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Reviews

Dust Storms and Their Impact on Ocean and Human Health: Dust in Earth's Atmosphere

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Abstract: Satellite imagery has greatly influenced our understanding of dust activity on a global scale. A number of different satellites such as NASA's Earth-Probe Total Ozone Mapping Spectrometer (TOMS) and Sea-viewing Field-of-view Sensor (SeaWiFS) acquire daily global-scale data used to produce imagery for monitoring dust storm formation and movement. This global-scale imagery has documented the frequent transmission of dust storm-derived soils through Earth's atmosphere and the magnitude of many of these events. While various research projects have been undertaken to understand this normal planetary process, little has been done to address its impact on ocean and human health. This review will address the ability of dust storms to influence marine microbial population densities and transport of soil-associated toxins and pathogenic microorganisms to marine environments. The implications of dust on ocean and human health in this emerging scientific field will be discussed.

Key words: long-distance transport, dust storm, aerobiology, pollution, microbiology

Introduction

> The dust falls in such quantities as to dirty everything on board, and to hurt people's eyes; vessels even have run on shore owing to the obscurity of the atmosphere. It has often fallen on ships when several hundred, and even more than a thousand miles from the coast of Africa, and at points sixteen hundred miles distant in a north and south direction.
>
> —Charles Darwin (1987)

The largest sources of dust to Earth's atmosphere are the Sahara and Sahel regions of North Africa and the Gobi, Taklamakan, and Badain Juran deserts of Asia. The current estimate for the quantity of arid soil that moves some distance in Earth's atmosphere each year is 2 billion metric tons (Perkins, 2001). Fifty to 75% of this quantity is believed to originate from the Sahara and Sahel (Moulin et al., 1997; Perry et al., 1997; Goudie and Middleton, 2001; Prospero and Lamb, 2003). While the Sahara/Sahel, Gobi, Taklamakan, and Badain Juran deserts are the dominant sources of soil to Earth's atmosphere, other regions of known dust storm activity include the arid regions of the continental United States (the Great Basin), Central America, South America (Salar de Uyuni), Central Australia, South Africa (Etosha and Mkgadikgadi basins), and the Middle East (Washington et al., 2003; Zhang et al., 2003). In general, high-energy storm activity over arid regions can result in the mobilization of significant quantities of soils into the atmosphere (Gillies et al., 1996; Qian et al., 2002).

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The Sahara and Sahel regions of North Africa serve as a source of dust to Earth's atmosphere throughout the year. Desert soils originating from this vast landscape can impact air quality in the Middle East, Europe, the Caribbean, and the Americas. The major source areas of dust in the Sahara include the Bodele depression and a region covering western Mali, southern Algeria, and eastern Mauritania (Goudie and Middleton, 2001; Middleton and Goudie, 2001). Although the overall size of the Sahara and Sahel regions of North Africa have not changed significantly during the last 24 years, the region has been under drought conditions since the late 1960s (Tucker and Nicholson, 1999). Annual rainfall rates in the Sahara and Sahel are influenced by atmospheric systems such as the North Atlantic Oscillation (NAO) and El Niño Southern Oscillation (ENSO). The NAO pressure system has been in a predominately positive (northerly) phase over the North Atlantic Ocean since the late 1960s which has corresponded with an overall decrease in rainfall over North Africa (Moulin et al., 1997). This has also corresponded with a general increase in the amount of African desert soil being delivered to the Caribbean and Americas (Prospero, 1999). Compared to the overall trend in dust deposition noted in the Caribbean, some of the highest deposition rates have corresponded with major El Niño events (Prospero and Lamb, 2003; Prospero and Nees, 1986). While dust transport out of North Africa may move north into the North Atlantic, Europe, and northwest into the Middle East at various times of the year, the most consistent transport is trans-Atlantic to the Caribbean and Americas (Fig. 1) (Perry et al., 1997). Trans-Atlantic dust transport generally occurs between latitudes 15° and 25° North (Graham and Duce, 1979). In the Northern Hemisphere summer (June through October), dust transport is to the mid-to-northern Caribbean and North America, and during the winter (November through May), transport is to the mid-to-southern Caribbean and South America (Graham and Duce, 1979). An intense dust storm impacting the Canary Islands between January 5–10, 1999, resulted in a estimated 175 million dollars (Euros) in road, harbor, and crop damage (Criado and Dorta, 2003). On January 7, 1999, during that same dust episode, a "blood rain" deposited an estimated 47 metric tons of dust on the Island of Terefe (Criado and Dorta, 2003). It has been estimated that 13×10^6 metric tons of African dust are deposited in the Amazon Basin each year (Swap et al., 1992).

