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The High Life: Transport of Microbes in the Atmosphere

By D. J. Smith, D. W. Griffin, and D. A. Jaffe

Microbes (bacteria, fungi, algae, and viruses) are the most successful types of life on Earth because of their ability to adapt to new environments, reproduce quickly, and disperse globally. Dispersal occurs through a number of vectors, such as migrating animals or the hydrological cycle, but transport by wind may be the most common way microbes spread.

General awareness of airborne microbes predates the science of microbiology. People took advantage of wild airborne yeasts to cultivate lighter, more desirable bread as far back as ancient Egypt by simply leaving a mixture of grain and liquids near an open window. In 1862, Louis Pasteur's quest to disprove spontaneous generation resulted in the discovery that microbes were actually single-celled, living creatures, prevalent in the environment and easily killed with heat (pasteurization). His rudimentary experiments determined that any nutrient medium left open to the air would eventually teem with microbial life because of free-floating, colonizing cells. The same can happen in a kitchen: Opportunistic fungal and bacterial cells cause food items exposed to the air to eventually spoil.

Unknowingly, Pasteur founded the field today referred to as aerobiology, the science that studies the diversity, influence, and survival of airborne microorganisms. Scientists now have the ability to monitor the movement of atmospheric microorganisms on a global scale. But long-term molecular-based measurements of microbe concentrations are still missing—such information is needed to improve understanding of microbial ecology, the spread of disease, weather patterns, and atmospheric circulation models.

Hard to Kill

Single-celled microorganisms have direct contact with the outside environment through a relatively thin plasma cell membrane, which allows them to be extremely efficient metabolic machines. The trade-off is that when environmental conditions worsen (e.g., the disappearance of water or nutrients, increased exposure to solar radiation, etc.), that thin barrier is all that stands between life and death.

Bacteria have developed a variety of defense mechanisms that enable them to endure the physical threats associated with airborne transport. For example, one of the most successful protective strategies for some bacteria during periods of stress is to form a dormant endospore (more commonly referred to as a "spore"; see Figure 1), a phase somewhat analogous to hibernation in animals. The metamorphosis from a normal parent cell into a dormant spore is controlled by the entire cell population (via "quorum-sensing" pathways). During the spore-building process, cells shrink and harden, intercellular contents are dehydrated, and an impermeable cell wall coating is reinforced to shield the interior. The rate at which a microbe forms a spore is temperature and species dependent, and, when completed, parent bacterial cells have been transformed from a size of 3–5 micrometers down to 1 micrometer. In many regards, a spore is a microbiological fortress, completely dormant with no active growth or metabolism, constructed for the purpose of indefinitely protecting DNA and conserving energy.

But spores can rapidly reactivate and resume normal cellular activity upon contact with water or nutrients, provided that certain biomolecules have not been damaged during the dormancy period. Ultraviolet (UV) radiation (particularly in the wavelength range of 200–315 nanometers) tends to be the main lethal factor for airborne microorganisms, but spore-forming bacteria have developed defenses against that problem too. Many species have the ability to stabilize DNA strands with small acid-soluble proteins (SASP), perform active repairs to damaged macromolecules, or synthesize photoprotective pigments.

Non-spore-forming bacteria (the vast majority of bacterial species, in fact) must rely on other tricks to survive atmospheric stress, for example, the ability to efficiently scavenge extracellular water and nutrients, generate higher concentrations of pigmentation, or repair molecules damaged by radiation. Both spore-forming and non-spore-forming bacteria are well represented in aerobiology literature, although viable non-spore-forming species tend to be less common at higher altitudes, where UV intensity is greater [*Smith et al.*, 2010]. Other airborne biological microstructures such as viruses and reproductive fungal spores may depend on associations with particulate matter to prevent the degradation of DNA. Shielding can be provided by organic (e.g., pollen) and inorganic (e.g., dust) particles, or even surrounding layers of dead cells.

Aerobiological Cycles

Wind is responsible for lofting of most atmospheric microbes from land or oceanic sources, but it is difficult to determine precisely how cells become and remain airborne. Aerobiologists have identified a variety of possible lofting mechanisms, including but not limited to dust storms, wave action on the ocean surface, pollution from forest fires, sewage plant emissions, and aerosolized topsoil associated with agriculture. While seasonal dust storms from the largest deserts on the planet in regions of North Africa and Asia may be the primary sources of airborne biomass [see *Kellogg and Griffin,* 2006], oceans, lakes, grasslands, forests, and agricultural fields are other regularly contributing ecosystems.

