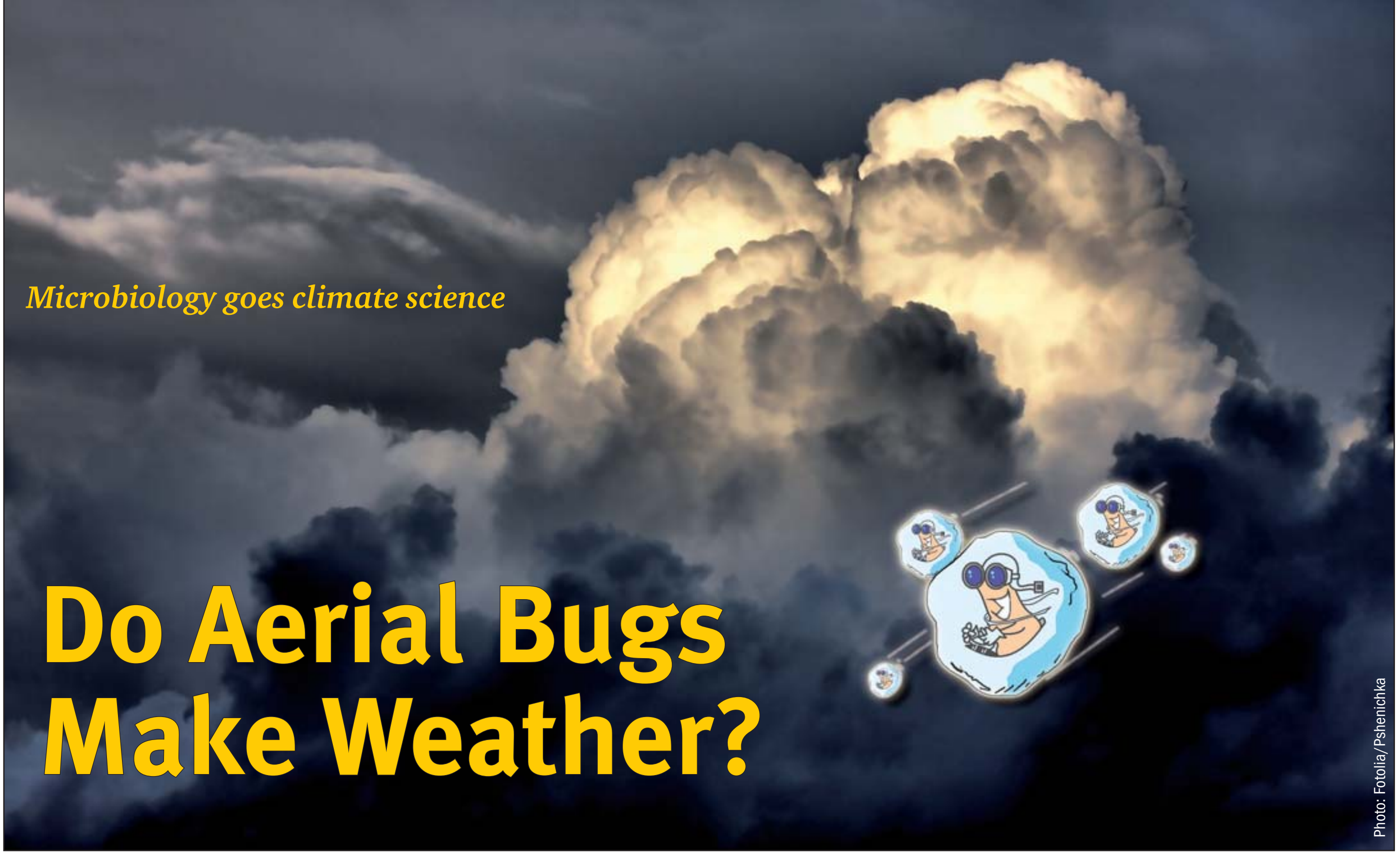

Photo: Fotolia/Pshenichka

*Microbiology goes climate science*

# Do Aerial Bugs Make Weather?

In all cultures of the world there have been periods in history when people carried out certain rituals, asking the weather gods for more rain or fewer storms. Native Americans or Africans danced and sang for the gods while sacrificing animals; ancient Chinese called on the dragons who they believed controlled the weather. The rain cycle was pieced together decades ago, however, mysterious forces, much smaller than gods or dragons, appear to be at work behind the clouds: bacteria.

