while at sea off the west coast of Africa, noted dust covering the deck and equipment of the *HMS Beagle* and floating as a film on the ocean surface and hypothesized from the prevailing wind patterns that its source was Africa[1,2].

Figure 1, panel A, shows a dust devil lifting soil into the Martian atmosphere. Dust devils are small tornado like whirlwinds not associated with clouds and are typically occur in deserts or other hot environments where heated air forms vortices as it rises. While short lived and weak in comparison to tornadoes, dust devils can lift soils hundreds of meters into the atmosphere. It is interesting to note that Benjamin Franklin, who was fascinated by dust devils, gave chase to one on horseback in 1755[3].

"The rest of the company stood looking after it, but my curiosity being stronger, I followed it, riding close by its side, and observed its licking up, in its progress, all the dust that was under its smaller part."
Benjamin Franklin, in a letter to Peter Collinson, August 25, 1755

Figure 1, panel B, shows a wall of desert dust moving across the Sahara desert. Large storm events and/or high-speed winds cause this type of soil lifting, and it is these types of weather processes that are responsible for lifting a majority of desert soils into the atmosphere. In these types of dust events, it is not uncommon for soils to reach altitudes in excess of 10 kilometers. Figure 1, panel C, shows a large cloud of dust, approximately, 1700 miles off the

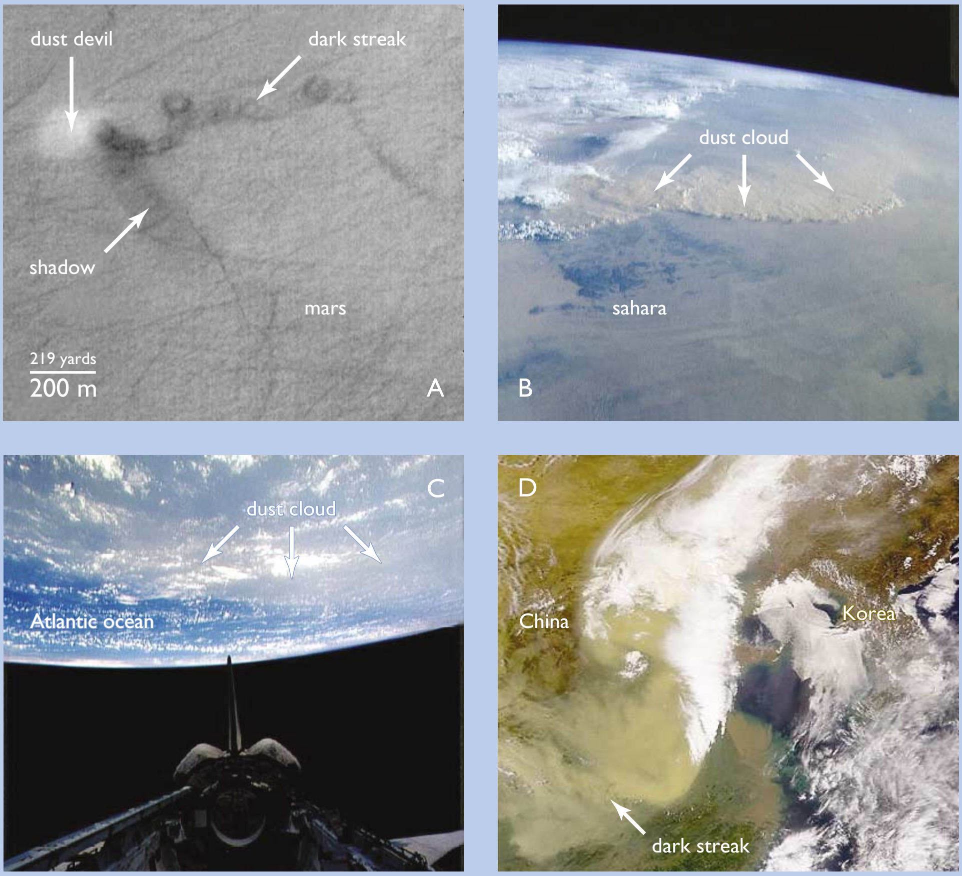


Figure 1 *A birdseye view of dust in the atmosphere of Mars and Earth.*

- Panel A *This image shows a Martian dust devil lifting shiny topsoil into the atmosphere and leaving a trail of exposed dark subsurface soil (dark streak) in its wake. NASA, Jet Propulsion Laboratory, Malin Space Science Systems – Mars Global Surveyor, Mars Orbiter Camera, Photo ID: MOC2-220-C. Pro methei Terra, taken on 11 December 1999.*
- Panel B *Dust Storm in the Sahara Desert in the vicinity of the Algeria/Niger border. NASA, Johnson Space Center Digital Image Collection – NASA Photo ID: STS049-92-071, taken on 16 May 1992.*
- Panel C - A *Saharan dust cloud moving across the Atlantic Ocean, approximately 1700 miles from the African Coast. NASA, Johnson Space Center Digital Image Collection – NASA Photo ID: STS043-96-002, taken on 11 August 1991.*
- Panel D *This dust cloud which can be seen moving off the east coast of China traveled across the Pacific Ocean and reached the west coast of the North America on 25 April 1998. Provided by the SeaWiFS Project, NASA/Goddard Space Flight Center and ORBIMAGE, taken on 16 April 1998.*