Unlike the Sahara and Sahel regions of North Africa, which generate dust storms throughout the year, dust

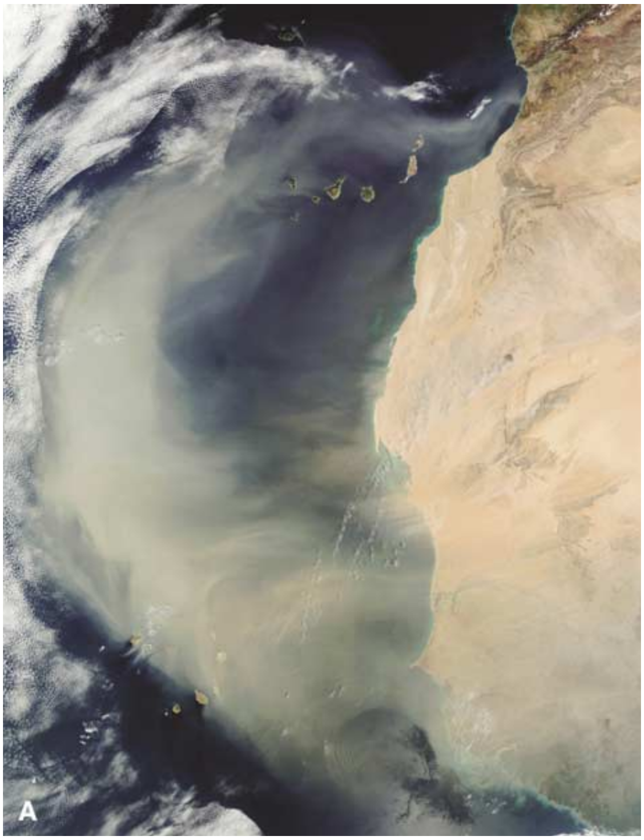

Figure 1. Dust storm moving off the West Coast of Africa, March 2, 2003. Image credit: Jacques Descloitres, MODIS (Moderate Resolution Imaging Spectroradiometer aboard National Aeronautics and Space Administration [NASA]'s Terra spacecraft) Rapid Response Team, NASA/Goddard Space Flight Center (GSFC). Visible Earth (VE) Record ID: 25150.

storm activity in the deserts of Asia are seasonal, with the majority of atmospheric transport occurring during the spring (February to May, Fig. 2) (Xiao et al., 2002). While Asian dust generation is seasonal, significant quantities are generated for global dispersion in the Northern Hemisphere. For example, isotopic composition identified Asian dust atmospherically deposited in the French Alps during an Asian dust event in 1990 that moved across the Pacific, the North American Continent, and then the Atlantic Ocean (Grousset et al., 2003). The Asian deserts are a significant source of airborne particulate matter to the Arctic with large dust events capable of moving an estimated 4000 tons per hour into the region (Rahn et al., 1977). In March of 1986, during a large Asian dust storm event, "giant" silica particles (> 75 μm) were detected in atmospheric and water-column samples at a site in the North Pacific that was > 10,000 km from their point of origin (Betzer et al., 1988). Trans-Pacific transport of particulate matter from

Asia to the Americas during the Asian dust season is well documented (Jaffe et al., 2003; Wilkening et al., 2000). A large dust event impacting the west coast off North America in 1998 reduced solar radiation levels by 30–40% and left a chemical fingerprint of deposited dust extending inland to the state of Minnesota (Husar et al., 2001). Asian dust activity has increased over the last 20 years, which is attributed to both climate change and desertification (Zhang et al., 2003). Between 1975 and 1987, the desertification rate in China was ~ 2100 km^2 per year (Zhenda and Tao, 1993).

Exposed lake beds provide significant sources of dust in and regions. Lake Owens, California, a drinking-water source for the city of Los Angeles since 1913 (then a surface area of 280 km^2) was drained dry by 1926 (Reheis, 1997). Lake Owens is now the dominate source of dust in the continental U.S. (Gill and Gillette, 1991). Lake Chad, located southwest of the Bodele depression in North Africa, had a surface area of 25,000 km^2 in 1963 that was reduced to a surface area of approximately 1350 km^2 by 1997 due to the current North African drought and to anthropogenic activity (Coe and Foley, 2001). Between 1960 (~ 68,000 km^2) and 1992 (~ 33,800 km^2), the surface area of the Aral Sea was reduced by approximately 50% due to the diversion of source waters for irrigation (Micklin, 1988). Dust storms originating from this exposed sea bed (~ 27,000 km^2) occur frequently (Fig. 3) (Micklin, 1988).

Some of the emerging questions in dust deposition to the oceans are: 1) What is the impact of dustborne nutrients on marine microbial communities? 2) How does this relate to general ecology questions associated with ecohealth (niche displacement and harmful algae blooms)? 3) What is the impact of dustborne toxins such as agricultural chemicals and industrial emissions on marine ecohealth? 4) What are the implications of dustborne microorganisms to downwind ecosystems?

