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The Global Transport of Dust

An intercontinental river of dust, microorganisms and toxic chemicals flows through the Earth's atmosphere

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By some estimates as much as two billion metric tons of dust are lifted into the Earth's atmosphere every year. Most of this dust is stirred up by storms, the more dramatic of which are aptly named dust storms. But more than mere dirt is carried aloft. Drifting with the suspended dust particles are soil pollutants such as herbicides and pesticides and a significant number of microorganisms—bacteria, viruses and fungi. We can gain some appreciation of how much microbial life is actually floating in our atmosphere by performing a quick calculation. There are typically about one million bacteria per gram of soil, but let's be conservative and suppose there are only 10,000 bacteria per gram of airborne sediment. Assuming a modest one billion metric tons of sediment in the atmosphere, these numbers translate into a quintillion (10^{18}) sediment-borne bacteria moving around the planet each year—enough to form a microbial bridge between Earth and Jupiter.

A couple of years ago when we first presented our research showing that living microbes were transported across the Atlantic in clouds of African desert dust, we were greeted with two responses. Some people thought that it was impossible for bacteria, fungi and viruses to survive a week-long trip in the atmosphere without succumbing to ultraviolet radiation, a lack of nutrients and desiccation. Others responded with the opposite view, remarking that it had long been known that microbes were capable of surviving long-distance transport. This second group is, in fact, absolutely correct: Nineteenth-century scientists knew that microbes could be carried long distances on the wind, but somehow that knowledge was forgotten.

Today scientists are just beginning to grasp the impact and full extent of African dust fallout. It's been estimated that 13 million metric tons of African sediment fall on the North Amazon Basin of South America every year. A single, large dust storm may deliver more than 200 metric tons. And the Americas are not the only dustbins for African sediments. Dust storms originating in North Africa routinely affect the air quality in Europe and the Middle East. Reports of a fine red layer of African dust on automobiles and snow are not uncommon in Western Europe.

Unfortunately, the impact of the sediment can be measured in more than mere tonnage. For the past few years we've been measuring and identifying the microbes present in the Caribbean air during African dust events. It turns out that about 25 percent are species of bacteria or fungi that have been identified as plant pathogens and about 10 percent are opportunistic human pathogens (organisms that can infect people who have a lowered resistance). There is now good evidence that the fallout has had direct consequences on human health and the health of coral reef communities in the Caribbean.

Here we consider what we've learned about the airborne transport of sediment across the globe, and review some of the remarkable studies in this reemerging field that had it origins more than 100 years ago.

What's Old Is New Again

> *From the several recorded accounts it appears that the quantity of dust which falls on vessels in the open Atlantic is considerable and that the atmosphere is often rendered quite hazy; but nearer to the African coast the quantity is still more considerable. Vessels have several times run on shore owing to the haziness of the air; and Harsburgh recommends all vessels, for this reason to avoid the passage between the Cape Verd Archipelago and the main-land.*
> —Charles Darwin, 1846

A survey of the scientific literature in many fields will often reveal cycles of study, with certain ideas coming into vogue, then dropping out of common use, and then reemerging as if never considered before. The study of air-borne microbes and pollen—aerobiology, or more accurately aeromicrobiology—is one of those fields.

The study of microbes in the atmosphere can be traced back to the early 19th century, when some early reports linked these tiny organisms to airborne dust. The German biologist Christian Ehrenberg described microscopic objects he found in atmospheric dust, and later reported finding *infusoria*—a historical term used to describe microorganisms, in the same vein as animalcules—in a dust sample collected by Darwin aboard the Beagle. The connection between microbes and dust may have inspired the British botanist Miles Berkeley to conclude: "The trade winds, for instance, carry spores of Fungi mixed with their dust, which may have traveled thousands of miles before they are deposited."

Louis Pasteur proved that there were living bacteria and fungi in the air while testing air samples in the mountains, and he noted that their concentrations varied widely at different locations. Detailed studies of such atmospheric variability were carried out by the French scientist Pierre Miquel in late 19th-century Paris. He took daily air samples in downtown Paris and in a park five kilometers outside the city center. He found more bacteria and fungi in the city than in the park, as well as seasonal variations indicating that there were more microbes present at both locations in the summer. He even divided the bacteria into groups based on morphology: *Micrococcus* (little round ones), *Bacillus* (rod-shaped) and *Vibrio* (boomerang-shaped). These names are still in use today.

