The Seeds of Climate

Aerosols are the salt in our climate soup. **Meinrat Andreae** and **Stephan Borrmann** from the **Max Planck Institute for Chemistry** are studying the impact of aerosols – tiny particles in the atmosphere – on clouds and precipitation.

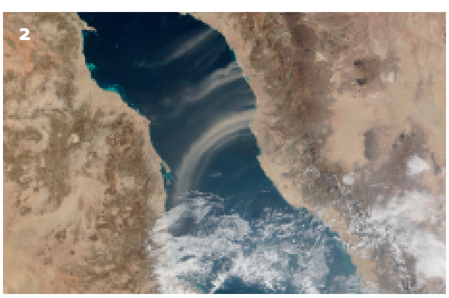
Storm over the Brazilian Amazon – this is where the scientists from Mainz study how clouds form in pristine air.

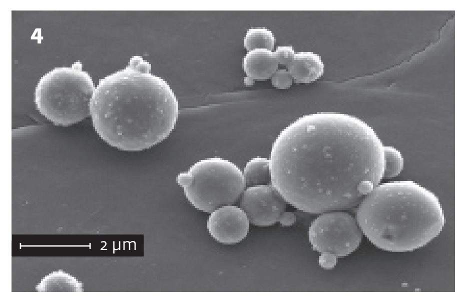
TEXT **ROLAND WENGENMAYR**

On the drive to the Max Planck Institute for Chemistry, it feels like something is missing. Not a single cloud is to be seen in the spring sky above the campus in Mainz. The natural phenomenon to which climate scientists Meinrat Andreae and Stephan Borrmann devote their scientific attention is making itself scarce today. Andreae is Managing Director at the institute and head of the Biogeochemistry Department.

A chemist by background, Andreae travels around the globe with his research team on a quest to find the last remaining regions with a primordial, pristine atmosphere untouched by the impact of human activity. When he finds one of these places, he studies how fine, naturally occurring particles, known as aerosols, affect clouds and precipitation – in other words rain, sleet, hail and snow. What he is doing is basic research, but a precise knowledge of the untouched climate also helps in understanding whether and how anthropogenic activity is changing it.

With him at the table is Stephan Borrmann, also a Director at the Max Planck Institute in Mainz. As head of the Particle Chemistry Department, he, too, examines the role of aerosols in the climate system. Borrmann's research department is also an institution of the University of Mainz, where he holds a professorship at the Institute of Atmospheric Physics. His group





has the world's only wind tunnel in which scientists can study the behavior of individual water drops and ice crystals under the conditions that prevail in clouds. Like Andreae, Borrmann also takes his team and equipment on round-the-world trips. Both teams use research aircraft – a kind of flying laboratory for climate scientists. Both groups also cooperate with colleagues from the Max Planck Institute for Meteorology in Hamburg (see "Sahara Dust over Barbados", page 27).

Andreae's group is particularly interested in how clouds form in pristine air, such as that above the Amazon rainforest. Members of Borrmann's team, for their part, are looking into the kind of gigantic clouds that churn in the skies above the equator. They thus travel predominantly to the tropical zones of Africa and Australia, where cumulus cloud stacks reach as high as 18 kilometers into the sky, compared with the maximum of 12 kilometers in our latitudes. Enormous weather systems with trade winds and monsoon rain are generated in the wide belt around the Earth's equatorial girth. "You could say this is where the Sun's energy comes crashing into our planet," explains Borrmann. "And part of that energy then spreads throughout our atmosphere."

Clouds still represent big white spots on the meteorological and climatological map. Scientists understand the basics, such as how clouds form and how they create precipitation. However, the enormously complex processes inside them that dominate the weather and, from a long-term perspective, the climate, is something that has thus far defied precise observation. The problem is that scientists and their instruments are unable to get inside many of the most interesting clouds – especially not in aircraft. Severe turbulence with wind speeds well in excess of 200 kilometers per hour and hailstones the size of hens' eggs would make any such attempt an act of suicide. Even the use of unmanned drones or weather balloons is too expensive due to the high risk of loss. And indirect, remote sensing meth-

Photos: MPI for Chemistry (top), NASA (2, left), MPI for Chemistry

1 Hundreds of thousands of fires burn in the Amazon during the dry season, some slash-and-burn and some field fires. As the blazes peak in September and October, they cover vast areas with dense smoke.

