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CLOUD CONTROL

The skies are alive with microbes that could be hijacking the weather, says Kate Ravilious

IT WAS a baffling case. In spring 1978, a menace was stalking the wheat fields of northern Montana. No matter what David Sands did to treat the seeds and soil, the crop was riddled with blight. So, on a hunch, he hired a small aircraft and took to the skies. Once inside the clouds, Sands reached out of the window, Petri dish in hand – and there it was. He had collared his suspect. Not only that, he came to believe that his discovery would solve the long-standing mystery of what makes it rain.

Sands's proposal that drizzle and downpours are summoned by microbes living in the clouds didn't go down well with atmospheric scientists. They were focused on dust particles and soot, and weren't about to listen to a plant pathologist. Having presented his idea a few times to little acclaim, Sands went back to investigating plant blight at Montana State University in Bozeman.

But discoveries in the past few years are making it look as if he was on to something. It now seems as if the skies are teeming with microbial life, and recent sorties into the clouds have returned evidence that specialist bacteria do indeed turn the dial to Downpour. There are even hints that some of the worst droughts in recent history were made by humans disrupting the delicate balance between bacteria and plants.

The good news is that by figuring out the role microbes play in the murky inner lives of clouds, we might be better able to predict the weather. We might even harness microbes' rain-making powers to quench the thirst of parched lands.

Clouds are both familiar and mysterious. They form when water vapour condenses into minute droplets or ice crystals, a process often hastened by tiny particles floating in the air known as aerosols, which give water molecules something to cling to. Yet when it comes to releasing that water, we're still in the dark as to why some clouds let loose a torrent while others don't shed a single drop.

The conundrum comes down to the physics of ice formation. Clouds produce rain or snow when the droplets they contain grow big enough to overcome atmospheric updraughts. Most of the time, falling involves freezing – ice crystals grow faster than liquid droplets, meaning they reach falling weight before being swept away to evaporate and vanish. But strange though it may seem, pure water in the atmosphere can remain liquid down to −40 °C. And although the molecular secrets behind this phenomenon are still puzzling, it means that water droplets in clouds usually need a bit of help to form ice.

That help comes in the form of "ice nucleators", airborne particles that provide the nucleus around which water molecules arrange themselves into the lattice structure of an ice crystal. Salts thrown up from ocean spray and mineral dust from desert winds can do the trick, and they are abundant in the skies. But they can't seed ice crystals above −15 °C, which is the temperature inside up to half of all clouds that form over land. There must be something else lurking in these common clouds.

When Sands took to the skies, he was following clues to this enigmatic ice-maker's identity that emerged in the early 1970s, when researchers showed that a leaf-dwelling bacterium called *Pseudomonas syringae* is a catalyst for ice formation even in relatively warm conditions. Why *P. syringae* evolved these instant-freeze powers isn't clear, but it might have been a way to get into a plant's tissues: spiky ice crystals pierce leaves and rip open cells, serving up the nutrients inside.

A decade or so after the discovery, and after Sands had published his theory, researchers ›

Something in the air: clouds often need help to generate a deluge

managed to isolate one of the genes that make ice-nucleating proteins. Many more species of microorganism boasting this ability then came to light, including various species of fungi. But still no one took Sands's idea seriously.

That began to change in 2007, when his hypothesis piqued the interest of two environmental microbiologists: Cindy Morris at the French National Institute for Agricultural Research in Avignon and Brent Christner, now at the University of Florida in Gainesville. The trio collected fresh snow from around the world and looked for evidence of biological ice-nucleating particles. They then tested their ice-making ability by placing them in pure water and cooling it to see when it would freeze (see diagram, opposite).

Once they had identified samples that froze at temperatures above −7 °C, they heated them to denature any proteins – on the assumption that this would deactivate any biological ice nucleators. When the droplets cooled again, most no longer froze above −7 °C, indicating that the vast majority of their ice-nucleating particles were biological.

High-flying life

Last year, Alex Michaud at Montana State University examined giant hailstones, which preserve a record of the original ice catalysts at their cores. He came to the same conclusion: the hailstones were born when biological particles transformed water into ice.

"It has long been a paradox that lots of ice-containing clouds form at temperatures warmer than −15 °C," says Christner. "We now think that bacteria may be at least part of the explanation."

And there are plenty of them up there. In recent years, we have found all kinds of microorganisms living at altitudes where they could influence the workings of clouds. In 2013, for example, a team led by Kostas Konstantinidis and Athanasios Nenes of the Georgia Institute of Technology in Atlanta published work looking at samples collected in 2010 at up to 10,000 metres above the Caribbean Sea, the Gulf of Mexico, the Atlantic Ocean and the continental US, as hurricanes Earl and Karl passed through. They clocked 314 different species of bacteria, most of which were alive. They also found roughly as many biological cells as soil and dust particles. "The cells have the potential to significantly affect the formation of clouds," says Konstantinidis.