Fertilization of the Oceans

> Environmentally iron occurs in two oxidation states, ferrous iron (Fe^{++})and feric iron (Fe^{+++}). Because of its greater solubility, ferrous iron is more readily available to the cell. The oxidized or ferric form that predominates in aerobic environments is less soluble and occurs primarily as insoluble precipitates. Thus, to obtain ferric iron, many aerobic microorganisms produce iron-binding, or chelating, proteins that render iron soluble and transport it into the cell.
>
> —VanDemark and Batzing (1987, p. 136)

The potential role of soluble (bioavailable) nutrients (particularly iron) as a limiting nutrient in marine waters drew interest in the early 20th century (Gran, 1931; Hart, 1934; Harvey, 1938). In the late 1980s and early 1990s, a number of iron fertilization ("Iron hypothesis") experiments demonstrated the influence of bioavailable iron (Fe^{2+} versus Fe^{3+}) on oceanic primary productivity (Martin et al., 1991, 1994; Behrenfeld et al., 1996). An iron fertilization study in which iron was added to a number of different marine surface waters resulted in increased phytoplankton growth rate two-to-three times background values (Martin et al., 1991). Research has also addressed the influence of aeolian iron on marine primary productivity rates in the iron-limited waters of the North Pacific (Barber and Chavez, 1991; Pahlow and Riebesell, 2000; Young et al., 1991). During the Asian dust season of 1986, a major increase in primary production was noted following desert dust deposition at an oceanic site in the North Pacific (Young et al., 1991). Those authors further noted that the iron content of the dust was ~ 10–15% of the total mass and that if only a fraction of that was soluble (~ 10%), it would have supported the observed increase in production (Young et al., 1991). Analysis of late Paleozoic icehouse algal bioherms (western equatorial Pangaea) and aeolian dust deposits illustrated a temporal and spatial relation between the two (Soreghan and Soreghan, 2002). In vitro dissolution experiments demonstrated that iron dissolved from Saharan dust can increase primary productivity rates, "especially in oligotrophic water" (Bonnet and Guieu, 2004). An eastern Atlantic north–south transect study of surface water and atmospheric nutrients illustrated a correlation between mean dissolved surface-water iron concentrations and Saharan dust deposition rates (Sarthou et al., 2003). Sediment trap studies in the Sargasso Sea and North Atlantic demonstrated the ability of Saharan dust to impact surface-water chemistry (Jickells, 1999). In Mediterranean Sea surface waters, it was shown that the bioavailable fraction of iron associated with Saharan dust deposition was capable of sustaining maximum primary production rates (Ozsoy and Saydam, 2001). Dissolved iron increased to 0.8 nM after dust deposition in Mediterranean surface waters, illustrating the significance of Saharan dust in the Mediterranean iron cycle (Guieu et al., 2002a). Remote-sensing gear detected an increase in surface-water biomass after a Gobi Desert dust storm traversed a site in the North Pacific (Bishop et al., 2002).

In support of the "Iron hypothesis," data obtained from Antarctic ice cores showed that historical periods of high aeolian dust transport resulted in increased primary productivity rates and a subsequent reduction of atmospheric carbon (Ridgwell, 2003). Those authors attributed approximately one-third of temperature variability during intraglacial periods to dust movement in Earth's atmosphere (Ridgwell, 2003). A climate shift between 1972 and 1976 resulted in a fourfold increase in atmospheric dust deposition to iron-poor marine environments (Hayes et al., 2001). Another climate change study found that population flux of dimethylsulfide (DMS) producing phytoplankton in the equatorial Atlantic may be influenced by nutrients delivered in clouds of Saharan dust (Henriksson et al., 2000). Those authors proposed that high DMS (which can serve as a cloud nucleus) production rates could result in greater albedo and thus cause global cooling (Henriksson et al., 2000). Atmospheric dust may have many effects on global climate.

Other nutrients that can be delivered to marine environments via desert dust transport include phosphorus and nitrogen. Approximately 1×10^{12} g of phosphorus are atmospherically delivered to the oceans each year (Graham and Duce, 1979). The proportion of phosphorus that is water soluble ($\sim 2.2 \times 10^{11}$ g per year) represents $\sim$ 10% of that delivered through river transport from the continents (Graham and Duce, 1979). Analyses of aerosols in Miami (FL), Barbados, and the Cape Verde Islands found that oceanic influx of soluble potassium from African dust events was probably negligible, while calcium influx may represent $\sim$ 10%, relative to river transport (Savoie and Prospero, 1980). Biomass burning south of the Sahara was identified as contributing to NO_3^- and SO_4^{2-} being transported across the Atlantic in clouds of Saharan dust (Talbot et al., 1990).

Research in the Mediterranean Sea noted that Saharan dust is the source of 30–40% of atmospherically delivered phosphorus and is the main source of dissolved iron (Guieu et al., 2002b). Another project demonstrated that dust storm-derived inorganic phosphorus and nitrogen could support $\sim$ 15–70% of new primary productivity in the southeast Mediterranean (Herut et al., 2002). A relation between organic nitrogen and Saharan dust events was recently documented along the Turkish Mediterranean coastline (Mace et al., 2003). Two large Saharan dust events accounted for $\sim$ 30% of the total annual atmospheric dust load in the eastern Mediterranean Sea (Kubilay et al., 2000). The authors of that study argued the need for long-term, high-frequency sample studies to characterize dustborne transport of nutrients to marine environments. Such characterization would allow better determination of the influence of dust on marine microbial population flux (Kubilay et al., 2000).