2 Dust storms – like this one over the Red Sea off the coast of Saudi Arabia – are natural sources of aerosols.

3 Smog over the Po Valley. The fine particles in the gray mist can delay the rain.

4 Fine particles of a spherical nature: Fly ash particles as seen under a scanning electron microscope.

ods, particularly those involving radar beams, do not – yet – provide a very precise picture of the swirling drops and ice crystals inside the clouds.

"A small thundercloud measuring ten by ten by five kilometers contains half a million tons of liquid water, finely dispersed in the form of mist," explains Borrmann. "A lot can happen in the interior and on the surface of a cloud like that." In addition, there is a huge amount of energy raging inside such a compact thundery cluster – easily the equivalent of a dozen small nuclear bombs. As Borrmann observes: "In my view, clouds represent the largest screw holding the climate system together, but they are also the phenomenon we know the least about." And this has serious consequences for weather forecasts: today's computer models are still notoriously inaccurate at predicting where and when precipitation is going to fall.

FLOATING PARTICLES CREATE CLOUDS AND PRECIPITATION

Even models of future climate development consider the effect of clouds only in very rough terms, even though clouds play a crucial role in what goes on. The models have great difficulty predicting how global precipitation distribution will shift as a result of global warming. "These changes will be at least as serious for mankind as the change in mean temperature," says Andreae.

Clouds are multilayered. The lowest layer of the atmosphere, the troposphere, is where the weather actually brews. Clouds in this layer consist of droplets, a growing quantity of which freeze with rising altitude. Above them there are wispy cirrus clouds consisting of fine crystals of ice. In the next layer up, the stratosphere above 12 to 18 kilometers, there is a huge gap in the clouds. Only between 75 and 90 kilometers into the atmosphere, in the mesopause, do we find clouds again – in an extremely thin veil of ice. >

SAHARA DUST OVER BARBADOS

The big cloud systems over the tropics are especially interesting from a climatological perspective. That is why the Max Planck Institute for Meteorology in Hamburg has embarked on a two-year field campaign in Barbados with a group led by Bjorn Stevens. Their aim is to study the interplay between aerosols, clouds, precipitation and the climate. They are accompanied by the two teams from Mainz headed by Meinrat Andreae and Stephan Borrmann.

Barbados is particularly interesting as it is among the easternmost islands in the Caribbean. When the trade winds blow across the Atlantic from the east in the early summer, they carry almost exclusively natural aerosols with them – above all Sahara dust. At other times of the year, the winds blow in different directions. Then they may carry with them, for instance, soot released by humans burning biomass. Under these circumstances, scientists can use the large-scale weather patterns that vary with the seasons to study how clouds and precipitation behave in their undisturbed state and how mankind influences them.

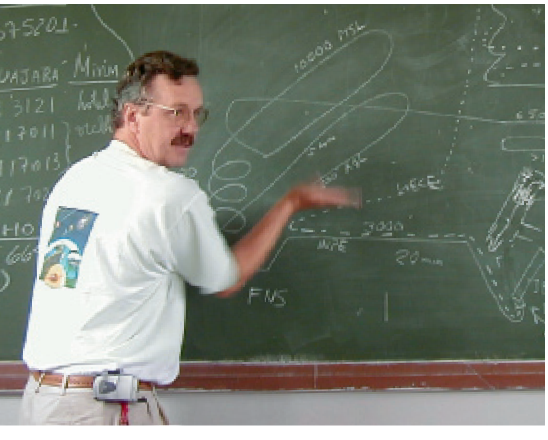
The measuring instruments have been set up on two peninsulas at the far east of Barbados so that anthropogenic influence is virtually excluded when the weather patterns come from an easterly direction. The remote sensing equipment includes laser systems that screen the atmosphere for water vapor content and aerosols. There is also a cloud radar. In addition, the *HALO* research aircraft, operated by the German Aerospace Center (DLR) and partly financed by the Max Planck Society, will fly over Barbados taking measurements. "Spies in the sky" complement the program: the so-called A-Train consisting of six NASA research satellites crosses the skies above Barbados as well. Climate scientists are hopeful that the elaborate system of measurements will deliver precise knowledge about aerosols, clouds and precipitation in the important equatorial region. This should then allow the simulation of more precise computer models of climate development.