coast of Africa which was moving across the Atlantic Ocean towards the Caribbean and Americas. Dust clouds such as these frequently move across the Atlantic and impact the Caribbean, Central America and the SE United States between the months of June and October[4]. In the northern hemisphere's winter, the pattern changes, such that the dust impacts South America and Trinidad, with maximum dust flux between February and April[5,6]. A Saharan dust cloud the size of Spain was photographed over the Atlantic by NASA's SeaWiFS satellite on 26 February 2000 (http://seawifs.gsfc.nasa.gov/SEAWIFS/HTML/dust.html). Figure 1, panel D shows a large desert dust cloud moving towards the coast of China. This desert cloud crossed the Pacific in 9 days and impacted the west coast of North America. NASA's Earth-Probe TOMS aerosol index (Box 1) is one example of the current capabilities of remote sensing technology in tracking dust as it moves around the planet.

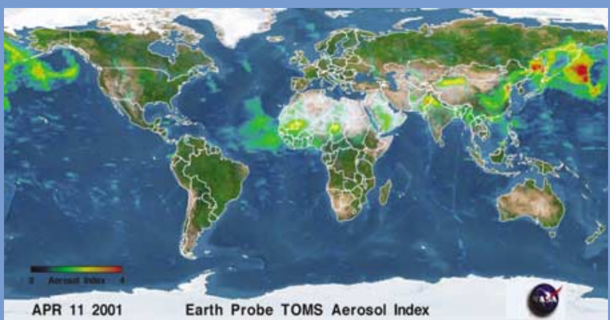
Estimates of the quantity of dust transported into the atmosphere have varied from 500 million tons annually (from all of the deserts combined), to as high as 1 billion tons annually from the Sahara and Sahel alone[7,8]. One of the primary benefits of global dust flux is that it may serve as a source of primary nutrients to nutrient depleted ecosystems. Desert dust has been identified as a significant source of primary nutrients (iron, calcium, etc.) to the oceans and it has been estimated that approximately 50% of the phosphorus transported to the oceans through the atmosphere comes from North African deserts[4,9,10].

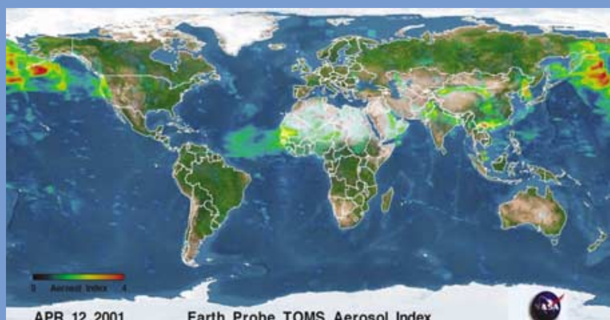
African desert dust fallout in the northeastern Amazon Basin has been estimated at 13 million tons per year with the majority of particle fallout occurring between the months of February and April[6]. These authors further point out that large individual dust events may deliver an estimated 480 million tons of dust to the region[6]. Research at the University of Miami has followed the Saharan dust flux on the Caribbean island of Barbados since 1965[11,12]. The noted increase in Saharan dust flux to the Caribbean and the Americas coincided with the onset of the current North African drought which began in the late 1960's[13]. One of the benefits of this dust transport is that many of the plants that live in the upper canopy of the South American rainforests derive their nutrients from the dust[5,6]. African dust has also been identified using element ratios (aluminum/calcium, aluminum/titanium, etc.) as an important source

Box 1

Panels A, B, C, and D are world-view images captured by NASA's Earth-Probe TOMS satellite. On April 11th, 2001 (panel A) an Asian dust cloud can be seen which extends from China to the west coastline of North America. In the next series of panels B (April 12th), C (April 13th) and D (April 14th) the Asian dust cloud can be observed moving onto and across the North American mainland. This desert dust cloud then continues to move off the east coast of North America, traversed the Atlantic Ocean and impacted Europe. These panels also show dust moving off the west coast of Africa and traveling across the Atlantic toward the Caribbean and South America.

There is currently a 20-year database of aerosol images produced by Total Ozone Mapping Spectrometer (TOMS) instruments. This database was compiled using two satellites equipped with TOMS, the first was the Nimbus-7, which operated between 1979 and 1993 and the second, the Earth-Probe which has operated since 1996. It should be noted that when the dust is confined to the boundary layer below 1 km, the standard Aerosol Index dust images may not show the presence of dust over a region. Most of the time, dust plumes are approximately 5 km from the sea surface, and are easily detected by TOMS. High resolution images that allow viewing of atmospheric dust below the boundary layer are available by contacting Goddard Space Flight Center. Images were captured at approximately 11:15am local solar time each day and are compliments of the Laboratory for Atmospheres, Goddard Space Flight Center, Greenbelt, MD. These images are retrievable from http://toms.gsfc.nasa.gov/. In addition to the available aerosol images, TOMS provides imaging and data on ozone, reflectivity and erythemal UV.





of parent material in Caribbean island soils, and provided the clay minerals needed for production of pre-Columbian Indian pottery on San Salvador island in the Bahamas[14,15].