An emerging concern in coastal environments is the ability of desert dustborne nutrients to trigger harmful algal blooms (Fig. 4). A Saharan dust event in July of 1999, which was tracked and observed to impact southwest Florida marine waters by utilization of remote-sensing technology, resulted in a 100-fold increase in *Trichodesmium* levels (a marine microbe that converts inorganic nitrogen to organic nitrogen, i.e., nitrogen fixation) (Lenes et al., 2001). Those authors speculated that if all the dissolved organic nitrogen detected during that bloom (three–fourfold the pre-bloom level) was converted to urea and ammonia, the nitrogen could have sustained the red-tide bloom (caused by the marine dinoflagellate *Karenia brevis*) observed in October of 1999 (Lenes et al., 2001). Saharan dust deposition of associated bioavailable iron has also been identified as a nutrient source for diazotrophic cyanophyte (photosynthetic nitrogen-fixing microbes) growth, which in turn provides nitrogen needed to sustain harmful algal blooms in the eastern Gulf of Mexico (Walsh and Steidinger, 2001). Long-range atmospheric transport of nutrients in clouds of desert dust has also been implicated as a causative agent in the increased frequency of toxic blooms caused by *Pseudo-nitzschia* spp. (a diatom) (Mos, 2001).

The implication of the research outlined to this point is that desert dust movement over ocean waters may affect marine population change at the microbial level in both short and long time frames. This is particularly important in oligotrophic waters such as those found in reef environments and in remote nutrient-depleted areas of the open ocean. With regard to reefs, corals have evolved to thrive in nutrient-depleted waters via symbiosis, and slight shifts in nutrient levels can affect reef health (via niche displacement, i.e., rapid unchecked growth of algae) whether the phenomenon is part of a natural cycle or the result of anthropogenic impact (i.e., desertification, runoff, etc.) (Shinn et al., 2000; Hallock et al., 1993). Desert dust has been implicated as a causative source of stress to coral reefs (Garrison et al., 2003; Shinn et al., 2000). The ability of dust to fuel blooms of harmful algae can affect marine microbial diversity and coastal health through massive kills of marine

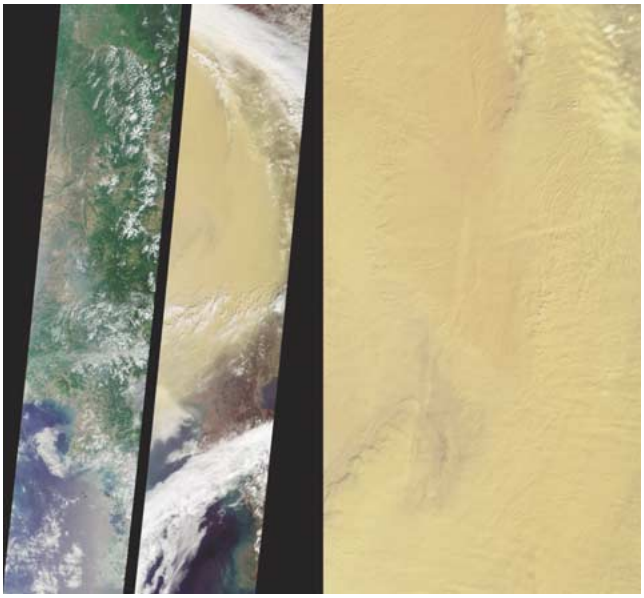

Figure 2. Dust storm over China and Korea. **Left image**: clear atmospheric conditions, July 9, 2000. **Middle image**: a huge dust storm impacts the same region, April 7, 2001. **Right image**: a close-up of the same dust storm, April 7, 2001. Image credit: NASA/GSFC/Langley Research Center (LaRC)/Jet Propulsion Laboratory (JPL), MISR (Multi-angling Imaging Spectroradiometer nadir-camera aboard NASA's Terra statellite) Team. VE Record ID: 7869.

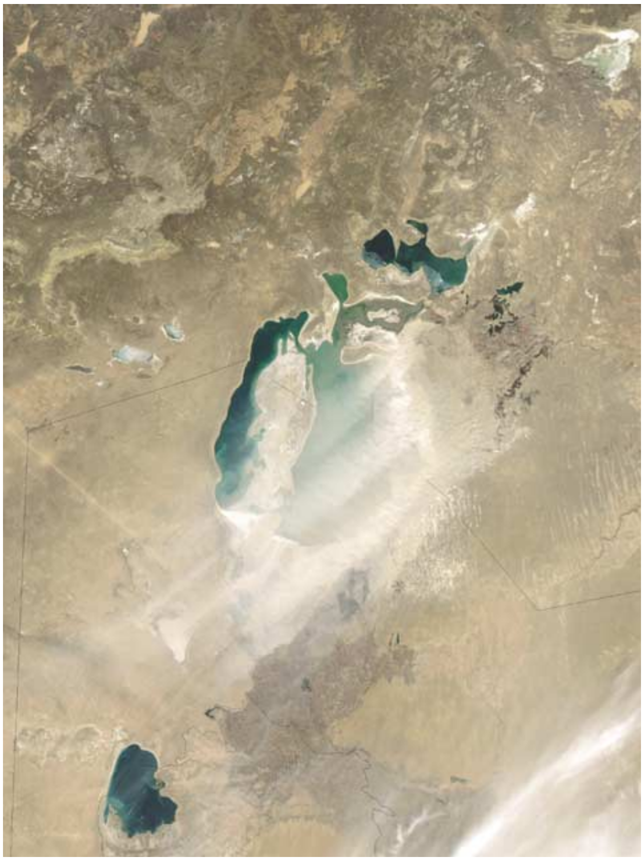

Figure 3. Dust storm over the Aral Sea (located between Uzbekistan and Kazakhstan), April 18, 2003. Image credit: Jacques Descloitres, MODIS (aboard NASA's Aqua spacecraft) Rapid Response Team, NASA/GSFC. VE Record ID: 25324.