At about the same time, the German bacteriologist B. Fischer was taking hundreds of air samples while on board a ship cruising in the Atlantic Ocean, between the Cape Verde Islands, the Azores, Barbados and Trinidad. Although his method of analysis is not clear, he found the sea air to be largely sterile, except very close to land. However, he noted that bacteria might be conveyed far out to sea by terrigenous dust, which was known to travel all over the world.

By the turn of the century, scientists were trying to define the upper limits of microbial life in the atmosphere by taking samples from both tethered and free-floating balloons. One of these scientists, the bacteriologist H. Cristiani, was so stunned to find both bacteria and fungi in a balloon sample from 1,300 meters above Geneva that he attributed the microbes to contamination from the balloon.

The following decade saw several scientists in Germany experimenting at even greater heights in the atmosphere. C. Harz used an aspiration pump to inject air from heights of 1,500 to 2,300 meters through a sterile filter into a nutrient gelatin. He noted that, just as variability has been observed among microbes from different geographic locations, so too did different layers in the atmosphere have radically different concentrations of microbes. Harz isolated both bacteria and fungi, but being a mycologist, he concentrated on the fungi. He identified fungal genera—*Penicillium*, *Cladosporium* and *Aspergillus*—that are still known to be among the most common airborne microorganisms.

In 1908 German scientists found viable bacteria 4,000 meters over Berlin. All the bacteria were of the spore-forming varieties, and most were highly pigmented—two protective mechanisms that should help the organisms survive in the atmosphere. The following year M. Hahn reported that there seemed to be a correlation between the amount of bacteria and the amount of dust found in samples taken during balloon flights.

Capturing of atmospheric samples from airplanes began in the 1920s, and it was heavily used for several decades. The work was driven primarily by the need to understand the long-range transport of economically destructive plant pathogens, such as the fungal rusts. The focus on fungi was due to the pervasiveness of the diseases caused by the various rusts, but it was also believed that phytopathic bacteria could only be carried very short distances by the wind. A flurry of papers was published describing air samples taken by airplane from all over the United States, Canada, England and Russia. Most of these studies reported on samples collected at altitudes between 500 and a little over 5,000 meters. But a 1930s flight into the stratosphere, sponsored by the National Geographic Society, raised the upper limit for detecting viable bacteria and fungi to over 21 kilometers above the Earth.

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From our perspective, we were most curious about studies involving flights over the Atlantic Ocean, far from the influence of land but not necessarily far from dust. In

the mid 1930s Fred C. Meier, a scientist with the U.S. Department of Agriculture, recognized the need to trace the long-range transport potential of organisms that could cause disease in plants and animals. He felt that information about the distribution of these pathogens in the atmosphere was critical to a well-planned control program. Up to this time, airplane samples had been taken only over land—there was no way to be certain how far the fungal spores had traveled from their original source. So Meier convinced Charles Lindbergh to take samples during a flight from Maine to Denmark, over uninhabited stretches of ice, water and mountains, which were unlikely to have significant fungal populations. The samples, which were taken by exposing sterile oil-coated microscope slides directly to the air by way of a long metal arm extending from the plane, contained some interesting catches. Meier identified a variety of fungal spores, pollen, algae, diatoms and insect wings from Lindbergh's samples taken over the North Atlantic. The results convinced him that "the potentialities of world-wide distribution of spores of fungi and other organisms caught up and carried abroad by transcontinental winds may be of tremendous consequence." Encouraged, Meier then enlisted the cooperation of the Army, Navy, Coast Guard and commercial airlines to sample air masses over the Caribbean Sea and Pacific Ocean. This promising and ambitious program was dealt a serious blow by Meier's untimely death in a 1938 plane crash during fieldwork.

Up to this point, all the data collected by airplane were qualitative—it was sufficient merely to find and identify airborne microorganisms. It was now time to start making actual counts, to attach some numbers to the variability. The first quantitative high-altitude study over the Atlantic was conducted by the Canadian scientists Stuart Pady and C. Kelly in the 1950s. Their sampling flights crossed the North Atlantic, from Montreal to London, during June and August of 1951. This corresponds to the African dust season in the Caribbean and the southeastern United States. They found that microbial concentrations depended more on the origin of the air mass being sampled—whether it was tropical or polar—than on the geographic location where the sample was taken. Tropical air was found to contain nearly 100 times more fungal spores than polar air.

