BIOLOGY

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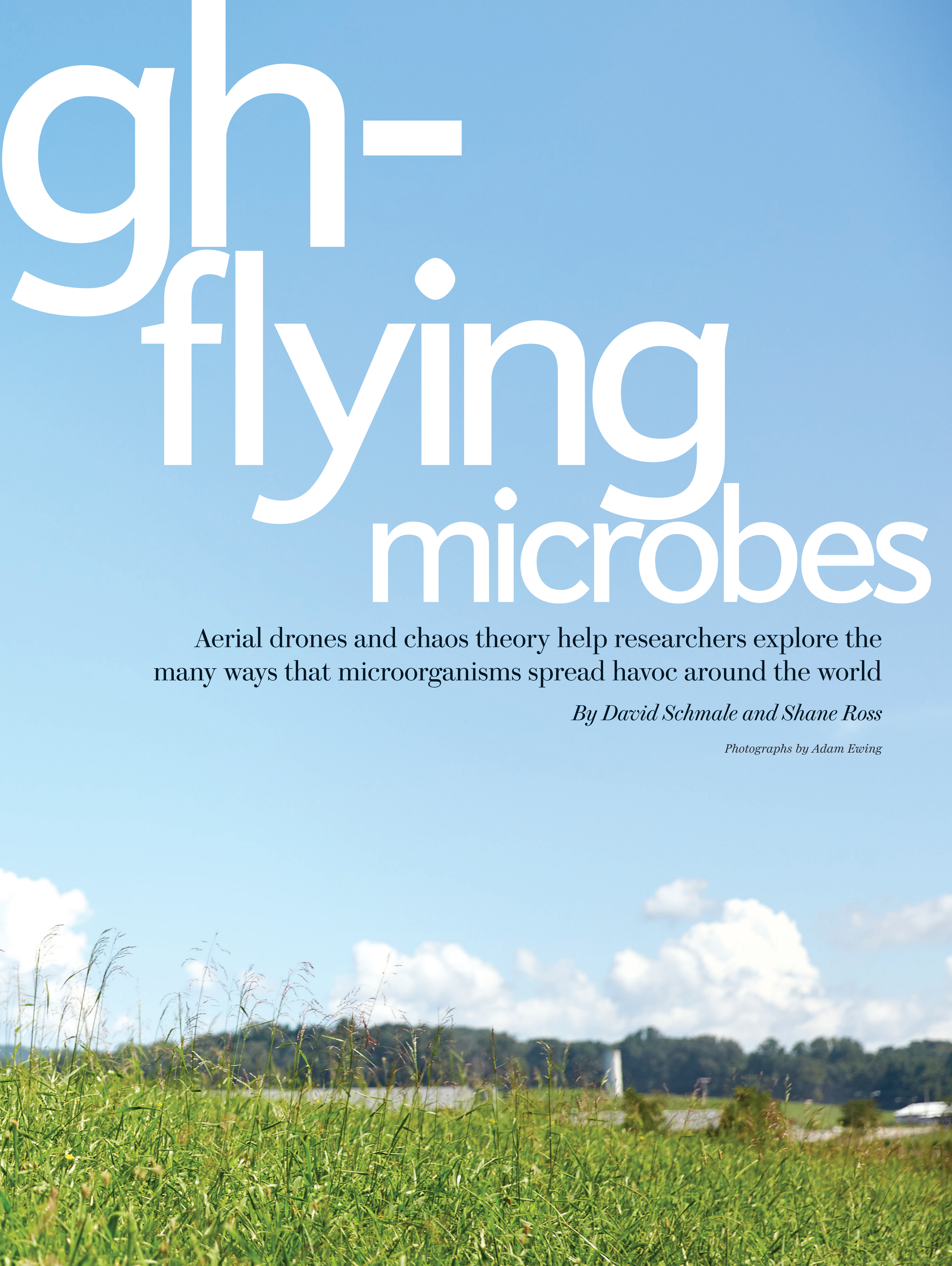
TAKEOFF: Investigators launch a drone modified to collect airborne micro-organisms from a field near Blacksburg, Va.