organisms. Harmful algal blooms can also impact human health via recreational and aerosol exposure and consumption of contaminated seafood. Harmful algal blooms offshore of coastal communities or in fisheries can also have a severe impact on economic health (Burkholder and Glasgow, 1997; Tester and Steidinger, 1997).

Health Implications of Airborne Soils and Soil-associated Toxins

> There's so much pollution in the air now that if it weren't for our lungs there'd be no place to put it all.
>
> —Robert Orben, U.S. Humorist

Exposure to airborne soils and pollutants is known to cause adverse health effects (Peters et al., 2001; Prahalad et al., 2001; Somers et al., 2002). Desert dust collected in Kuwait in 1991, 1992, and 1995 was found to cause cellular membrane and DNA damage (Athar et al., 1998). In another Kuwait study, atmospheric dust samples containing post-oil-fire pollutants were shown to inhibit host immune responses (Ezeamuzie et al., 1998). Exposure to desert dust combined with organic matter was observed to cause opportunistic infections of the lung (Korenyi-Both et al., 1992). A study involving 850 school children in the United Arab Emirates found an asthma prevalence rate of 13.6% and an allergic prevalence rate of 72.9% (Bener et al., 1996). Analysis of these data using logistic regression identified dust storm exposure as one of the significant predictors of these illnesses (Bener et al., 1996).

Allergic reactions can arise from exposure to airborne fungal and bacterial spores in dust. In addition to the microorganisms themselves, microbial molecules such as endotoxins (membrane lipopolysaccharides shed by Gram-negative bacteria) and fungal mycotoxins can trigger respiratory stress (Braun-Fahrlander et al., 2002). Areas heavily impacted by desert dust, such as the Aral Sea and the Caribbean, have some of the highest incidences of asthma in the world (Bener et al., 1996; Howitt, 2000). A study in Barbados documented a 17-fold increase in the incidence of pediatric asthma from 1973 to 1996, with