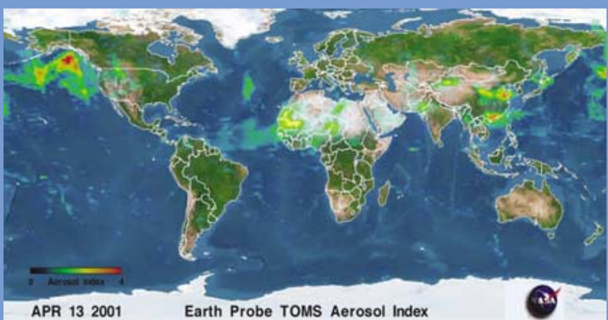
Analysis of data obtained during a 5 day Asian dust event which impacted Alaska in 1976 concluded that a similar event originating in Asian deserts could carry as much as 4000 tons of dust per hour into the Arctic[16]. Clouds of desert dust originating in the Gobi and Takla Makan deserts of Asia are capable of global dispersion. One of the benefits to the worldwide dispersion of Asian desert dust clouds is that they have been identified as sustaining Hawaiian rainforests growing in highly weathered soils by providing phosphorus to the ecosystems[17].

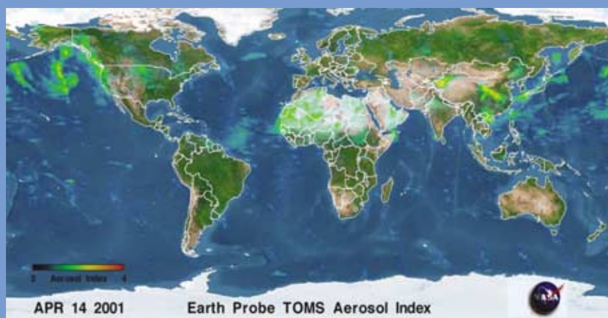
The GEOS 1 satellite observed a large dust storm over the American midwest on 23 February 1977, which obscured about 400,000 km^2 and was reported over the mid-Atlantic Ocean 2 days later[18]. Most of the satellite images of desert dust traversing the planet have typically originated from the continents of Africa, Asia and North America. While the deserts in these three continents do serve as a significant source for dust mobilization, satellite imagery has also shown significant dust activity originating on the continents South America and Australia. Considering the overall scale of dust movement in the atmosphere, it is surprising that there are only a few fragmented groups of scientists investigating the dust mobilization, atmospheric transport, atmospheric microbiology, and implications to ecosystem and human health which the impact of human activity has on the ever-evolving atmospheric dust budget.

Desertification: the human contribution

Desertification of semi-arid and arid lands occurs by both natural processes and human activity. Long term natural processes include continental drift (semi-arid regions are transported into arid zones over a period of millions of years) and climate shifts due to changes in atmospheric chemistry or the planet's orbit[19]. The Ice Ages of the Pleistocene Epoch in comparison to today's environment are good examples of climate variation. Low sea levels and arid environments are typical of ice ages. Just 14,000 years ago, at the end of the last glacial period, one could stand on dry land where Looe Key, Florida now exists (a popular dive and snorkeling site in the Florida Keys) and look down the slope of the Florida platform at the Gulf Stream flowing over 120 meters below its current level[20]. Ice core analysis has shown that during this period (~14,000 to 16,000 years ago), airborne dust was much more prevalent than in the previous 10,000 years (16,000 to 25,000 years ago)[21]. A good example of a short-term natural process is in the African Sahel where on a yearly scale, desert areas expand or contract depending on regional rainfall patterns[22].

Human activities that have contributed to desertification include farming and irrigation. It has been estimated that the planet loses over 10 million hectares (~29 million acres) of farmland per year to unsustainable farming methods[23]. One of the best examples of the impact of farming on desertification is the Dust Bowl Days of the 1930's in the American Midwest. The promise of nutrient-rich soil and get-rich-quick farming caused mass migration to the region. The resulting combination of vast tracts of farmland, detrimental agricultural





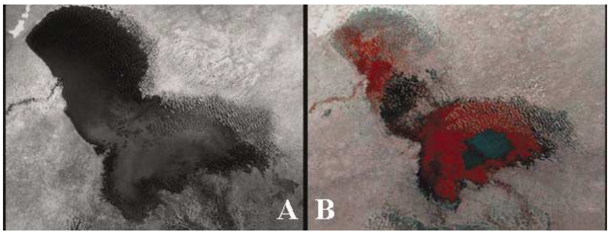


Figure 2 *Lake Chad, West Africa.*

The surface area of the lake was estimated to be approximately 25,000 km² in 1963. Current surface area estimates are approximately 1,350 km².