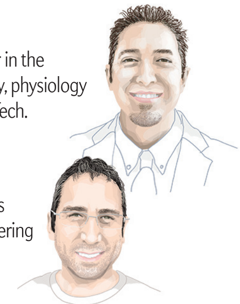
gh-flying microbes

Aerial drones and chaos theory help researchers explore the many ways that microorganisms spread havoc around the world

By David Schmale and Shane Ross

Photographs by Adam Ewing





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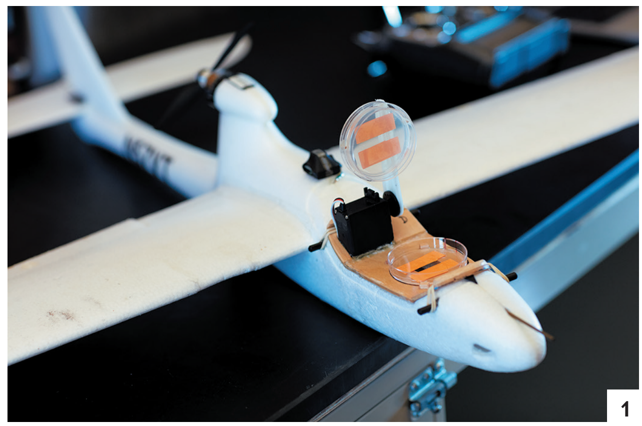

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The air around us is teeming with microscopic life. With every breath we take, we inhale thousands of bacteria, viruses and fungi.

Scientists have known for almost 150 years that some of these airborne microbes cause disease in plants, domestic animals and people. More recently, we have learned that microorganisms may also affect the weather by allowing water to freeze at warmer temperatures and triggering the onset of precipitation. Astonishingly, a few of these microbes drift on large currents of air to cross oceans and continents. New tools and technology are helping investigators learn more about where these organisms originate, how they spread and the often unexpected ways in which they affect our world during their travels.

For more than a decade the two of us have been chasing some of the pathogens that are particularly harmful to agricultural crops, causing billions of dollars in losses around the globe every year from a wide range of ailments, including blight and poisoning by toxins. One of us (Schmale) studies the aerobiology of microorganisms that cause plant disease; the other (Ross) develops mathematical models that describe and predict how currents of air move across short and long distances. We teamed up in 2006 to trace the routes by which plant pathogens spread from one field, region or continent to the next.

To that end (and unique to our collaboration), we deploy a small fleet of airborne drones equipped with sampling devices to collect and analyze the microbes from the lower atmosphere. Every sampling mission turns up a wide range of interesting organisms—many either not well studied or previously unknown to science. We have developed new tools for understanding the long-distance transport of microorganisms in the atmosphere and formed new hypotheses about how far some microbes might travel with the wind and how they might help trigger rain, snow and other forms of precipitation.

Eventually our work may enable agricultural officials to monitor disease-causing microorganisms in the air, predict where they might travel and thus identify which fields to treat or quarantine. Such information will allow farmers to decide, among other things, which crop varieties to plant or when to spray fungicides or other compounds to protect their yields. We have focused much of our research on one pathogen in particular, *Fusarium graminearum,* a fungus that has spread farther and faster over the past few decades than ever before thanks in part to climate change and no-till practices that have increased crop residue in fields, allowing the infection to persist from one year to the next. Whenever agricultural experts, ourselves included, worry that further global warming could significantly threaten the world's food supply in the near future, we are thinking about the explosive spread of this and other fungi that render grains unfit for consumption.

TOXINS IN YOUR FOOD

MANY PEOPLE ARE UNAWARE of just how devastating disease-causing microbes can be to agriculture. One of the worst plant ailments

IN BRIEF

One of the most widely devastating crop ailments is fusarium head blight (FHB), which primarily affects barley, oats and other small grains and which has been spreading into new regions of the globe in a changing climate.

Because the fungus that causes FHB travels through the air, the authors deployed drones and developed sophisticated simulations to try to determine how far these pathogens can travel. The latest findings show that these microorganisms can be transported by various weather systems for tens to hundreds of kilometers along intricate and ever changing highways in the sky.

The work may eventually help farmers protect their crops by monitoring the spread of plant pathogens and determining the most effective countermeasures.