This is essentially where the field stayed for the next 40 years. Most studies pertained to fungal spores and ignored bacteria. This may seem odd, because the German scientists Lange and Jochimsen discovered in the 1920s that inestimably large numbers of bacteria are carried along with dust into the atmosphere. And scientists in the 1930s and 1940s recognized that some bacteria could survive light, a range of temperatures and lack of moisture in the atmosphere. The long-range transport of these bacteria was both theorized and deduced from their presence in Antarctica. All of these findings were essentially forgotten or ignored.

As others have speculated, perhaps there was a perception that the long-range airborne transmission of bacteria had an insignificant effect on human health and the economy. Most of the serious transmissible agricultural diseases are caused by fungi, and the few studies done on the downwind dispersal of bacteria from concentrated sources, such as sewage treatment plants and harvesters, found that the range seldom exceeded a kilometer. Because there was no known process that could inject a large bacterial inoculum into the atmosphere, there seemed little reason for further study.

A Giant Inoculum

A process that could transfer enormous numbers of microorganisms into the atmosphere was identified in the late 1990s, when satellite images revealed the astonishing magnitude by which desert soils are aerosolized into giant clouds of dust. The energy for this massive launch into the atmosphere comes from rapidly moving high-pressure systems and storms that produce powerful winds. Once carried aloft, the sediments and their tiny inhabitants are swept along by the whims of atmospheric circulation patterns, often settling many thousands of kilometers from their site of origin.

The Sahara and the Sahel regions of North Africa, which have been in a drought since the late 1960s, are believed to be the most significant sources of airborne sediments. The Sahara desert covers the Republic of Mali's northern half, and the semi-desert lands of the Sahel stretch south toward Guinea and Burkina Faso. Unfortunately, the nature of what is borne aloft is also affected by cultural practices in the region.

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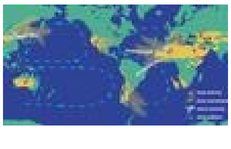

Although it is culturally rich, Mali is economically poor. Basic sanitary facilities are lacking, and the Niger River, which flows through thousands of kilometers of Mali's arid lands, is the repository for all types of waste, including animal feces and excreted pharmaceuticals that are used against a broad spectrum of human diseases. Once a year, the river deposits a load of fine sediment on the floodplain, along with whatever else it carries. People plant crops in small garden plots on the newly deposited soil, add pesticides, and burn garbage to fertilize the soil. Traditionally, the garbage consisted of animal and plant waste, but in the past two decades its composition has changed to plastic products and rubber tires. Hundreds of small fires burn day and night, creating black smoke and releasing plasticizers, polyaromatic hydrocarbons and dioxin, and concentrating heavy metals. These combustion products readily adsorb to the clay soil particles, which are then advected into the atmosphere by strong winds. The small particles also adsorb chemicals from the atmosphere—other pesticides, combustion products and cosmogenically produced radioactive isotopes.

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All of these particles, chemicals and microbes eventually land somewhere. Joe Prospero, of the University of Miami's Rosensteil School of Marine and Atmospheric Sciences, has been recording the amount of dust that is transported to the Caribbean and the Americas since 1965. He's found a direct correlation between the worsening African drought and an increase in the amount of dust landing on the Caribbean and the Americas. Prospero's research group has also cultured numerous colonies of bacteria and fungi from the atmosphere over the island of Barbados, noting that their concentrations increase sharply with increasing concentrations of African dust in the region.

Kevin Perry of San Jose State University has also noted a distinct pattern in the distribution of the African dust as the prevailing winds shift with the seasons. From June through October most of the African sediments land on the Caribbean and North America, and from November through May they fall on South America.

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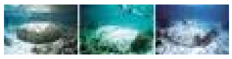

Other scientists have been studying the prevailing wind patterns to determine the routes of various infective agents from Africa to the Caribbean and the Americas. Among the crop pathogens that make their way across the Atlantic are those that cause sugar cane rust *(Puccinia melanocephala),* coffee rust *(Hemileia vastatrix*) and banana leaf spot *(Mycosphorella musicola)*. The Caribbean-wide sea-fan disease agent *Aspergillus sydowii* is also found in the Caribbean atmosphere during African dust events. Sea fans and other coral reef organisms have experienced a steady decline since the late 1970s. We expect that future research will show that many other coral diseases are spread by dust from both Africa and Asia.