Bacteria are abundantly present everywhere, forming the largest biomass on the planet. For a long time, it has been known that microorganisms exist even in the atmosphere, just like anywhere else. Could it be that they play an influential role up in the sky and maybe even influence the weather? In recent years, evidence has emerged that bacteria might stimulate precipitation and even be involved in climate change.

The idea is closely related to a process crucial to rain and snow formation: ice nucleation. It might come as a surprise to many but pure water doesn't freeze at 0°C. In fact it can stay liquid until -40°C. In order for water to freeze at any temperature warmer than this, some help is needed. If some particles, for example small bits of dust, are present to keep the moving molecules of super-cooled, liquid-water still, water can condense and crystallise around them to form droplets. If heavy enough, the water droplets then fall from the clouds to the earth as rain or snow. Particles that help the process of ice nucleation happen are called ice nucleators and can usually increase the freezing point of water up to about -15°C.

## The Rainmaker

Some bacteria can function as ice nucleators, too, capable of catalysing the freezing of water at even higher temperatures of up to -2°C. These bacteria are usually found in large numbers on different plant species. Their unusual ice nucleation activity at high temperatures was discovered in the 1970s but it wasn't until some years later that they became an official suspect in climate matters. In 1982, David Sands, a plant pathologist from Montana State University, published on the idea that bacteria might exist in considerable numbers in the clouds and stimulate rain by their ice nucleation activity. Moreover, he coined the term 'bioprecipitation', when he presented his study of cloud samples at the Hungarian Meteorological Service meeting. However, given the distance between the fields of microbiology and climate sciences, the story remained largely in the background until more than 25 years later.

Cindy Morris is the director of the Plant Pathology research unit at INRA, Avignon, France, where she studies fruit and vegetable crop diseases. She was doing her training at the University of Wisconsin when ice nucleation active bacteria were discovered. "I worked on the same bacteria, I didn't work on the ice nucleation aspect but every Wednesday we talked extensively about ice nucleation... so I had a huge training about it." In the lab where Cindy was working there was a graduate student who worked on bio-aerosols and the emission of bacteria into the atmosphere. "So we knew they went up and David Sands had actually found them in the clouds."

Years later, Morris hadn't stopped thinking about the airborne bacteria. In a meeting with David Sands in 2000, both microbiologists realised that they had to try pushing forward the idea that this biological "factor" should be considered in cloud physics. "Most bacteria we know can cause ice nucleation are associated with plants," Morris says "so the idea is that maybe we are missing some critical things we could be doing in terms of how we manage the landscape. If those bacteria are being emitted from plants, could we grow plants with the express purpose of generating these organisms for creating rain?" She also admits the complicated aspects of such an endeavour, "You need to know where you are going, to have an effect and how much you need to have an effect. Those are the questions that we are trying to work on."

## Bacteria in the clouds

Thus, various studies were done to observe the ice nucleation activity of bacteria in the laboratory and to measure their respective emission rates to the atmosphere. It was shown that bacteria could survive in cloud water for a few days (*Atmos Chem Phys Dis-*

*cuss*, 7, 5253–76). The next step was to determine the concentration of bacteria in the clouds and their global atmospheric distribution.