- Panel A *31 October 1963, Argon Satellite.*
- Panel B *2 January 1997, NOAA 14 AVHRR bands 2 1 1.*

Photographs obtained from: http://www.gsfc.nasa.gov/gsfc/earth/environ/lakechad/chad.html

practices such as part-time farming, and the onset of what turned out to be a 10 year drought, resulted in an ecological disaster that drove over ¼ of the population from the region.

"It covered up our fences, it covered up our barns,
It covered up our tractors in the wild and dusty storm.
We loaded our jalopies and piled our families in
We rattled down that highway to never come back again"
Woody Guthrie, The Great Dust Storm, Dust Storm Ballads, 1940

A Dust Bowl cloud that impacted Washington D.C. in 1934 was used by Dr. Hugh H. Bennett to help spur the United States Congress to pass the Soil Conservation Act of 1935. The purpose of the Act was to implement farming practices and other measures that would limit soil erosion by both winds and precipitation.

Another example of human induced desertification in the United States is the fate of Lake Owens, California. Lake Owens, which is located in southern California, had a surface area of approximately 280 km² in 1913, the year in which the City of Los Angeles tapped it as a source of water. By 1926 the only thing that remained was dry lakebed which has since served as a source of dust[24]. Estimates as high as 8 million metric tons being transported from this site into the atmosphere each year have been reported[25].

Desertification has affected Africa more than any other continent. Over 60% of the continent is composed of deserts or drylands, and severe droughts are common. Although much of the Sahara and Sahel has been in drought conditions since the late 1960's, the overall size of the desert did not change between the years of 1980 and 1997[22,26]. An area in Africa where desertification has been impacted by both nature and human activity, is Lake Chad (West Africa). Figure 2 shows two satellite images of Lake Chad taken in 1963 (panel A) and 1997 (panel B) respectively. The surface area of Lake Chad in 1963 was 25,000 km², and due to regional drought conditions and irrigation practices its surface area is now 1/20 its 1963 size (~1,350 km²)[27]. Fifty percent of the lake's surface area decline has been attributed to water diversion/irrigation[27].

The surface area of the Aral Sea (located within both Kazakhstan and Uzbekistan), which was the fourth largest lake in the world in 1960 (~68,000 km²)[28], has decreased approximately 50% over the last 30 years (1992, ~33,800 km²). This has been attributed to the irrigation schemes, which diverted river source waters for cotton production. Dust clouds originating from storm activity over approximately 27,000 km² of exposed seabed are common[28].

Another country that has significant desertification problems is China. Approximately 27.3% of China (2,622,000 km²) is affected by desertification. The average annual desertification rate was estimated at 2,100 km²/yr between 1975 and 1987[29]. Human factors such as population growth, deforestation (building, farming, firewood scavenging), and overgrazing have been identified as contributing to desertification in China[30]. A report from the US Embassy in Beijing (April of 1998) reported range wars between herders and farmers in the Ningxia Hiu Autonomous Region. Harvesting of grasslands by the farmers has been identified as the chief cause of desertification in that region. The report further stated that maps of severe poverty areas coincide with high population growth, desertification and environmental devastation (http://www.usembassey-china.org.cn/english/sandt/desmngca.htm).

Public health: the impact of airborne desert dust

The human lung is not designed to accumulate particulate matter. While evolution has provided us with a means to remove particulate matter from air (the hair and mucus glands in our noses), this defense system can be quickly overwhelmed when air contains high levels of particulates. Without regard to the constituents that may be associated with dust (herbicides, pesticides, radioisotopes, bacteria, fungi, viruses, etc.), soil alone can cause human disease. Silicosis is a disease caused by breathing sand quartz, a common component of desert soils. Inhalation of quartz soils can cause tissue scarring and fibrosis of the lungs. Symptoms of silicosis include shortness of breath, fever, fatigue, and in severe cases, the disease can be fatal. While this disease is usually associated with occupational exposure (mining, cement work, etc.), studies have shown that those individuals residing in silicate rich environments are at risk of developing the disease[31]. Exposure to quartz soils has also been implicated as a causative agent in lung cancer, autoimmune, and nonmalignant renal diseases[32]. The Centers for Disease Control reported 206 deaths in the United States due to silicosis in 1996[33]. The World Health Organization reported that approximately 24,000 deaths due to silicosis occur each year in China (http://www.who.int/inf-fs/en/fact238.html).

Due to widespread use of pesticides and herbicides in farming, airborne transport of toxin laden soils poses an additional threat to human health. In the town of Dashkhous located close to the Aral Sea, phosalone (an organosphosphate pesticide) concentrations in airborne dust were 126 mg/kg[34]. Hospitalizations and illnesses due to phosalone exposure have been reported[35]. Analysis of human breast milk collected from 92 women in southern Kazakhstan showed that the levels of beta-hexachlorocyclohexane (an organochlorine pesticide residue) were some of the highest concentrations published in scientific literature[36]. Additional research in the region found high concentrations of this pesticide residue and dichloro-diphenyl-trichloroethane compounds (DDT, banned in the United States in 1973 but still being used worldwide due to its effectiveness and low cost) in the blood of children[37]. Airborne transport of pesticide laden soils can also impact both surface and groundwater quality[38]. Transport of toxin laden soils to water supplies can impact the availability of drinkable water and result in the bioaccumulation and biomagnification of toxins in aquatic food sources.