The pathogens notwithstanding, the dust itself has complex effects on plant life in the Western Hemisphere. On the one hand, the iron-rich African dust serves as a nutrient for plants in the upper canopy of the South American rain forest. But this airborne fertilizer has also been implicated as a cause of algal blooms in Florida's coastal waters by the red tide agent *Karenia brevis.*

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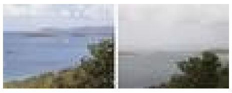

The African dust events also have a direct effect on human health. African dust is reported to be a vector for the meningococcal meningitis pathogen *Neisseria meningitis* in sub-Saharan Africa. Outbreaks of meningitis often follow localized or regional dust events, and these typically result in many fatalities. Across the ocean, a number of investigators are currently studying a possible link between African dust events and high rates of asthma in the Caribbean. For example, there has been a 17-fold increase in the incidence of asthma on the island of Barbados since 1973, which corresponds to the period when the quantities of African dust in the region started to increase.

Some of the dust particles are so small that once they are inhaled into the lungs they cannot be exhaled. Anything present in the dust is also carried deep into the lungs, close to the capillary beds. What might be the effects on human health? Consider that some of the contaminants are endocrine disrupters (pesticides and polyaromatic hydrocarbons), some are carcinogens (dioxin and radioactive isotopes) and others are simply toxic to cells (heavy metals).

Not Merely Out of Africa

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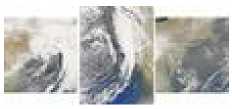

The deserts of Asia are also a significant source of airborne sediments during spring in the Northern Hemisphere. In April of 2001 a large dust cloud originating in the Gobi Desert of China moved eastward across the globe, crossing Korea, Japan, the Pacific (in five days), North America (causing sporadic reports of poor air quality in the United States), the Atlantic Ocean and then Europe. The progress of this event was captured in the daily aerosol images made by NASA's Earth Probe TOMS (Total Ozone Mapping Spectrometer). (See http://toms.gsfc.nasa.gov/aerosols/aerosols.html. Images from April 11 to April 14, 2001, show the cloud moving over the Pacific.)

Desertification on the perimeters of China's deserts between 1975 and 1987, which was attributed to overgrazing, deforestation and less-than-optimal farming practices, was estimated to take place at a rate of 2,100 square kilometers per year. An estimated 4,000 metric tons of Asian desert sediments per hour impact the Arctic during large dust storm events. Transport of pesticides and herbicides into the Arctic from farming regions along the perimeter of the Asian desert regions is common. These chemicals have been identified in animal tissues and in human breast milk among the indigenous populations in the Arctic.

Dry lake beds also serve as a source of airborne dust because of the small particle size of their sediments in comparison to most terrestrial sediments. Lake Owens in southern California, which the city of Los Angeles drained after tapping it for drinking water in 1913, has a dry lake bed area of approximately 280 square kilometers. Each year about 8 million metric tons of lake-bed sediment are transported into the atmosphere.

Lake Chad in North Africa, which had a surface area of 25,000 square kilometers in 1963, is now merely one-twentieth that size (about 1,350 square kilometers) as a result of prolonged drought and diversion of water for agriculture. Human activity near the lake has contaminated the surface sediments, and we believe that these can be transported to the Caribbean and the Americas.

The Aral Sea, which had a surface area of about 60,000 square kilometers in 1960, is now less than half its original size because of the diversion of source waters for agricultural purposes. The formation of dust clouds over its seabed during a storm is common, and high concentrations of pesticides and herbicides have been reported in airborne sediments. Exposure to these regional dust storms has resulted in illness and hospitalization, and DDT residues have been found in human breast milk.

How High? How Far? How Much?