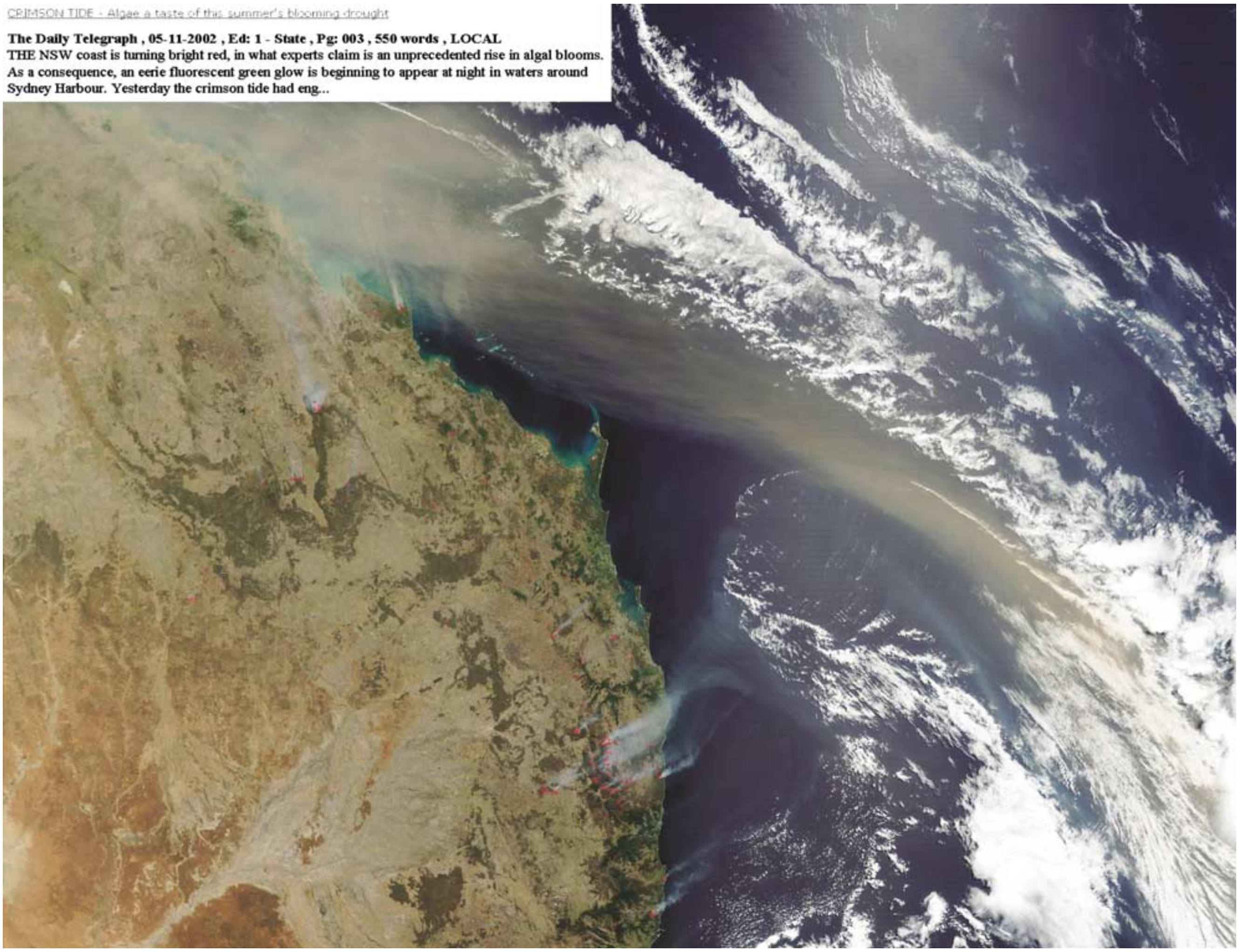

Figure 4. A dust storm that originated in central Australia moves out over the Coral and Tasman Seas, October 23, 2002 (El Niño year). Red dots on image mark active fires. Base image credit: Jacques Descloitres, MODIS (aboard NASA's Aqua spacecraft) Rapid Response Team, NASA/GSFC. VE Record ID: 20295. Newspaper clipping from the Daily Telegraph reporting an algae bloom in and around the waters of Sydney Harbor, November 5, 2002.

incidence rates of 18–23% (Howitt, 2000; Howitt et al., 1998). Blades et al. (1998) continue to investigate the relation between African dust and asthma on Barbados, but thus far their data do not suggest a direct link. Those authors have hypothesized that the microbial component of the dust maybe more important in triggering asthma, and therefore numbers or types of microbes may correlate to asthma incidence more clearly than total dust concentrations. More recently, researchers in Trinidad have completed a retrospective ecological study that links increased hospital visits for pediatric asthma to African dust events (Gyan et al., 2002). The statistical analysis for that study incorporated a lag time between the dust event and the hospital visit, something not accounted for in the Barbados study (Gyan et al., 2002). Prospero (1999) found that significant fractions ($\sim$ 50%) of respirable dust particles in South Florida during the summer months are African in origin. That author further noted that South Florida receives $\sim$ 2.5 times less African dust than values observed at a dust monitoring site on Barbados (Prospero, 1999).

In Turkmenistan, respiratory disease is a significant health problem, causing $\sim$ 50% of childhood disease (O'Hara et al., 2000). Dust deposition rates in that study were determined using dust traps and ranged from 50 to 1679 kg per hectare (O'Hara et al., 2000). Those authors found pesticides associated with the dust/soil particles and reported that the highest concentration observed was 126 mg of Phosalone kg^{-1} of dust (O'Hara et al., 2000). Phosalone is a known human toxin and highly toxic to aquatic organisms http://www.pesticidinfo.org/Detail_Chemical.

jsp?Rec_Id=PC33413) (O'Malley and McCurdy, 1990). A human health study conducted in the same region (Kazakstan) found organic pesticides in almost all of the human breast milk and serum samples analyzed (Hooper et al., 1997). Those authors implicated dust storm activity around the Aral Sea as one of the sources of exposure (Hooper et al., 1997). Dewailly et al. (2000) concluded that prenatal organochlorine exposure may be a risk factor for acute otitus media in Arctic Inuit infants. A number of studies in the Arctic have demonstrated a wide distribution of pesticides and herbicides in marine surface waters, soils, the atmosphere, and animals (terrestrial and marine), and have implicated long-range atmospheric deposition from Eurasia as the likely source (Burkow and Kallenborn, 2000; Chernyak et al., 1996). Other toxins that have been identified in atmospherically delivered dust include arsenic and radioisotopes. Holmes and Miller (2004) estimated that ~ 20% of atmospheric arsenic deposition in the southeastern United States is African in origin. In a Saharan dust "red rain" event in Greece on April 9, 2000, researchers found radioactive particles (Cesium-137, a beta-emitting mutagen) of Chernobyl origin (Papastefanou et al., 2001).