The DLR's *HALO* aircraft is engaged in atmospheric research.

Photo: DLR

Cumulonimbus clouds like these in the skies above Africa can contain up to 100 million tons of water. They give rise to ferocious storms.

All clouds have one thing in common: neither they nor precipitation would exist if there were no dust from natural or anthropogenic sources in the air. Aerosols are the salt in the climate soup, and the Sun is what powers the stove to cook it. The Sun heats the ground and the surface of the water in lakes and oceans, making the water evaporate. The rising vapor would really like to condense into liquid water in the colder air at high altitude – but there is never enough natural humidity to form stable water droplets out of the invisible water vapor. It is only when aerosols come into play that the water molecules have a suitable place to land. Thus, an envelope of water can form around a particle: a little droplet is born. If the temperature falls below about minus 15 degrees Celsius, as it does higher up, the droplet would freeze into an ice crystal.



Instructions for the pilot:
Meinrat Andreae outlines the flight profile for a measurement flight in the Amazon.

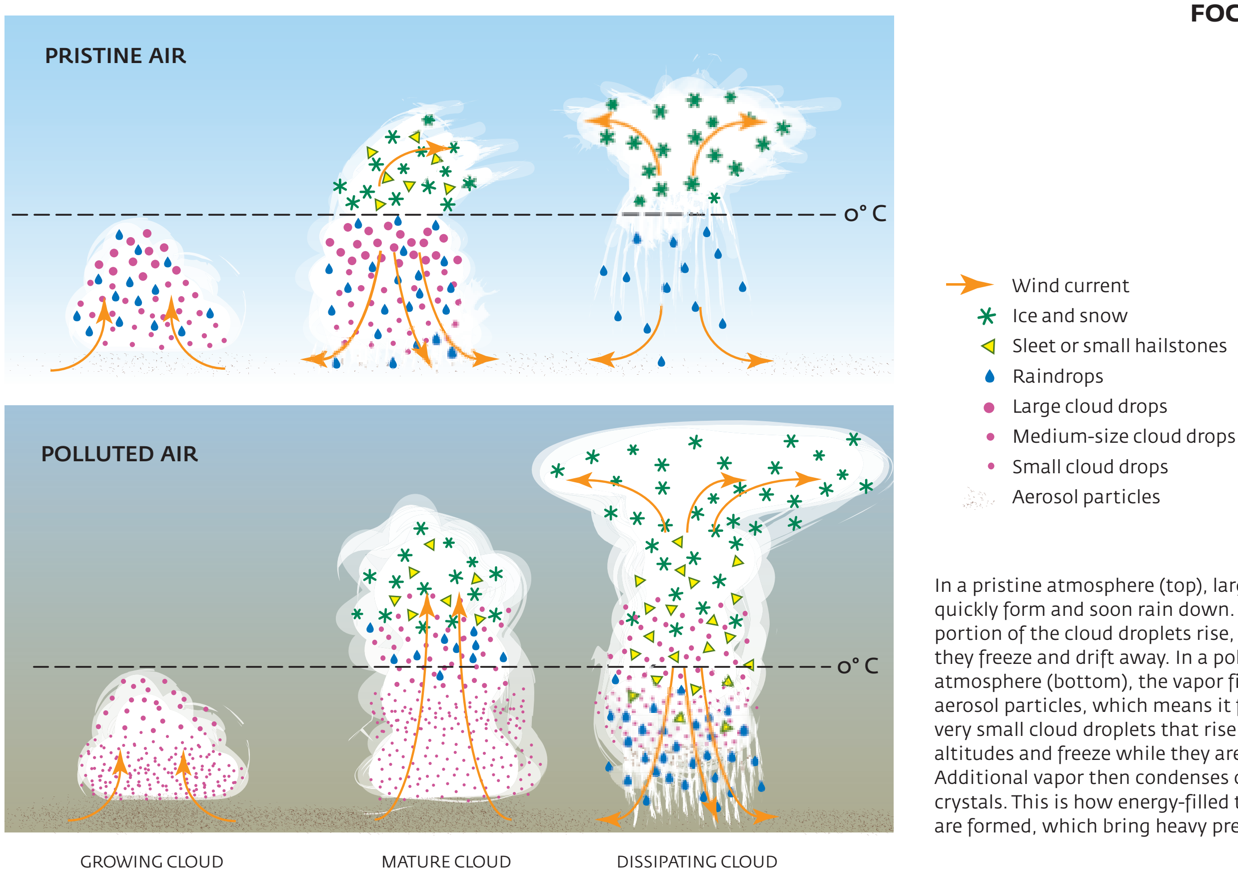
THE SIZE OF THE PARTICLES DETERMINES THEIR IMPACT