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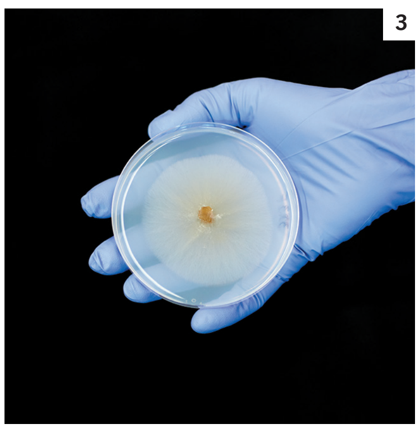
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FLIGHT PLAN: Drones used to study microbes in the lower atmosphere carry specially adapted petri dishes that can be opened and closed from the ground (*1*). A drone flies a preprogrammed route (*2*). And a spore collected from the air grows into a pure culture of *Fusarium* in the lab (*3*).

is fusarium head blight (FHB, commonly referred to as scab), which bleaches the heads of wheat, barley, oats, and other small grains and fills the kernels with chemicals called mycotoxins. When ingested in large enough amounts, these mycotoxins make people and livestock very sick, often causing them to vomit. Because grain containing the toxins often cannot be separated from healthy grains, harvested crops must be tested and destroyed if they contain more than a trace amount of toxins.

Several different species of the fungal genus *Fusarium* cause FHB around the world. *Fusarium asiaticum* has long been a problem in central China, from which it has recently begun spreading northward. *F. graminearum* is predominant in the U.S., where it wreaked havoc in corn in the 1970s, causing many pigs to become sick (this outbreak led to the discovery of the mycotoxin deoxynivalenol, which causes pigs to vomit and refuse to eat their feed). Because controlling FHB is so expensive, it has rendered the planting and harvesting of wheat increasingly unprofitable in many states in the U.S. where wheat is commonly grown.

F. graminearum survives winter by hiding out in plants that are left lying on the ground after the previous year's harvest. In the spring and summer, fungal structures called perithecia develop on these residues and forcibly discharge *Fusarium* spores into the air. These spores, in turn, land on the newly emerging anthers of wheat and silks of corn. The spores germinate, and the fungus spreads through the plant, ultimately leading to the accumulation of mycotoxins in the grain. The cross-contamination from one crop to another is why agriculture extension agents advise farmers to avoid planting wheat in fields immediately after they have been used to grow corn or other crops that are susceptible to FHB.

WALLS OF AIR

ONE OF THE GOALS of our collaborative research is to understand how microorganisms are transported over long distances in the atmosphere. As a first step, we decided to measure how far *F. graminearum* can move through the air from an infected field over the course of a day or night.

With funding from the U.S. Wheat and Barley Scab Initiative and the Virginia Small Grains Board, we conducted a series of experiments in commercial wheat fields in Virginia. We took one particular strain of *F. graminearum* that we had isolated from elsewhere in the state and characterized it down to the level of its DNA. In this way, we could distinguish it from the strains that already existed in the fields that we were about to study. Then we spread cornstalks infested with our test fungus over an area about the size of half a hectare and set out a series of petri plates to capture any potential *Fusarium* spores at various distances on the ground from the site of inoculation.

In one set of experiments, we recovered spores from our test strain almost one kilometer from where it had originally been released. But there was no telling how much farther some of the spores might have traveled because one kilometer was the limit of our recovery effort. At any rate, it now seemed clear that *Fusarium* spores could travel much farther than most researchers had previously anticipated.

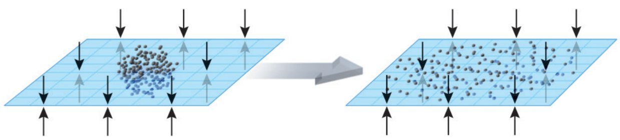
Rather than just continuing to distribute petri plates on the ground farther and farther afield around the state to look for our unique *Fusarium* spores, we decided to search for microorganisms in the air above the fields we studied. The higher up we found the microbes, the more likely we could turn to some of the complex mathematical calculations that meteorologists use to track

BASICS

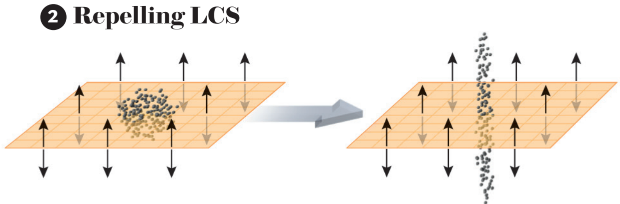
Walls of Air

The movement of air, like that of other fluids, creates certain patterns—such as the Atlantic jet stream—whose shape is influenced by temporary "walls," known as Lagrangian coherent structures, or LCSs, made of air. These features fall into two main categories: walls that mostly attract air currents (and any particles they contain) and walls that mostly repel nearby parcels of air. The complex mathematics that governs these structures (*depicted below in blue and orange*) determines whether a mass of particles—such as fungal spores—eventually scatters all along the wall's surface ❶ or forms a column on either side of the LCS ❷.