Dust Delivers Pulses of Microorganisms

> [Louis Pasteur's]... theory of germs is a ridiculous fiction... How do you think that these germs in the air can be numerous enough to develop into all these organic infusions? If that were true, they would be numerous enough to form a thick fog, as dense as iron.
>
> —Pierre Pochet, Professor of Physiology at Toulou, *The Universe: The Infinitely Great and the Infinitely Small*, 1872

Large clouds of desert dust also carry a sizable inoculum of microorganisms—bacteria, fungi, and virus-like particles. As a rough approximation, a conservative estimate of 10^4 bacteria per gram of soil and 1 million tons of airborne soil moving around the atmosphere each year, amounts to 10^{16} dustborne bacteria (this estimate does not include the prevalent populations of fungi and viruses). Recent counts of viable microbes from small-volume (< 200 liters) air samples collected in Africa (Kellogg et al., 2004) and the Caribbean (Griffin et al., 2001a; Griffin et al., 2003) during dust events indicate that hundreds of bacteria and fungi, particularly spore-formers, are capable of surviving airborne transport of considerable distances (transoceanic). Total direct counts from the Virgin Islands (Griffin et al., 2001a) found bacterial numbers an order of magnitude higher than what was culturable and also detected viral-like particles in the samples. Earlier reports documented long-distance aerosol transport of plant pathogens, particularly fungal rusts, since the 1930s (reviewed in Griffin et al. 2001b). Among the microorganisms identified from dust events in the Virgin Islands, 25% were plant pathogens and 10% were opportunistic human pathogens (Griffin et al. 2001a). From similar samples collected during dust events in Mali (West Africa), 10% of the bacteria identified were animal pathogens, 5% were plant pathogens, and 27% could be characterized as opportunistic human pathogens (Kellogg et al., 2004).

In our work to date, many of the microbes we have identified from air samples taken during dust events are similar or identical to known soil bacteria or fungi. However, many are also similar or identical to isolates previously characterized from aquatic environments. It has been argued that samples collected from the Caribbean may include marine bacteria that have been aerosolized by wave action (Blanchard and Syzdek, 1970; Zobell and Mathews, 1936) and incorporated into the dust cloud as it crossed the Atlantic ocean. However, these "marine" bacteria have been identified in samples collected in Bamako, Mali, which is hundreds of miles inland and upwind from the ocean (Kellogg et al., 2004). An early study of aerosolized terrestrial versus marine bacteria found that many soil bacteria were euryhaline (tolerant of a wide range of salt concentrations) suggesting that they could survive in sea water (Zobell and Mathews, 1936). Given the versatility of microbes, and the little that is currently known about microbial biogeography, this should not be surprising. The question then becomes whether these microbes, many of which appear to be tolerant of the marine environment, can become established after being deposited in the ocean. Are they able merely to survive or can they reproduce? Are they capable of competing for a niche with the local microflora? No work to date has conclusively answered these questions, but several avenues of research suggest that that the answers may be yes.

In recent decades, there have been increasing numbers of reports of marine diseases and epidemics, affecting a wide range of organisms including plants, invertebrates, and mammals (as reviewed in Harvell et al., 1999). Attempts have been made to connect these disease outbreaks with either anthropogenic impacts or climate change

(Harvell et al., 1999; Hayes et al., 2001). Of particular interest is the connection among dust, iron, microbes, and climate change. Hayes et al. (2001) have postulated that the iron in desert dust, in addition to triggering harmful algal blooms, may also trigger growth of opportunistic marine microbial pathogens previously held in check by nutrient limitations. These pathogens may be present in the transported dust or may already exist in the ecosystem receiving the dust.

The search for a connection between African desert dust and Caribbean-wide coral reef decline launched the U.S. Geological Survey (USGS) Global Dust Project in 2000 (http://coastal.er:usgs.gov/african_dust/). Eugene Shinn and colleagues (Shinn et al., 2000) hypothesized a causal relation between two decades of coral reef decline occurring simultaneously across the entire Caribbean and the coincident increase in African dust being monitored in Barbados (Prospero and Nees, 1986). The first substantial evidence of a microbial link was provided when the causative agent of sea fan disease was identified (Smith et al., 1996). The disease, known as aspergillosis, is caused by *Aspergillus sydowii* (Geiser et al., 1998; Smith et al., 1996). This terrestrial fungus is capable of infecting the sea fans, but is unable to reproduce in sea water. Continuous influx of new fungal spores is required in order for the infection to spread and endure. Runoff from islands is a possible source, but Shinn et al. (2000) has suggested that fungal spores could be transported via dust events. The USGS Global Dust Project group sent air samples taken during dust events in the Caribbean and Africa to Garnet Smith (University of South Carolina at Aiken) to be tested for the presence of this fungus. The infectious form of the fungus was detected in the very first air sample analyzed and proved to be present in dust collected from Africa and the Caribbean (Wier et al., 2004).

In following up on a disease outbreak in Caribbean sea urchins (*Meoma ventricosa*), Kim Ritchie [personal communication, Mote Marine Laboratory, Sarasota, FL] isolated bacteria from the spines of urchins that were found to have identical 16S ribosomal DNA sequences to bacteria in the water column as well as bacteria isolated from African dust events sampled in the Virgin Islands. Her work is summarized in Garrison et al. (2003). One of the bacteria was genetically identified as 98% similar to *Bacillus mojavensis*, originally characterized from the Mojave Desert in California. Although not associated with a disease state, *Bacillus pumilus* has also been identified from Caribbean sea urchins, the surrounding marine environment, as well as from African dust samples collected in the atmosphere above the Virgin Islands and in Africa (Garrison et al., 2003; Griffin et al., 2001a, 2003; Kellogg et al., 2004).