Borrmann explains what happens in detail. Actually, it is not unusual for several molecules of water to come together accidentally and form a cluster even without the presence of aerosols. However, these tiny structures measuring just a few nanometers – millionths of a millimeter – are at high vapor pressure: they cannot withstand the molecules' heat-induced urge to move, and they break apart. It is only when droplets get bigger that the forces between the molecules and on the droplet surface are sufficient to bind the clusters of water molecules together. But a cloud droplet in the Earth's atmosphere does not reach this kind of physically stable size unless it has an aerosol particle as its nucleus.

Human activity is accompanied by soot, dust, organic particles, sulfuric acid droplets and other fine particles. Over densely populated areas, there are at least a hundred times more aerosols in the air than there were before our ancestors learned how to make fire. But even back then, there were clouds and it rained. That is because sea salt is one of the natural aerosols that act as cloud seeds. The wind draws it out of the oceans in droplets of spray and then dries the droplets to form fine salt particles on which vapor can later settle.

Saline particles also reach the atmosphere over land, as do desert dust, sulfuric acid droplets, mineral dust and, occasionally, soot from forest fires caused by lightning bolts and volcanic eruptions. Even plants increase the presence of natural aerosols by releasing organic vapors, such as the terpene molecules from coniferous forests, whose oxidation products stick to fine particles in the air. And even fungal spores can be found among the aerosols.

Photos: NASA/JSC (top), Hebrew University – Daniel Rosenfeld (bottom)



In a pristine atmosphere (top), large raindrops quickly form and soon rain down. Only a small portion of the cloud droplets rise, whereupon they freeze and drift away. In a polluted atmosphere (bottom), the vapor finds many aerosol particles, which means it forms only very small cloud droplets that rise to high altitudes and freeze while they are up there. Additional vapor then condenses on the ice crystals. This is how energy-filled thunderclouds are formed, which bring heavy precipitation.

Graphic: Roland Wengenmayr

Chemical differences have very little impact on whether the particles form clouds, says chemist Meinrat Andreae – which surprised even him: "When I began this research, I was looking for a lot more significant effects from the chemical variablilty of the aerosols." What is most important is the size of the particle: from about 60 to 80 nanometers in diameter and larger is the size at which a particle becomes active as a cloud seed. "Interestingly, it turns out that particles from different sources display similar cloud-forming properties if they are the same size," explains Andreae.

Cloud droplets also do not simply swell into actual rain drops by absorbing water vapor as soon as they have reached a few micrometers – thousandths of a millimeter – in diameter. "The growth of a cloud droplet can be nicely reproduced in the lab," says Borrmann. "But if you want to make a droplet measuring hundreds of micrometers in diameter out of one that was just tens of micrometers in size, you would be waiting weeks." That is because, left completely to their own devices, the water molecules would move far too slowly through the air and into the cloud droplets. In a case like that, a drop would never reach a diameter of one half to one millimeter – the size at which it would have sufficient weight to make it through the updrafts and down to Earth, explains Borrmann.