In 2008, Brent Christner and colleagues from Louisiana State University analysed samples of snowfall from different continents: from the Antarctica, the French Alps and Canada. In their study published in *Science* (319:1214), they reported that a large proportion of ice nucleators in the samples were of biological origin, including different bacteria. The results showed the ubiquity and abundance of bacteria in the biosphere, which bolstered the idea of their participation in the ice nucleation phase of precipitation.

Christner and colleagues gathered their samples from fresh snowfall in mid and high-latitude locations, including areas devoid of extensive vegetation, and the measured concentration of bacteria was theoretically enough to expect a significant effect on ice nucleation in the clouds. Nevertheless, according to Christner, it was still difficult to determine whether the bacteria detected in their samples originated from the high clouds or rather from lower altitudes in the atmosphere. Additional evidence was needed to prove their significant existence in very high altitudes as well as their active involvement in the initial stage of precipitation. Fortunately, to address these questions, researchers have a sort of crystal ball to look into bacteria's past footprints in the clouds and that is hailstones.

## Hail the hail

Hailstones are among the worst manifestations of a vicious thunderstorm. Such a storm producing hailstones, which break windows and damage agricultural crops, belongs to a category of events that pushes the weather alarms to their limits. Hailstones are ice balls that can grow to as large as twenty centimetres in diameter with layer upon layer of ice. They have at least one advantage for researchers: unlike rain and snow, samples of hail provide a reliable way to look for aerial bacteria. The preserved core of these hailstones, which is the first part to develop in the clouds, can tell a lot about what happened at the ice nucleation phase. If bacteria are found at the core of the hailstone, it means that they were originally present in the clouds.

That was the reason why, right after a hailstorm in June 2010, Alexander Michaud ran around the Montana University's campus collecting fallen hailstones before they melted. Michaud and his colleagues gathered a number of samples, some of which were as big as five centimetres in diameter. Using these hailstones as "a record of the cloud and the storm", Michaud hoped "to show that biological ice nucleation is present at the core of the hailstone".

The search for microorganisms in the hailstone's layered ice was successful. The team detected more than 1,000 bacterial cells in each millilitre of melted hailstones, also in the core (American Society for Microbiology meeting in May 2011) – one more piece of evidence for the presence of bacteria when the formation of hailstones occurs, which lent more credence to the bioprecipitation concept.

So, are the bacteria to blame for causing hail? Or do we have to thank them for rainfall? The extent of bacterial impact in atmospheric processes is still unclear. Nevertheless, researchers are already trying to find out how we can use the new knowledge in order to encourage more rainfall and prevent hail from forming.

## Weather modification

Since its discovery in 1946, cloud seeding, a method based on the ice nucleation property of some particles, has been used to alter the atmospheric processes leading to precipitation. One chemical ice nucleator, or cloud seed, commonly used in this practice is silver iodide. Particles of silver iodide are sprayed into clouds to induce rain by helping the formation of water droplets when the temperature is not low enough for them to form spontaneously.

This method of weather modification can also be used to reduce the size of hailstones by increasing the number of ice nucleators that attract water, therefore making more but smaller droplets that are not big enough to become damaging hailstones. Based on the same principles, ice nucleator bacteria could act as cloud seeds in methods of weather modification. With the potential impact of aerial bacteria in mind, it has been suggested that, theoretically, creating surfaces with plants that are good sites for bacterial ice nucleators in areas with high frequency of hail could be an alternative solution to this problem. Similarly, the same approach could be taken to produce more rain or snow.


Photo: National Center for Atmospheric Research

Hailstones: bad for crops and buildings but good for science.

This is how some types of bacteria that were formerly known merely as 'plant pathogens', or, at best, 'accidental travellers in the atmosphere' might become useful after all. But what are these invisible microorganisms at the centre of the spotlight?

## The 'accidental' traveller

In 1970, Russell C. Schnell, a PhD student at the University of Wyoming, who worked on the sources and composition of atmospheric ice nuclei, carried out a series of experiments on an observation made by his thesis advisor Gabor Vali. The latter had noticed a difference between pure sand and soil containing high concentration of organic matter in their respective ice nucleating abilities. The soil collected from the surface of the ground proved to be a better ice nucleator compared to pure clays or sands lacking organic content.