Long range atmospheric transport of pesticides to the Arctic has been discussed, reviewed and demonstrated by numerous authors[39-41]. The Arctic is routinely impacted by clouds of desert dust originating from areas in Asia and Africa that use pesticides and herbicides to maximize crop yield and to counter threats to public health. Bioaccumulation of pesticides in Arctic animals is widespread and public health research has concluded that prenatal exposure to pesticide residue could pose a risk to the health of Inuit infants[42,43]. Additionally, desert dusts could also serve as a nutrient source in marine environments which could trigger the production of marine toxins via harmful alga blooms (red tides)[44].

Exposure to airborne microbes and biologically derived particulate matter can cause allergic responses. The National Institute of Allergy and Infectious Diseases identifies airborne dust as the primary source of allergic stress worldwide

Table 1 human airborne pathogens

agent	disease
bacteria	
yersinia pestis	the 'black plague' which killed off ¼ of Europe's population in the 14th century
bacillus anthracis	anthrax
mycobacterium tuberculosis	tuberculosis
legionella pneumophila	legionnaires' disease
bordetella pertussis	whooping cough
corynebacterium diphtheriae	diphtheria
chlamydia psittaci	psittacosis
haemophilus influenza *streptococcus pneumonia* *neisseria meningitidis*	bacterial flu, bacterial meningitis
fungi	
cryptococcus neoformans	cryptococcosis
aspergillus sp.	aspergillosis
coccidioides immitis	coccidiomycosis
histoplasma capsulatum	histoplasmosis
blastomyces dermatitidis	blastomycosis
virus	
rhinoviruses	the 'common cold'
Influenza viruses	viral flu
herpes virus -3	chicken pox
hantavirus	hantavirus pulmonary syndrome
poxvirus - variola virus	smallpox

(http://www.niaid.nih.gov/pulications/allergens/intro.htm). The World Health Organization estimates that between 100 and 150 million people suffer from asthma with an annual death rate of 180,000 (http://www.who.int/inf-fs/en/fact206.html). The majority of exposures to allergens occurs outdoors and research has shown that once sensitized to an allergen (e.g., fungal spores), small quantities of the allergen can elicit acute reactions[45,46]. Areas such as the Aral Sea and the Caribbean, where desert dust activity is common, have some of the highest recorded incidence of asthma on the planet[47,48]. Barbados has experienced a 17-fold increase in the incidence of asthma between 1973 and 1996, and acute asthma attacks accounted for 22.3% of emergency room visits at Queen Elizabeth Hospital in 1999[49]. This observed increase in incidence has coincided with the increased dust flux from the Sahara and Sahel to the Island[12]. 'Al Eskan Disease' which is also known as 'Desert Storm Pneumonitis,' is a human disease caused by inhaling desert soils which contains pigeon fecal material[50]. 'Desert Lung Syndrome' is another human disease associated with breathing desert soils[51]. Exposure to dust laden air containing endotoxins and mycotoxins, which are produced by gram-negative bacteria and fungi respectively, is known to cause disease and death[52,53]. Endotoxins are membrane components (lipopolysaccharide complex) of gram-negative bacteria that are shed into the environment during growth or released during death. Endotoxin exposure typically results in fever and respiratory stress. Mycotoxin is a general term used to define a wide group of molecules produced by many different species of fungi. Exposure to them can cause reactions that range from flu-like illnesses to death.

Table 1 lists some of the well-known pathogenic bacteria, fungi and viruses which are transmitted through airborne transport. Many of the fungi in Table 1 and viruses such as the Hantavirus are typically transmitted in dust. The World Health Organization has identified drought and dust storm activity in the sub-Sahara region of Africa as causing regional outbreaks of meningococcal meningitis. *Neisseria meningitidis*, the infectious agent, causes approximately 500,000 cases and 50,000 deaths every year (http://www.who.int/inf-fs/en/fact105.html). *Coccidioides immitis* is a human fungal pathogen, which causes a disease known as Coccidioidomycosis. The association of outbreaks of this disease with exposure to desert dust clouds in the Americas is well documented[54,55]. Infections with this pathogen range from asymptomatic to lethal in its disseminated form. Outbreaks of Coccidioidomycosis (also called Valley Fever) in Kern County (California) during the years of 1991 through 1993 cost an estimated 66 million dollars (U.S.) in medical expenses[56].

In addition to the obvious risk associated with exposure to pathogenic airborne microorganisms, exposure-response studies have shown that individuals who are exposed to non-pathogenic airborne microbes are at a higher risk of developing symptoms of disease than those who are not exposed[57]. Isolates of *Escherichia coli,* which is commonly used as an indicator of water quality, were found in both indoor airborne dust and outdoor settled dust in an air quality study conducted in Mexico City[58]. This finding suggests that pathogenic microorganisms that are fecal-oral pathogens may possibly pose a public health threat through airborne transport and contamination of food and water sources.