A MISTED-UP WINDOW AS A FLAT CLOUD

Raindrops, however, are formed by collisions between cloud droplets. How that works can be demonstrated nicely with a plant spray bottle. "If you spray water on a window pane, you will have a two-dimensional cloud," explains Borrmann. If you then spray more droplets of water on top of this mist, some of the fine droplets merge into heavier drops. They begin to run down the window pane. "And your two-dimensional cloud is raining," says Borrmann. It is very similar with real clouds: droplets that become slightly heavier by chance fall downward, colliding with other cloud droplets on the way and assimilating them. That is how they swell to the size of a raindrop.

However, this vivid experiment masks a fundamental difficulty: the exact mathematical description of this collision-coalescence process delivers equations that are solvable only by approximation. Minor errors are unavoidable, and they can have major effects in cloud simulation programs. "Besides the difficulties in describing cloud turbulence mathematically, this is one of the main reasons why computerized clouds still don't rain correctly," explains Borrmann: "It is actually very hard to accurately predict just when and how any kind of precipitation is going to fall."

Things are no less complicated when a raindrop finally does fall, which it does at speeds of up to 35 kilometers per hour. In order to observe exactly what happens here, the scientists would need to plummet downward with the raindrop. Or they could turn the whole thing upside down by blowing against the drop from below with an artificial updraft keeping it suspended against the force of gravity. And that is exactly what the world's first vertical wind tunnel does. Borrmann's group operates the tunnel, which can even precool the air to minus 30 degrees Celsius in order to study how cloud ice – in other words sleet, snow and hail – is formed.

A few years ago, the scientists in Mainz were able to use the tunnel to

» The aerosols' role as condensation seeds is crucial in this atmospheric steam engine. They are what determine when and where it rains.

discover how a raindrop behaves as it falls. The drop is deformed into a kind of mushroom shape in the air stream and begins to oscillate. "This happens as a result of turbulence or collision with other drops or aerosol particles," explains Borrmann. Eventually the oscillation becomes so strong that the drop bursts apart.

Surprisingly, this always results in two smaller drops, as the Mainz-based scientists demonstrated. They even described in precise mathematical terms how the drops oscillate. As Borrmann says, "Our goal is to enable computer modelers and radar meteorologists to incorporate more precise formulas in their models or measuring instruments and thus improve the accuracy of their forecasts."

In nature, a raindrop seldom reaches the ground on its first fall. Updrafts send it soaring back into the heights, then it falls again – often freezing and then partially thawing in the process. That is why large hailstones have the internal appearance of onions if you cut them open. Cloud droplets and ice crystals experience similarly rapid ups and downs, too, sometimes even evaporating completely.

Given the complexity of these processes, it is no wonder that scientists have been arguing for years over whether aerosols released by human activity have an effect on clouds and precipitation levels. Recently, Meinrat Andreae and fellow scientists from the University of Jerusalem developed a model that facilitates for the first time a deeper understanding of the aerosol mechanism in clouds.

RAIN FALLS MORE QUICKLY IN PRISTINE AIR

"In our model, we look at a cloud as a kind of steam engine," explains Andreae, smiling. When the Sun evaporates water from the ground, the vapor carries a large part of the solar energy with it as it rises into the air. When it condenses on a cloud seed in the cooler air at high altitude, the energy stored in the vapor is released as latent heat. Just like in a steam engine, the heat is converted into kinetic energy, in this case air circulation. This drives the updraft and causes the cloud droplets and ice crystals to climb.

In this atmospheric steam engine, the aerosols play a crucial role as condensation seeds. They determine when and where it rains. The pristine air above the Amazon rainforest contains very few particles. The sunlight thus penetrates almost unfiltered right down to ground level and evaporates a great deal of water. However, the vapor finds only a few condensation seeds in the air. Consequently, very large drops form while the vapor is rising, which soon rains down heavily on the virgin forest once again.