Torrent et al. (2004), reported septicemia in a loggerhead turtle (*Caretta caretta*) found off the Canary Islands. The causative agent *Staphylococcus xylosus*, a bacterium, was cultured from aerosolized dust collected in Bamako, Mali (Kellogg et al., 2004). The Canary Islands are located off the coast of northern Africa and are frequently and severely impacted by Saharan/Sahelian dust.

Opportunistic pathogens (microbes that typically do not cause disease in healthy humans) can cause disease or colonize wounds in immunocompromised individuals. As noted above, 10–27% of the microorganisms cultured from African dust events have been identified as genetically similar to opportunistic human pathogens. The smaller number (10%), from air samples collected in the Virgin Islands, is composed mainly of a few fungi (*Aureobasidium* sp., *Aspergillus* sp., and *Cladosporium* sp.) that are capable of causing skin or respiratory infections, and a few bacteria (ex. *Kocuria* sp. and *Microbacterium arborescens*) that were originally identified from human noma lesions in Africa (Griffin et al., 2001a, 2003). The larger figure (27%) is from air samples collected in Mali, Africa, where the dust is much more dense and is enriched with microbes, relative to the dust that reaches the Caribbean (Kellogg et al., 2004). Examples of the bacteria isolated from Mali samples include many species of *Bacillus*, some of which are associated with gastrointestinal illness, several bacteria associated with septicemia, and two isolates (*Kocuria* sp. and *Staphylococcus gallinarum*) identified from noma lesions in Nigerians. Most of these potential pathogens do not cause respiratory diseases in healthy individuals, so inhalation of dust containing them is unlikely to trigger infection. However, most of the drinking water in the Caribbean is collected from rooftop drainage and stored in cisterns. It remains to be determined if dust contamination of the water could result in numbers of microbes sufficient to cause disease by ingestion.

Several disease-causing microbes are typically transmitted on local scales (within continents) by dust. In the United States in the early 1990s, outbreaks of Valley Fever (caused by the fungus *Coccidioides immitis*) were associated with dust storms (Jinadu, 1995; MMWR, 2003). Hantavirus illnesses in the Midwest are also dust-associated (the inhalation of aerosolized rodent feces). In sub-Saharan Africa, the World Health Organization identified dust storm activity as a cause of regional outbreaks of bacterial meningitis (Besancenot et al., 1997; Campagne et al., 1999; Hodgson et al., 2001; Mohammed et al., 2000; Molesworth et al., 2002). Analysis of a 28-year period of cerebrospinal meningitis outbreaks in Benin (West Africa) demonstrated a relation between the disease and Saharan dust storms (Besancenot et al., 1997). To date, no known pathogens such as these have been identified from trans-oceanic dust, and there are no proven cases of intercontinental outbreaks caused by microorganisms transported in desert dust.

It remains to be determined if dust-borne microbes play a role at the nexus of oceans and human health; that is, whether an organism like *Vibrio cholerae* can be aerosolized from one endemic area to a downwind ecosystem, establish a viable niche in the new marine environment, and directly impact human health as a result.

Conclusions

As progress has been made in understanding the influence of desert dust on ocean and terrestrial processes, it has become apparent that this natural planetary process plays a significant role in primary productivity, diversity flux, and climate change. The use of bioavailable iron by photosynthetic microorganisms may have beneficial (reduction of atmospheric CO_2 levels to counter CO_2 buildup via emissions) or negative impacts (accelerated algal growth rates in reef systems and harmful algal blooms). We are often asked that since dust has always moved through Earth's atmosphere, "Why do we think it may pose problems now?" We have always felt that "Why now?" is the use and or release of pollutants (industrial, agricultural, etc.) in dust source or downwind regions. Thus, dust particulates may be, or may become, carriers of toxic substances as they are mobilized into the atmosphere or traverse downwind emission sites. The end result is that, in addition to the native dust constituents, dust-associated toxins of human origin may be impacting the health of downwind ecosystems through direct (toxin accumulation) or indirect (immunosuppression) means. This, in turn, leads us into the field of aeromicrobiology and how dust-associated microorganisms may now play a more pathogenic role in downwind ecosystems. From the dust-transport microbiology data cited, it is clear that a very diverse population of microorganisms, including fungi, bacteria, and viruses is moving vast distances in Earth's atmosphere, and a significant fraction (20–30%) of this cultivable population (bacteria and fungi) consists of species capable of causing disease in a wide range of organisms (trees, crop plants, and animals). As would be expected, most of these potential pathogens are opportunistic in nature (can only cause infections in immunocompromised, immunosuppressed organisms, or in life stages where the immune system is immature or in a natural state of decline, i.e., aged individuals). Long-term exposure to desert dust (like that seen in the Caribbean) carrying both immunosuppressant constituents and pathogens may create conditions conducive for novel outbreaks of disease. Ongoing and future research in this emerging scientific field should provide a better understanding of atmospheric dispersion of pollutants and disease-causing agents, how the dispersion affects ocean and human health, and how we can effectively mediate anthropogenic influences.

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