That doesn't mean they are, though. It's possible these microbes inadvertently got dragged along on dust particles. To find out if microscopic life forms are making it rain, you have to see what they're up to inside clouds.

That's exactly what Kim Prather, an atmospheric chemist at the University of California, San Diego, has been doing, sucking in ice crystals from rain clouds over Wyoming, the Caribbean island of St Croix and the Sierra Nevada mountains in California. After analysing the chemical composition of the particles on which crystals have formed, Prather and her colleagues have found that roughly 40 per cent of the particles in the most rain-laden clouds are biological in origin.


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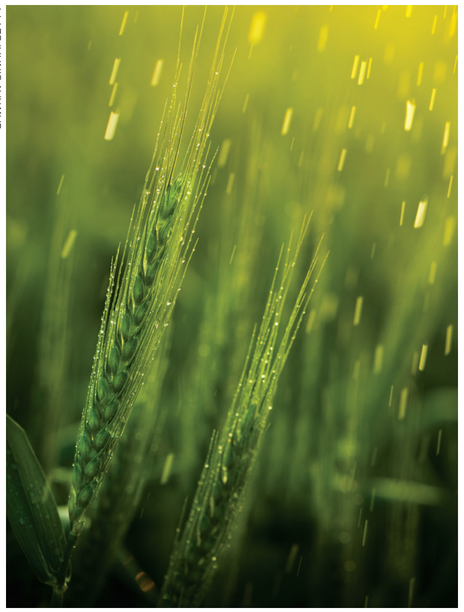
A fungus may have precipitated the US Dust Bowl of the 1930s


GAWRAV SINHA/GETTY

Wheat plants can be bred to harbour more bacteria that help ice form in clouds

Prather has also found that these biological particles often coincide with dust that has travelled vast distances across the world, typically from the deserts of Africa or China. "In one instance we were able to see the dust travelling across the Pacific and anticipate the subsequent snowfall," she says.

All of which amounts to tantalising evidence that microbes do indeed seed ice in warm clouds. But while Prather continues to swish through these clouds, she has yet to catch bacteria in the act.

Even if she does, some people question whether there are sufficient numbers up there to make a difference. They point out that soot and natural mineral particles are more abundant, and therefore more likely to hold sway. However, last year Daniel O'Sullivan at the University of Leeds, UK, showed that there are other tiny organic particles to be factored in: fragments of fungi can also do the job. "Soils contain a huge reservoir of these nanometre-scale particles," he says. And then there are microscopic phytoplankton in the oceans, some of which are ice nucleators, launched into the atmosphere via sea spray from breaking waves.

Besides, Christner points out, microbes don't have to control global precipitation patterns to influence certain regions. "We're not saying that bacteria explain all the world's weather, but I think there are certain conditions and times of year when these things load up the atmosphere and have a significant effect," he says.

If bacteria are influencing our weather, even if only in a particular cast of clouds, could they be a key component in self-contained rain factories? Soon after he found *P. syringae* hiding out in the clouds, Sands proposed a feedback loop: leaf-dwelling microorganisms are lofted into the atmosphere, where they seed ice crystals and make rain, thereby securing their own dispersal and ensuring a good drenching for their plant hosts.

Whether microbes evolved this ability to quickly freeze water at relatively high temperatures in order to rip open and feed on host plants, or as a defence against ice forming inside their own cells, it's perfectly plausible to think that it might have been co-opted as a way to reach pastures new.

"The atmosphere is like a giant freeway system, but it is also a lethal place to be, so it is possible that they evolved their ice-nucleating ability to get themselves down again," says Christner. Maybe the *P. syringae* that Sands pulled out of the clouds above Montana were instigating the instant freeze that would bring them back down to Earth.

Host plants could be in on the act too, providing a cosy home for bacteria in return for rainfall. A unique record of ice-nucleating particles isolated from air samples collected at locations across southern Australia, dating all the way back to 1956, has revealed an intriguing pattern. When Morris and retired meteorologist Keith Bigg compared this data with records of weather and land use, they discovered that in certain locations the probability of rain increases following a rainstorm. Agricultural land was particularly prone to this phenomenon, and Morris thinks that could be because the crops are prime real-estate for ice-nucleating bacteria.