However, where air pollution causes increased aerosol concentrations, cloud formation and precipitation distribution can change dramatically. The model developed by Andreae and his Israeli colleagues delivers a convincing picture of this. As air pollution levels grow, the rising vapor finds more aerosols that can act as condensation seeds. As a result, more but smaller cloud droplets form, which slows the formation of raindrops. The cloud thus does not rain down on its point of origin, but continues to rise higher. The falling atmospheric pressure causes the rising air to expand and cool down, as in a cooling aggregate. More water then condenses on the cloud seeds and some of them freeze to form ice crystals. Condensation, for its part, releases energy and drives the atmospheric steam engine even more intensely.

As the aerosol concentration rises, another important attribute of the aerosols comes into play: they screen out more and more of the Sun's radiation and prevent it from reaching the ground, causing less water to evaporate. In extreme cases, this can even inhibit the formation of clouds and precipitation entirely. The water vapor that remains then drifts away from the cloud's point of origin rather than raining down upon it.

MORE RAIN, BUT WHERE?

Andreae thus has a scientific explanation for why a thick pall of smog can form over major forest fires or densely populated areas without any rain falling to the ground. "In China there has been a major shift in precipitation frequency, and the cause of this is thought to be the increase in aerosol pollution over northern China," explains the chemist, adding, "But on a global scale, there is always as much precipitation coming down as there is water evaporating." It just rains elsewhere. In those places, the clouds, full to overflowing, empty their contents in the form of devastating heavy rainfall, which can cause floods, landslides and mudslides.

Stephan Borrmann mounts a measuring instrument onto a plane in Kiruna in northern Sweden. His team will use it to study polar clouds in the stratosphere, which contribute to the formation of holes in the ozone layer.

Photo: MPI for Chemistry

High cumulus clouds in the tropics, such as these over the Costa Rican coast, are what really interest Stephan Borrmann.

Such extreme weather events could well become more frequent as the march of global warming continues. Like a steam engine that runs faster when the fire burns hotter, the movement of the air and the circulation of water would also accelerate in the atmosphere. “A warmer world is also a wetter world,” says Andreae, “But a faster water cycle does not necessarily mean there would be more water available for agricultural use.” After all, water also evaporates out of the ground more quickly when temperatures are higher.

So the role of aerosols in the climate is complex. Despite the breakthrough with the new model, which Andreae helped bring about, scientists are not even close to deciphering all of the precise mechanisms involved in the formation of clouds and precipitation. What is more clear-cut, though, is the impact of aerosols in blocking out sunlight: they have a net cooling effect on Earth’s climate. So would dirtier air be a good thing in the face of impending global warming? “Some people reason that we should let the chimneys smoke to slow global warming,” says Andreae. “That is not only unethical, it is also complete madness!” As he points out, “With aerosols, we might be able to reduce global warming by a degree or two, but that is as far as it goes.” In contrast, the effects of manmade greenhouse gases, some of which remain in the atmosphere for centuries or longer, add up over the long term. It is impossible for aerosols to counterbalance that, given that they disappear from the air within a week or two anyway. “And the idea of cooling the Earth by injecting aerosols into the stratosphere, a process known as geoengineering, would mean playing a risky and irresponsible game with the future of our children and grandchildren,” says Andreae.

Meinrat Andreae and Stephan Borrmann have a clear message for the politicians. They have no doubt that we have already turned the climate’s heating controls up dangerously high. Andreae believes that current computer models on climate development have probably underestimated the warming effect of greenhouse gases – for lack of good cloud models. “The targets that the scientific world has communicated to politicians are pretty clear,” says the climate scientist. “The only question is how they can be implemented economically and politically.” ◂

GLOSSARY

Vapor pressure
Liquids change to gases below vapor pressure – in other words, liquids, such as water, evaporate. High vapor pressure means that water evaporates easily – even in cold atmospheric layers.

Collision-coalescence process
When two cloud droplets collide, they coalesce into one.

Latent heat
Amount of heat absorbed or released during a phase transition, such as when water evaporates or freezes. The temperature does not change.

Photo: Stephan Borrmann