The current dogma is that most airborne pathogens are only transmitted over short distances, i.e. an individual acquiring the 'flu' or 'common cold' by inhaling aerosolized virus(es) from the sneeze or cough of an infected person. Although the transmission of Coccidioidomycosis or meningococcal meningitis through desert dust cloud exposure has been documented, it has only been shown to occur within the confines of a continent. An intriguing question arises: Can desert dust clouds move pathogens around the planet, and is there a limit to the type of airborne pathogen that can move in this manner?

Our laboratory is currently funded by USGS and NASA to investigate the possibility that microbes being transported across the Atlantic Ocean in clouds of African dust are reaching the Caribbean (St. John, US Virgin Islands) in a viable state. Most of the dust clouds originating in Africa take 5 to 7 days to traverse the Atlantic, and it was originally believed that exposure to UV light during the trip would inactivate any microbes present. Research to date has shown that the number of bacteria and fungi that can be cultured from air samples is more than 10 times higher when African dust is impacting the region than when it is not[59]. We now believe that the dust in the upper altitudes of dust clouds attenuates UV light, allowing microbes at lower altitudes to survive the trip[59,60]. Other factors which may effect

Figure 3 *Northern movement of African dust to the British Isles. This image shows a cloud of African desert dust moving off the West Coast of Africa and being transported north by a snaking wind current to the British Isles. This image was taken by NASA's SeaWiFS Satellite on February 13, 2001. Photograph obtained from http://seawifs.gsfc.nasa.gov/cgibrs/seawifs_browse.pl*

microbial survival in dust clouds include temperature and relative humidity. Movement of desert dusts over the lower latitudes of the Atlantic or Pacific Oceans would occur in atmospheric regions of moderate temperature and relatively high humidity, factors which would aid microbial survival. Using a nucleic acid stain to look at total microbes present in the samples (direct count assay), bacteria-like and virus-like particles were approximately 10 times higher during dust-events than during non-dust-events[59]. In comparing the cultivatable versus direct count data, less than 1% of the total microbial population present were recovered on the nutrient agar used for analysis. Microbial ecology studies have shown that a cultivation rate of 1% or less is typical in most environmental settings[61,62]. It is important to understand that microbes that did not grow on the nutrient agar used in our research might instead grow on a different nutrient agar or source (e.g. lung tissue). In short, the cultivable microbes that we have observed likely represent only a small percent of what is actually alive and capable of growth. Furthermore, microbial ecology studies have shown that in environmental samples the total viral population present is usually 10 to 100 times the total bacteria population[63]. This total viral population may be composed of viruses that infect bacteria, fungi, and animal cells. The direct count data demonstrate that viruses are present in the St. John dust-event samples, and the next phase of the study will employ molecular assays such as the polymerase chain reaction (PCR) to determine if any of a select number of the more prevalent pathogenic human viruses are present. Using ribosomal sequencing via PCR to identify the bacterial and fungal isolates collected in the Virgin Islands has shown that approximately 10% are opportunistic human pathogens and 25% are plant pathogens[59].

Ecosystem health

The effects of desertification on humans also extend beyond the primary consequences of airborne pathogens and pesticides, which affect us directly. There are the further ramifications of those pathogens which infect plants and animals we depend upon for food or which hold important ecological roles. The estimated economic damage caused by invasions of non-native plants, animals, fungi and microbes is over $138 billion per year[64]. Epidemics of infectious disease have been equated with the problem of invasive species, as both are a function of social and economic human interactions[65]. Many of these 'invaders' are unwittingly imported as a consequence of international trade and travel, however, there is an unknown percentage of microbes which 'book their own airfare'—are transported by the wind. There are a surprising number of reports of long-range transport of plant pathogens. The majority of these infec-

Box 2

Corals and coral reefs have declined throughout the Caribbean since the late 1970s. Significant changes occurred in 1983. These serial underwater photographs from Carysfort reef in the Florida Keys are typical of changes that occurred throughout the region over the past 30 years. The black and white photo was taken in 1960 and was part of a coral growth-rate experiment. The metal pins marked by the arrows on the photograph protrude 10 cm from the surface of the coral and were measured periodically to determine outward growth. In 1971 the same Brain coral was surrounded by a thicket of rapidly growing Staghorn coral *Acropora cervicornis*. By 1988 all of the Staghorn coral had died and the Brain coral had badly deteriorated. The reef remains in poor condition and has not recovered from the condition shown in the photograph taken in

tious invaders are fungi, whose dispersal spores provide protection from UV light and other harsh environmental conditions. Culturing of air samples and specific detection are relatively new developments, so in most cases the fungal diseases were tracked based on the geography of the outbreaks, prevailing winds, and timing.

The potato blight (*Phytophthora infestans*) which caused widespread famine in the 1800s is thought to have originated in Mexico or South America, and was then transferred to Europe via infected potatoes[66]. Once the fungus arrived in Europe, however, its rapid spread across the continent and to the British Isles is attributed to airborne transmission. This pathogen destroyed entire fields in a matter of days and rapidly spread downwind by releasing spores.

A 10-year, $25 million dollar Global Initiative on Late Blight (GILB) began in 1996 in response to the appearance and spread of new, more virulent, forms of this fungus[67]. This international collective of scientists hope to develop resistant strains of potatoes, thereby preventing or lessening the estimated $3 billion in crop losses occurring each year.