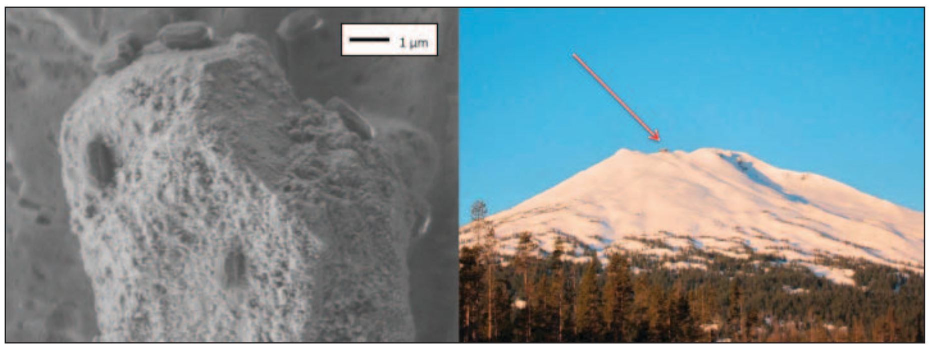

Fig. 1. (left) In an image taken by a scanning electron microscope, tiny (1-micrometer) ovoid bacterial spores sampled from the atmosphere are attached to a large dust particle. (right) Arrow points to the Mount Bachelor Observatory, located in Oregon at 43.98°N, 121.69°W. The observatory collects atmospheric samples that are now being analyzed for microbial content. Continuous collection of such samples will generate a long-term record of atmospheric microbes that may shed light on transport patterns and residence times of microorganisms in the atmosphere.

Burrows et al. [2009b] reviewed the sources and sinks of airborne microbiology and estimated that the annual flux of bacteria to the atmosphere is 40–1800 billion grams. This profusion would explain why, in recent decades, the aerobiology community has obtained microbial samples from many different atmospheric environments, ranging from urban centers to remote continental areas, and even at altitudes of up to 77 kilometers in the mesosphere [see *Smith et al.*, 2010]. Historically, aerobiologists have probably undervalued the amount of airborne biology by using enumeration techniques that depend on the cultivation of microbial strains in the laboratory. Future use of molecular-based assays and the implementation of long-term atmospheric studies will generate more accurate regional abundance estimates.

Implications

The distances microorganisms can travel before returning to the surface depend primarily on (1) the size of the cell and attached particles, (2) rates of cloud formation, and (3) wind or other meteorological forces. Most microbes larger than a few micrometers that find their way into the troposphere (below an altitude of 12 kilometers) fall out relatively quickly due to gravitational settling or precipitation. Numerous studies [*Burrows et al.*, 2009a, and references therein] have shown that many cloud condensation nuclei (CCN) and ice condensation nuclei (ICN) responsible for climate and precipitation patterns are in fact airborne microorganisms (living or dead). It is anticipated that more dust (and microbes) will be introduced into the atmosphere with each passing year as worldwide deforestation increases desert acreage. Exactly how higher concentrations of airborne microorganisms will interact with other variables that drive weather and precipitation (temperature, location, winds, and season) is another major unknown in the climate change equation.

While lower tropospheric microorganisms fall or rain out, cells that reach the upper troposphere or the stratosphere (between 12 and 45 kilometers in altitude) can stay aloft much longer and travel significantly greater distances around the globe. Although no stratospheric sampling mission has been able to identify the exact source of sampled microbes or measure precise residence times at those higher altitudes, it is thought that volcanic eruptions, strong storms (thunderstorms, hurricanes, and monsoons), and air traffic probably all contribute to the biological content in the upper atmosphere. The residence times for microorganisms might depend on dominant atmospheric circulation patterns (e.g., Brewer-Dobson cycles that eventually send stratospheric air back to the surface at the poles). Micron-sized stratospheric aerosols were observed during the 1991 eruption of Mount Pinatubo, with some particles remaining airborne for 5 years before falling out. If used as a proxy, this event demonstrates the potential for stratospheric microorganisms to stay aloft for years and be globally dispersed [*Smith et al.*, 2010]. However, to test ecological hypotheses related to this possibility, more frequent missions to the stratosphere to measure microbial origin, concentration, and viability are needed.

The potentially long residence times of microorganisms in the atmosphere are important to the health of human populations, crops, and livestock, because it takes only one viable microbial pathogen to propagate disease. As a result, understanding airborne transport, movement, and dilution of microbes is an interesting and relevant scientific problem. Already there are documented examples of the long-distance spread of pathogens blowing in the wind. For example, the foot-and-mouth disease virus (FMDV) has traveled across the English Channel on airborne desert dust [*Griffin et al.*, 2001]; wheat stem rust has floated from the Mississippi River valley to regions of Canada; and, more recently, scientists have identified elevated concentrations of influenza viruses in the atmosphere when dust emanating from China reached the island of Taiwan [*Chen et al.*, 2010].

Although the ability to identify and isolate the spread of disease has improved substantially in the past few decades, the genetic diversity of modern crops is smaller than at any time in recent history. Most industrial agriculture is based on growing monocultures—producing one single crop over a large area—often clones with identical genes. Although naturally diverse plant populations can have genetic variants resistant to disease, in agricultural fields the homogeneity allows for invading pathogens to conquer quickly. From a national security perspective, if context is shifted from agriculture to biological warfare, then there is a clear need to research, develop, and implement measures that mitigate or prevent the spread of airborne pathogens. This may include improving the ability to track the movement of airborne microbes with

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fixed-site monitoring, aircraft, and satellite technologies.