The organic matter in the soil usually derives from decomposed vegetation. In an attempt to trace back this organic content, Schnell examined the original green vegetation above the ice-nucleation-active soil. He collected the leaves, crushed them into little pieces and immersed them in distilled water to determine the ice nucleus contents. He didn't find any good ice nuclei in the washes, so he left the wet preparations in plastic bags and forgot about them.

## Impossible findings

About a week later, Schnell noticed something peculiar, "The liquid in the formerly green leaf washed preparations had gone murky. I tested the liquid and ice nucleation activity was at -1.3°C." This was an unusually high temperature that Schnell was surprised to have measured. "I showed the results to an imminent cloud physicist who told me that obviously the equipment I was using was in error as what I was reporting to him was not possible. No one had ever seen anything like that."

On his return to the University of Wyoming, Schnell repeated the tests and obtained the same results. He collected a set of samples from fresh or dead leaves and let them decay, either in the presence of oxygen or under anaerobic conditions. He then measured the concentrations of ice nucleators in the samples. In a letter to *Nature*, he finally reported the finding: those leaves undergoing active decomposition under aerobic conditions had the highest concentration of ice nuclei. Not having yet identified them as bacteria, Schnell termed these ice nucleators as "leaf-derived nuclei" or LDN. He suggested that given the great abundance of ice nucleators provided by decomposing vegetation, this highly common process could be a source of atmospheric ice nucleators (*Nature*, 236:163-4).

## A semi-active dispersal mechanism?

The LDN was later examined by microbiologists and finally *Pseudomonas syringae* was identified as the organism causing the high nucleation temperatures (*Appl Microbiol*, 28:456-9). At that time, *P. syringae* had been best known for causing frost damage to plants. Frost damage occurs in plants that cannot tolerate formation of ice on their cells. *P. syringae* mediates freezing at relatively high temperatures, the ice then pierces the cell membrane and makes the internal nutrients available to the bacteria.

*P. syringae* and other ice-nucleating bacteria have proteins with a specific structure, which seems to be responsible for organising water into a crystal-like ice pattern. In fact, rather than being passive wanderers in the clouds, bacteria may even have evolved to use this ice-nucleating ability to facilitate their own dispersal through the water cycle. Morris notes, "Even if they can't cause a significant amount of rain, this process is probably a semi-active way for this bacteria to drive their dissemination." She goes on to explain, "There are two things about rain. You can cause a water droplet to fall from the sky but it may never get to earth. It can evaporate or be of such a small volume that you cannot measure it as rain, even though it does the job of bringing the bacteria back down to earth." For those who study how bacteria spread from plant to plant, it is interesting to consider the feedback between terrestrial ecosystems and clouds. If bacteria rely on the rainfall to spread to new habitats, according to Christner, this would be a key element of the bacterial life cycle that should be studied further.

## One more player in climate change

Airborne microorganisms, however, do not only meddle with ice formation in the clouds; they can also transform organic chemicals in the atmosphere through their metabolic activities. It has been shown that atmospheric bacteria are not only capable of metabolising by feeding on available nutrition in the clouds but they can also grow and reproduce there. New studies in recent years suggest that this metabolic activity of living microbes could be involved in the chemistry of organic compounds found in the atmosphere. These compounds, which are mainly carboxylic acids and aldehydes, originate either from fuel burn or from oxidation of hydrocarbons. They are easily broken down by sunlight and turned into carbon dioxide ($CO_2$).

In the laboratory, microorganisms can happily metabolise organic compounds and researchers can measure the rate at which the oxidation process occurs. Through the same mechanism, when present in the clouds, microorganisms can contribute to oxidation pathways along with chemical and photochemical processes that normally happen in the atmosphere.