Another potato disease, 'potato blackleg' is a soft rot caused by the bacteria *Erwinia carotovora* and *Erwinia chrysanthemi*. These bacteria are dispersed by wind after being aerosolized by splashing raindrops, as well as being carried by insect vectors (another type of 'airborne' dispersion). These microbes have been detected in air samples in Scotland several hundred meters from potato fields, as well as on insects trapped near vegetable refuse dumps[68].

Lentils have been grown as a commercial crop in western Canada since the early 1970s, but the disease lentil anthracnose (*Colletotrichum truncatum*) was not seen until 1987[69]. Buchwaldt et al.[70] describe huge dust clouds generated by the harvesting machines, which they estimate contribute to the dispersal of *C. truncatum* spores over 240 meters distance. While they acknowledge the obvious role wind has played in the spread of the disease across the country, this report does not speculate on how the disease might have arrived in Canada. In building a case for wind dispersal, it is noted that seed infection by *C. trancatum* is very rare, and that transmission from seed to seedling is even less likely, if it occurs at all[70]. A review of lentil diseases also lists the origin of anthra-

1998. Examination during the 4 decades of observation showed that Staghorn death began in 1979 but peaked in 1983. This species, along with *A.palmata* (Elkhorn coral) and the reef urchin *Diadema* sp. suffered about 90 percent mortality throughout the Caribbean during 1983. One of the highest rates of recent African dust flux into the Caribbean occurred in 1983. In addition, a Caribbean-wide disease in Seafans caused by the soil fungi *Aspergillus sydowii* began in 1983. This species of fungi has been identified and cultured from atmospheric African dust collected in the Caribbean. For on overview of the potential threat of African dust to reef health in the Caribbean please visit http://coastal.er.usgs.gov/african_dust/

cnose as uncertain, for the above described reasons, and suggests that it may have been introduced with faba beans, as some species of the fungus also infect that crop[69]. Since lentil is a common crop in Asia, we speculate that the original spores may have been carried to western Canada in clouds of Asian dust, which seasonally blow across the Pacific[71].

Seasonal atmospheric transport of spores is known to occur in the Americas. The "*Puccinia* Pathway" describes the 'migration' of the fungal wheat pathogen *Puccinia graminis* from southern Texas and northern Mexico to the northern United States and Canada in the spring, and then back again in late summer and fall[72].

A series of blue-mold epidemics in United States tobacco were attributed to aerosol transport of *Peronospora tabacina* spores: Connecticut 1979-1980, North Carolina 1980, and Kentucky 1981-1982[73]. Trajectory-analysis models suggest the original inoculum came into America from the Caribbean.

Transoceanic transport has also been surmised for a number of other fungal plant pathogens. As water currents follow the wind, one common path for these microbes mirrors that of the historical slave route: Africa to the Caribbean to the Americas. A classic example of this is the spread of sugarcane rust (*Puccinia melanocephala*) in the late 1970s[74]. Retrospective calculations based on wind trajectories concluded that the fungal spores could have crossed the Atlantic from the Cameroons in Africa to the Dominican Republic in the Caribbean in as little as 9 days. Within a year of its establishment in the Dominican Republic, sugarcane rust had spread to both North and South America (Florida and Venezuela, respectively). Similarly, coffee rust (*Hemileia vastatrix*) is speculated to have traveled from Africa to Brazil within 5 to 7 days[75], which would be consistent with the pattern of winter dust storm movement. In one year (1933-34) the spread of banana leaf spot (*Mycospherella musicola*) was mapped as originating in Australia, then following a path to Africa and then to the Caribbean; a total of over 15, 000 miles[76]. There is also the possibility of transatlantic movement of the citrus canker pathogen *(Xanthomonas campestris or X. citrii), as Xanthomonas campestris* is one of the most widely recorded bacterial pathogens in Africa, and is found in 17 out of 20 countries including Sudan and Somalia[77].

There is less information available concerning the aerosol transmission of animal pathogens. Several studies of dust collected from surfaces on poultry, pig, and dairy farms have shown that the dust contained fungi such as *Aspergillus* and *Cladosporium*[78] as well as the bacterium, *Salmonella*[79,80]. Windblown desert dust carrying fungi caused an outbreak of aspergillosis in desert locusts[81]. A small study on the salmon pathogen *Aeromonas salmonicida* detected the bacteria in aerosolized spray up to 104 cm (over 21 feet—the length of the testing room), and hypothesized that it could easily travel further distances[82]. Meteorological data and molecular techniques were employed to determine the source of the pseudorabies virus (cause of Aujeszky's disease in pigs) after outbreaks occurred in Denmark in December 1988[83]. The evidence suggested the infections were a result of airborne transport of the viral pathogen from Germany[83].