> *I always thought the most significant thing that we ever found on the whole. . . Moon was the little bacteria who came back and lived and nobody ever said [anything] about it.*
> —Apollo 12 Commander Pete Conrad (1991), on isolating viable cells of *Streptococcus mitis* from Surveyor 3, which had been sitting on the surface of the moon for over two and a half years

From a microbiologist's perspective, one has to ask whether there is a limit to the distance and the altitude that microbes can travel (and survive) in the Earth's atmosphere. In the late 1970s, Soviet meteorological rockets equipped to take high-altitude air samples demonstrated that cultivable fungal spores can be found as high as 77 kilometers above the Earth's surface. The Soviet scientists exposed these pigmented fungi to a battery of harsh conditions, including ultraviolet rays, low temperatures, repeated freezing and thawing, and high vacuum levels. The fungi survived all of these insults. One of the project's microbiologists, A. A. Imshenetsky, also noted that a greater number of microbes are found in the mesosphere after a dust event than during normal atmospheric conditions.

Michael Zolensky of NASA's Johnson Space Flight Center in Houston, Texas has told us that pollen grains have been found at altitudes between 17 and 19 kilometers during high-altitude flights that were ostensibly designed to collect extraterrestrial sediments falling on the Earth.

Our research group at the U.S. Geological Survey's Center for Coastal and Regional Marine Studies in St. Petersburg, Florida, has documented an increase in the numbers of airborne microorganisms in the U.S. Virgin Islands during an African dust event. During normal atmospheric conditions we can culture about 0.01 colony per liter from 200 liters of air. During an African dust event the numbers of cultivable microbes may rise more than 10 times—above 0.1 colony per liter at the same sites.

Using a nucleic acid stain (or direct-count assay) to count the microbial populations in these air samples reveals that the cultivable bacteria represent only 0.1 to 1.0 percent of what's really there. In other words, there are many more organisms present that are either dead or can't grow on the nutrient agar, which is used for analysis. This is a common trend noted in studies of microbial ecology. The direct-count assay also demonstrates that virus-like particles are present in these samples, and one of our current research objectives is to characterize and identify this fraction of the airborne microbial community.

It is obvious from historical and current research projects that microorganisms and microscopic particles of biological origin are transported to great heights and over great distances. It should not be surprising that microorganisms can tolerate the stresses associated with long-range transport in Earth's atmosphere, because microbes are the most tolerant and adaptive organisms on the planet. It's been suggested that a shielded Bacillus spore (hiding in the crevasse of a sediment particle) could survive interplanetary or even interstellar transport!

An Air Bridge

At this point we are just stepping through a door into a wide-open area of research. It's clear that sediments from one continent can be transported over vast distances in the atmosphere and affect the air quality nearly halfway around the globe. What are the implications of this planetary process? Can pathogenic microbes transported in dust from one part of the planet to another account for sporadic outbreaks of disease? What types of disease-causing microorganisms can survive long-range atmospheric transport? Can these microbes successfully compete with the indigenous microbial community and become established? Can harmful chemicals transported thousands of miles around the planet impact the health of ecosystems?

These are but a few questions from a list of many, and they demonstrate the depth of our ignorance. It is important to recognize that the knowledge in this field is based on occasional point samples and not on continuous surveys. The results are affected by many factors, including location, altitude, season, weather, wind and the methods used to collect the samples. Understanding the potential ramifications of atmospheric transport of hazardous material and organisms may have fundamental importance for the health of a society. There is an air bridge that spans the great oceans, and we haven't been paying much attention to it.

Dust Sickness

A scorching drought and formidable winds during the 1930s "Dust Bowl" devastated the southern plains of the United States. The catastrophe spurred politicians to enact legislation, and it inspired photographers and folk singers to record the dramatic event in images and song.

An eyewitness account from a Kansas wheat farmer gives a sense of what it must have been like:

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> Since breathing is unpleasant even indoors while a dust storm is at its height, people sought relief through wearing wet cloths over their faces.... But the practice soon proved to be a dangerous one.... The constant breathing of damp air, aggravated by the dust, frequently led to pneumonia, with many deaths resulting.
>
> ... The dust I had labored in all day began to show its effects on my system. My head ached, my stomach was upset, and my lungs were oppressed and felt as if they must contain a ton a fine dirt.
>
> —Lawrence Svobida
> *An Empire of Dust*
>
> *A dust storm hit, an' it hit like thunder;*
> *It dusted us over, an' it covered us under;*
> *Blocked out the traffic an' blocked out the sun,*
> *Straight for home all the people did run,*
>
> —Woody Guthrie, 1940
> "Dusty Old Dust (So long it's been good to know yuh)"

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