> "Bacteria could be a key component in self-contained rain factories"

Morris and Sands are looking at rainfall patterns over the last century at more than a thousand sites across the western US, searching for evidence of a feedback cycle involving clouds, plants and bacteria. Results so far show strong positive rainfall feedback along the Sierra Nevada and in the agricultural area around Phoenix in Arizona. "Some vegetation appears to release more ice-nucleating bacteria after rainfall, which brings another rainfall cycle," says Sands.

With that in mind, Sands believes that humans have been unwittingly modifying the weather since the dawn of agriculture. "When farmers grow a crop of food they are also growing a crop of bacteria, and that will pay out rain downwind," he says. That means intensive cultivation of just one or two species of crop that play host to ice-nucleating bacteria can have disastrous consequences.

Take the development of the wheat belt in the US Midwest during the early 20th century. The species planted were particularly vulnerable to wheat rust, a fungal pathogen that happens to be an accomplished ice nucleator. It seems counterintuitive, but Morris now suspects that a series of wheat rust epidemics might have played a part in creating the Dust Bowl conditions that plagued the North American prairies in the 1930s. "Ploughing will have released millions of wheat rust spores, creating so many ice nuclei that they couldn't grow big enough to rain," she says. "They might have produced so many ice nuclei that they constipated the clouds."

If we have accidentally shaped weather in the past, can we do it deliberately in future? The US has a long tradition of sending up planes to catalyse ice formation by spraying the skies silver iodide. Only last year, Los Angeles County responded to the drought in California by forking out half a million dollars to a cloud-seeding contractor, attracting criticism because there is scant evidence to suggest silver iodide increases rainfall.

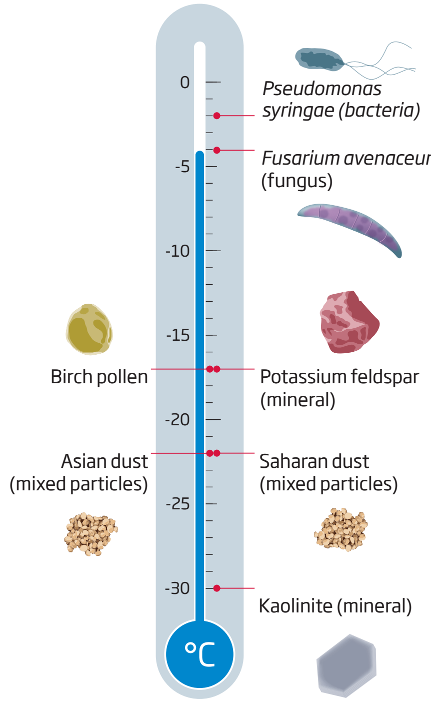
Sands thinks natural ice-makers could offer a better solution. He and Morris are exploring the possibility of squeezing more rain from the skies by filling the ground with plants that harbour ice-nucleating bacteria. The trick would be to cultivate just enough of these microbes to seed ice crystals without clogging up the clouds.

One option is to find and selectively breed plants that harbour the greatest abundance of ice-forming microbes with a view to making them even more desirable residences. Morris and Sands are already searching the US for candidates. "We hope to be able to breed the plants that harbour the most ice-nucleating bacteria and plant them in the right places to help seed rain," says Morris.

There is another option. Working with colleagues in Syria, Sands and Morris have analysed 25 types of wheat to find strains of *P. syringae* that don't harm particular types of wheat. Using the non-pathogenic varieties to coat wheat seeds, the researchers were able to increase the number of rain-making bacteria on the leaves. "Eventually seed companies might be able to put these bacteria on seeds to change the plants' microflora and favour rainfall," says Sands.

Assisted freezing

To make it rain, clouds usually have to form ice crystals. Pure water droplets may stay liquid down to −40°C, but microscopic particles can kick-start ice formation at a range of temperatures



SOURCE: MURRAY ET AL., CHEMICAL SOCIETY REVIEWS, VOL 41, P 6519

Temperatures shown taken from lab tests using standardised concentrations of particles in water droplets

Droughts aren't likely to become a thing of the past, however. "You can't induce rainfall if there is no water vapour in the air," says Morris. No matter how accomplished we become at seeding clouds, the amount of moisture available to fall in a given place will always be dependent on global weather patterns – and they are changing fast.

Consider California. It receives much of its rain from an atmospheric river known as the Pineapple Express, a band of moist air carried all the way from Hawaii. The Golden State has been so dry for so long primarily because of shifts in the timing and route of this moisture-laden weather system, and this sort of change is expected to become more common. Even when we do get the right kind of air blasting in, a warming climate might make it too hot for bacteria to do their thing.

Having only just begun to appreciate the role these high-flying microorganisms might play in shaping the weather, it would be a crying shame if we left them with no clouds in which to perform their rain-making alchemy. ■

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