The severity and economic impact of the recent and on-going battle against foot-and-mouth disease (FMD) in Great Britain merits this virus being discussed separately. Almost 2 decades ago, several numerical models were developed and tested to assess the risk of airborne spread of FMD within and to Great Britain[84-86]. The initial model, which was tested with data from past outbreaks, showed most airborne virus traveled no more than 10 km over land[84], although there were reports from Scandinavia that foot-and-mouth disease was being transmitted by air north from Germany into Denmark and later into Norway and Sweden (>100 km)[85,86]. Even incorporating that knowledge, it was thought highly unlikely that FMD virus would be able to cross the English Channel from France to Britain (a distance of 250 km). However, just a year later a series of outbreaks on the coast of France proved that longer transport was possible. Beginning March 4, 1981, there were 14 outbreaks in France (13 in Brittany and 1 in Normandy), followed by outbreaks directly across the Channel in England (Jersey and the Isle of Wight) on March 19 and 22[86]. Favorable meteorological conditions combined with the earlier models predicted spread to those exact locations. Biochemical analysis found no difference between the French and British viral isolates, which were all serotype O[86]. New models were developed which described a rare but not impossible set of circumstances which would allow airborne transmission of the virus over longer distances, and that those conditions were most likely to be met when the transport took place over ocean water rather than land[85,87].

The origin of the current epidemic is still being debated, however the British Ministry of Agriculture believe illegally imported meat to be the root cause of FMD introduction. We would like to propose another possibility, in light of the already documented cases of airborne transmission listed above. Satellite photos (see Figure 3) from February 13, 2001, show a tongue of Sahara dust curling up from the coast of Africa and blowing over the British Isles and parts of Europe that day and the next. The present foot-and-mouth-disease outbreak began on February 19, 2001, which is within the average incubation period of 3 - 8 days (the range is 2 - 21 days). There are seven serotypes of the FMD virus, and the strain infecting Britain is the same serotype as the prevalent strain in northern Africa (Type O). The largest previous outbreak in Britain (1967) also occurred in February, the time of year when wind patterns are most likely to cause African dust to blow north. It is furthermore worth noting that most of the Scandinavian outbreaks took place in February[87]. Finally, the type O serotype of FMD is endemic in South America, which receives tons of Saharan dust every winter, due to wind patterns. While no FMD virus has been isolated from African dust, nor molecular techniques used to compare the strain in Britain to those of northern Africa, we still believe this possibility should be considered, for future planning, if nothing else.

Least studied is the effect of airborne microbes on undomesticated animals. Recent news reports detail sudden infections befalling birds, prairie dogs, amphibians, dolphins, turtles, manatees, sea otters, seals, and corals[88]. A link has been proposed between the increased flux of African dust over the Atlantic, and the decline of the Caribbean coral reefs[89] (see Box 2). The strongest evidence in favor of this connection is the identification of *Aspergillus sydowii* as the infectious agent responsible for Caribbean sea fan mortality, isolating that same fungus from air samples of African dust, and then proving the fungal isolates from the air could successfully infect healthy sea fans[90].

Conclusion

What is most surprising is the lack of microbiological research in the field of planetary dust movement. Given our current state of knowledge and available tools we should have a much better defined understanding of the global transport of bacteria, fungi and viruses. Just from a microbial ecology perspective, the implications are fascinating. Long range movement and survival of microbes in the atmosphere should not be astonishing given that wherever we look we find them, whether it is around deep sea vents, in hot springs or in deep sub surface oil deposits. Several research papers were published after an African storm blew desert locusts from Africa to the Caribbean islands of Barbados and Dominica[91,92]. If a terrestrial macro-scale organism like a grasshopper can survive transoceanic transport, then so can the much more versatile, tolerant and adaptive microbes.

We know from our own work that bacteria (both spore-forming and not), viruses, and fungi are capable of traveling thousands of kilometers in the atmosphere in association with dust clouds, and that some of them are pathogenic. Both Asian and African dust clouds are routinely tracked by satellites as they move across continents and oceans. The potential for dustborne microbes to be transported to remote locations and establish new niches and infections may occur every second of every day. To quote a recent editorial in *Science*:

"We have made the globe a biological Cuisinart, and we will either have to deal with the consequences or use our scientific capacity to improve forecasting and monitoring."[65].

There is a clear need for research in the field of desert dust transport and its impact on human and ecosystem health, and the emerging field of dustborne microbiology. Hopefully, increased awareness of these processes will precipitate more interest from funding agencies, and allow the formation of global initiatives which can properly address the world-wide issue.

Acknowledgement

We would like to thanks Dr. Jay R. Herman of NASA for the TOMS images used in Box 1.

Keywords: Desert dust, atmosphere, human health, ecosystem health, infection, microbes

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Eugene A. Shinn, *a senior geologist with the United States Geological Survey, has a long history of tidal flat and coral reef research. He became interested in the effects of dust on coral reefs in the early 1990s when the usual causes of reef decline such as, deforestation, sewage disposal, oil spills, dredging, etc., did not explain simultaneous reef declines in far-flung parts of the Caribbean. Since 1996, Shinn has touted increasing flux of African dust to the Americas as a cause of many environmental ills including the severe decline in Caribbean reefs that began in 1983. Today he feels more strongly that long distance transport of toxins and pathogens in soil dust is a field too-long-ignored.*

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