A group of investigators led by Pierre Amato from the Clermont University in Clermont-Ferrand, central France, sought to quantify the importance of such biological oxidation pathways. For their study, presented last year at the international meeting of the American Society for Microbiology, they collected samples from clouds at a height of more than 1,500 metres. The team se-

### More than just *Pseudomonas syringae*:

Photo: Fotolia/George Mayer

Bacteria identified in cloud water belong mainly to the genera Pseudomonas, Sphingomonas, Staphylococcus, Streptomyces, and Arthrobacter. According to Amato *et al*. (*FEMS Microbiol Ecol*, 59:242-54) others include:

- Alphaproteobacteria: Sphingomonas sp., Aurantimonas and Methylobacterium
- Betaproteobacteria: Massilia and Zoogloea
- Gammaproteobacteria: Moraxella and Pantoa
- Firmicutes: Bacillus and Paenibacillus
- Bacteroidetes: Pedobacter, Flavobacterium, Sphingobacterium
- Actinobacteria: Micrococcus, Saccarothrix, Kocuria, Agromyces, Cellulomonas, Tetrasphaera, Leucobacter, Luteococcus, Agrococcus

A new paper by the same author is soon to be published with about 200 other bacteria isolated from cloud water.

lected five representative microbial strains from cloud water and put them in tubes next to organic compounds to see at what rate the biodegradation of these compounds occurs. They reported that microbial activity represents a real alternative route for the oxidation of organic compounds in cloud water. Therefore, these microorganisms can help the oxidation of organic compounds in the atmosphere and contribute to the increase of greenhouse gas in the atmosphere (*Appl Environ Microbiol*, 76 (1): 23-9).

## Microbiologists reach to the skies

Altogether, the topic of weather-influencing microbes is a prime example that many exciting things in science happen when people from different fields come together. This February, the American Academy of Microbiologists released a report, calling for integration of the latest insights from microbiology into climate models. The report, which is based on a meeting convened by the Academy in 2011 where experts from microbiology and climate sciences participated, aimed to identify key strategies for bringing those fields together. The recommendations made by the Academy are mainly focused on modelling the interplay between microbes and organic compounds, as well as the production of nitrous oxide by soil microbial communities, in order to characterise the biogeochemical transformations. The report calls for creating a framework where interdisciplinary collaborations and training can be facilitated.

This initiative for collaboration between climate scientists and microbiologists is not the first, though. In 2006, Morris had constructed a network of cloud physicists and biologists who have since been working together and co-publishing. "We are working with cloud physicists who use modelling to see once you have clouds enriched with [ice nucleation active] organisms, what is going to happen in terms of precipitation." Noting that the focus recommended by the Academy's report is slightly different from her research, Morris nevertheless believes that "the basic call for bringing together physics and biology is pertinent. And not just for climate, for many subjects".

This, however, can be harder than it seems. According to Morris, physicists and biologists do not have the same culture, "It's shocking. The way we publish, the way we organise our collaboration, our motivations – everything is different." Nevertheless, she believes such questions at the joint of different disciplines are exactly the kind of questions we need to be working on today, to make the link between research and society or the environment.

## Potential benefits on the horizon

The rain-inducing potentials of microbes, as well as their contribution to the rising levels of carbon dioxide, arguably brings them right into the centre of one of the world's foremost problems. As such topics are interdisciplinary in nature they can only be addressed by a network of scientists from different fields. While atmospheric scientists measure the concentrations of bacteria in the atmospheric aerosols, study their emission mechanisms and estimate the impact of meteorological conditions, microbiologists take a closer look at the microscopic air life in order to discover how we can use all its potentials to our benefit.

Somehow, we have now arrived at new rituals to call upon invisible forces for good weather; only that our dances happen in the laboratory and our prayers are sent up in the form of cloud sampling balloons.

Bahar Gholipour