❶ Attracting LCS

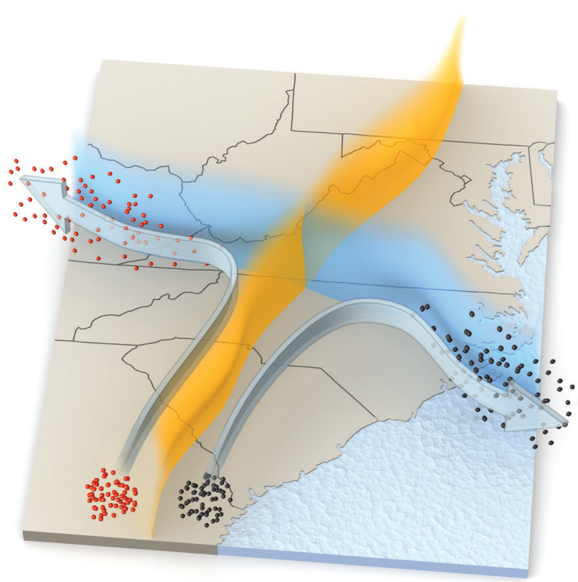


❷ Repelling LCS



LCS Walls Create Different Patterns of Airflow

The intersection of an attracting LCS (*blue*) with a repelling one (*orange*) creates a particular flow of air known as a saddle point. In the example below, two groups of particles that start fairly close to each other travel hundreds of miles in opposite directions once they hit the center of the saddle point.



weather to determine how far they could theoretically travel.

Thus, we customized a number of drones (unmanned aerial vehicles) with unique sampling devices to collect and analyze microorganisms during flight. With funding from the Emerging Frontiers and Dynamical Systems programs of the National Science Foundation, we used the drones to collect some of the *F. graminearum* spores that were already floating over our heads in Virginia. Analyzing the resulting data suggested that some of these fungi had been airborne for several hours—long enough to have been stirred by large-scale weather patterns spanning hundreds of kilometers.

Further investigation revealed that short-lived, invisible moving "walls of air" play a major role in determining how far these fungi travel and where they land. These atmospheric features, formally known as Lagrangian coherent structures (LCSs), arise whenever different currents of air (or any other fluid, for that matter) run into one another or travel around an obstacle, such as a mountain or the wing of an airplane. The currents' initial direction and speed at the moment of contact determine where various air particles will travel next, creating patterns that can be simulated by computers, using the complex mathematics of chaos theory and a specialized branch of physics known as nonlinear dynamics.

As you might expect, these temporary walls of air drive much of the weather we see on any given day. Intricate, ever changing LCS patterns have been shown to shape, concentrate and divide the air over the Atlantic Ocean, for example, in such a way that the winds of a hurricane either gather strength or dissipate as the storm moves over the water. Less extensive interfaces determine how airborne pathogens climb, dive and swirl through a valley, sometimes landing on one farm but not the adjoining property. By tracking LCSs over time and space, we have formulated hypotheses about where various microbial threats to a particular region are likely to come from and where they might go next. As we get better at developing this information, farmers may find it as useful to consult our microbial forecasts as they do the weather report.

Fusarium fungi are just the tip of the iceberg. Because microbes travel through the atmosphere, they clearly do not respect international boundaries. A deadly strain of wheat stem rust (Ug99) has been bouncing around the African continent from its origins in Uganda since the late 1990s; growers in Australia and North America are particularly worried about its potential arrival via regular atmospheric currents over the Indian and Atlantic oceans, respectively. Soybean rust initially rode into the U.S. from South America on Hurricane Ivan in 2004; it currently hides out in the U.S. South during the winter and makes its annual entry into the Northeast and the Midwest via predictable air routes each growing season (the fungus is unable to survive harsh winters). A coalition of agricultural stakeholders has even established a national monitoring network to keep tabs on this pathogen's seasonal spread every year.