Long-Term Sampling

Airborne microbes can be sampled through high-altitude aircraft, balloons, and rockets, but none of these platforms can provide the data needed for long-term observations, preferably spanning seasons but ideally spanning years. To fill this data void (for further details, see *Burrows et al.* [2009a, 2009b]), well-established atmospheric research sites from numerous locations around the globe should begin taking aerobiological measurements. Here in North America it would be prudent to establish a network of monitoring sites on the West Coast, Rocky Mountains, and East Coast to track the spatial distribution and movement of airborne microbial populations.

In 2009, microbiologists and atmospheric scientists began collecting airborne microorganisms at the Mount Bachelor Observatory (MBO; http://www.atmos.washington.edu/jaffegroup/modules/MBO/) in central Oregon (43.98°N, 121.69°W), located 2.7 kilometers above sea level (Figure 1). Operated by the University of Washington since 2004, this research station is equipped with instruments for measuring atmospheric composition (carbon monoxide, ozone, aerosols, nitrogen oxides, etc.) and other relevant meteorological variables. Published literature from MBO has identified transpacific pollutants originating from Asia [e.g., *Weiss-Penzias et al.*, 2007] and Asian dust [e.g., *Fischer et al.*, 2009], in addition to short-lived episodes of lower stratospheric air intrusions. The diverse types and origins of air at MBO make it an ideal location to study the seasonal abundance and diversity of microbes.

Initial results have already yielded a wealth of information. In springtime, dust is the dominant aerosol type at MBO, and many aerosols collected can be traced back to Asian industry, fires, deserts, or other sources of emissions. Unlike previous aerobiology studies that relied upon culturing methods (i.e., viable cells), the use of molecular-based assays at MBO allows scientists to quantify the total amount of airborne biological material, both living and dead. Preliminary data from quantitative polymerase chain reaction (qPCR) analyses suggest that airborne bacteria outnumber fungi by an order of magnitude. Overall, microbial abundances are expected to correlate with dust concentrations, and it is also expected that diurnal and seasonal variations will be observed [e.g., *Burrows et al.*, 2009a]. DNA from isolated microorganisms may help determine the origin of air samples arriving in central Oregon and provide a new tool to trace atmospheric transport pathways.

These studies, if carried out for multiple seasons, may help answer some fundamental aerobiological questions. For example, what are the concentrations and fluxes of microbes in the free troposphere? How do abundances in stratospheric and tropospheric air compare? What meteorological conditions, aerosols, or pathogens are associated with the measured biomass over time? By studying a specific (transpacific) atmospheric pathway with surface, satellite, aircraft, and model-based observations, MBO scientists may be able to generate an unprecedented analysis of the transport of airborne microorganisms between continents, something that can be used as a case study for any number of the important environmental and population health issues that involve aerobiology.

Acknowledgments

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Author Information

David J. Smith, Department of Biology and Graduate Program in Astrobiology, University of Washington, Seattle; E-mail: djsone@uw.edu; Dale W. Griffin, Environmental and Public Health, U.S. Geological Survey, Tallahassee, Fla.; and Daniel A. Jaffe, Department of Atmospheric Sciences, University of Washington, Bothell

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NEWS

Robots Could Assist Scientists Working in Greenland

GREENLAND—Tom Lane and Suk Joon Lee, recent graduates of Dartmouth University's Thayer School of Engineering, in Hanover, N. H., are standing outside in the frigid cold testing an autonomous robot that could help with scientific research and logistics in harsh polar environments. This summer, Lane, Lee, and others are at Summit Station, a U.S. National Science Foundation (NSF)–sponsored scientific research station in Greenland, fine-tuning a battery-powered Yeti robot as part of a team working on the NSF-funded Cool Robot project.

The station, also known as Summit Camp, is located on the highest point of the Greenland Ice Sheet (72°N, 38°W, 3200 meters above sea level) near the middle of the island. It is a proving ground this season for putting the approximately 68-kilogram, 1-cubic-meter robot through its paces, including improving Yeti's mobility capabilities and field-testing the robot. (See the electronic supplement to this *Eos* issue for a video of Yeti in action (http://www.agu.org/eos_elec/).) During field-testing, plans call for the robot to collect data on elevation and snow surface characteristics, including accumulation. In addition, the robot will collect black carbon and elemental carbon particulate matter air samples around Summit Camp's power generator to help study carbon dispersion over snow.

Yeti is rigged out with two science decal–adorned rectangular boxes that are bordered by olive-colored metal and held shut by bungee cords (one box is packed with four motor controllers, a signal processing board, and an onboard computer; the other is available for other instruments as needed); thick tires for efficient driving over the firm snow; and a GPS device to measure surface roughness to 2 centimeters vertically to help Yeti surmount sastrugi, which are waves in snow that can be 10–20 centimeters high and that are created by prevailing winds. Yeti also has a radio antenna that can currently give the robot about an 8-kilometer range (with hope for a 10- to 15-kilometer range) from a laptop computer that Lane has harnessed around his neck. A trailing blue sled attached to Yeti by canvas straps can be used by researchers to carry a variety of instruments.

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Tom Lane checks on the Yeti robot on the snowfield at Summit Camp, in Greenland. Photo by Randy Showstack.