Intriguingly, many of these microbes could not survive such long journeys through the atmosphere on their own. For one thing, prolonged exposure to the ultraviolet radiation of the sun can kill them. But microbes that manage to attach themselves to dust particles can be shielded from the sun's sterilizing glare. Scientists such as Dale Griffin of the U.S. Geological Survey have documented several well-established lanes of global dust trans-

Illustration by Emily Cooper

port, which connect Africa to Europe and Asia, for example, or Asia to the U.S. Indeed, an estimated hundreds of millions of tons of Saharan dust—and their attendant microbes—land in Florida every year. Besides setting off hazy days and stunning sunsets, these dust clouds could unleash serious ecological destruction in their wake. Recent work has suggested that some causal agents of coral disease in the Caribbean—aspergillosis of sea fans in particular—may have been transported in African dust. The increasing desertification of northwestern Africa compounds the danger as more and more marginally arid land turns to dust that can bear and shield a greater number of plant-killing microbes half a planet away.

WIND AND WATER

MICROBES DO NOT JUST SPREAD DISEASE while traveling in the sky. They may also help create the weather over land, lakes and oceans. Meteorologists have long known that hail, snow and rain typically fall from the sky only after the formation of tiny ice crystals in clouds. Whether a snowflake or a raindrop forms around the ice depends on certain environmental conditions, including the presence of particles—such as soot—that allow water to freeze at warmer temperatures than usual. (Pure water freezes at temperatures as low as about –38 degrees Celsius.)

In 1982 David Sands of Montana State University and his colleagues posited that something else—namely the bacterium *Pseudomonas syringae*—could also serve as the nucleus for ice crystals in the atmosphere. Subsequent research hinted at a possible mechanism. Certain strains of *P. syringae* produce a particular protein on the cell's surface that traps water molecules in such a way that they start creating a crystal lattice. On the ground, strains producing these ice-forming proteins can cause frost damage to crops. But the microbes can also soar aloft into clouds where the temperature is far below zero degrees C. If enough of these bacteria produced sufficient ice-nucleating proteins in the sky, Sands thought, they could conceivably trigger the formation of raindrops or snowflakes.

Or at least that is the idea. Since Sands's paper, researchers have found plenty of *P. syringae* in bulk samples of rain and snow. Whether the microbes are primarily responsible for the onset of precipitation or mostly tagging along for the ride is tough to prove. Ski resort operators are not waiting for a definitive answer, however: many of them use commercial ice nucleators that contain bits of *P. syringae* to create artificial snow during warm winter days.

Sands's hypothesis inspired us to see if we could find any other microorganisms in the atmosphere that might initiate precipitation. Supported by the Dimensions of Biodiversity program of the National Science Foundation, research conducted by Schmale and his colleagues has shown that microbes associated with precipitation are far more diverse than originally expected. In Virginia, Boris Vinatzer and Schmale have collected many different types of bacteria and fungi in the atmosphere and in precipitation that can serve as ice nucleators, at least in the lab. And the diversity of microbes associated with precipitation appears to differ depending on geographical location. A better understanding of why each of these microbes predominates in different regions could help us better predict weather patterns. And perhaps we could eventually use some of these microorganisms to develop tools for making it rain in arid regions or areas beset by drought.

MICROBE CATCHERS: Ross (*left*) and Schmale (*right*) study the transport of microorganisms along highways in the sky.

Ultimately we hope to combine what we have learned about microorganisms in water droplets with our calculations about Lagrangian coherent structures to describe what happens in the air immediately above the surface of lakes, rivers and oceans. We have already begun collecting microbes over water using teams of unmanned boats and aerial drones. The mathematical equations needed to describe the mixing of microbe-laden air and water from crashing waves, sweeping winds or even the splashing impact of rain are more complex than anything we have attempted so far. Because water covers about 70 percent of the planet, however, we have no doubt that what we find will reveal fascinating new ways that microbes travel the globe. SA

MORE TO EXPLORE

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FROM OUR ARCHIVES

Walls of Water. Dana Mackenzie; July 2013.

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SCIENTIFIC AMERICAN ONLINE Watch Schmale describe different ways that microbes surf the air at ScientificAmerican.com/feb2017/drone