RISKY COOLING

TEXT: TIM SCHRÖDER

Volcanoes are sources of ideas. When they erupt, they emit large amounts of sulfur dioxide, cooling the climate. This has prompted experts to discuss whether geoengineering involving the targeted release of the gas could reduce global warming. Ulrike Niemeier from the Max Planck Institute for Meteorology in Hamburg is investigating the feasibility of the idea and the dangers it might entail.

The Pinatubo eruption was enormous. When the Philippine volcano blew off its summit in June 1991, a gigantic ash cloud ascended into the sky. It plunged the island of Luzon into darkness in the middle of the day. Huge amounts of ash rained down on an area as large as Baden-Wuerttemberg, Bavaria, and Hesse combined. It buried streets under a layer that was sometimes several meters deep. Hundreds of people died, and tens of thousands lost their homes. The eruption was so powerful that ash and gases were blasted into the stratosphere, three times higher than commercial airliners fly. The mountain shook for hours, simultaneously spewing out eight million metric tons of sulfur dioxide. Within just a few days, long-range air currents in the stratosphere dispersed the gas over the entire northern hemisphere. And this led to an interesting phenomenon: the Earth became cooler.

We've long known why such cooling occurs. Sulfur dioxide reacts in the atmosphere with water vapor to form sulfuric acid, which reacts further to form sulfate particles. These remain airborne for a period, reflecting a portion of the Sun's rays striking the Earth. This cools the underlying layers of the atmosphere, explaining why climate researchers find the eruption of Pinatubo, one of the strongest volcanic eruptions in the previous century, so intriguing.

"The eruption clearly proved that sulfur dioxide has a measurable effect when it enters the atmosphere," explains Ulrike Niemeier, a scientist at the Max Planck Institute for Meteorology in Hamburg. For years, Niemeier has sought to describe how the sulfur dioxide and ashes emitted by volcanoes affect the Earth's atmosphere. She uses computer simulations to model the effects of volcanic gases on the climate. These include major eruptions in prehistoric times of so-called super-volcanoes, which were many times more powerful than Pinatubo. The eruptions of the Yellowstone volcano about two million years ago, for example, released approximately 200 times more matter than Pinatubo did in 1991. Using computer simulations,

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Models for climate engineering: active volcanoes such as Nishinoshima, 1000 kilometers south of Tokyo, release huge amounts of sulfur dioxide. Particles form from this gas and remain suspended in the atmosphere, reflecting sunlight back into space.

A change of course in research: Ulrike Niemeier researches the impact of volcanic eruptions on the climate, increasingly focusing on the possible effects of seeding the Earth's atmosphere with sulfur dioxide.

PHOTO: TOM PINGEL FOR MPG

Niemeier has calculated how these gigantic quantities may have been distributed throughout the Earth's atmosphere – how the matter cooled down and ultimately altered the global climate.

Over the last 15 years, volcanic sulfur dioxide's cooling effect has led to a shift of Niemeier's research from her original focus – the role volcanoes play in the climate – toward a different field of climate research. The impetus has been anthropogenic warming of the Earth's climate, raising the question of whether we might be able to artificially cool it down. One of the first scientists to suggest this idea was the atmospheric chemist Paul Crutzen, who for many years was the Director of the Max Planck Institute for Chemistry in Mainz. Crutzen published a provocative paper on the subject in 2006. To counteract the impact of the continuous increase in carbon dioxide emissions, he asked whether humanity might need to use technology to intervene in the climate in the future to mitigate the worst effects of climate change. Such climate fixes became known as geoengineering or climate engineering (CE), which now encompasses a wide range of technical strategies. Targeted climate interventions generally fall into two categories: carbon dioxide removal (CDR) and radiation management. The aim of CDR is to remove carbon dioxide from the air, bind it, and safely store it in the long-term. The reforestation of huge, previously unforested areas is under discussion, as is fertilizing the sea with iron to stimulate algal growth. "At present, the most realistic and reasonable solution appears to be systems that filter carbon dioxide out of the air or capture it from the exhaust gases of power stations and industrial plants," says Ulrike Niemeier. This method is known as carbon capture and storage (CCS). The Dutch are already working on implementing it. As part of the Porthos project, in the coming years, a pipeline is to be laid at the Port of Rotterdam parallel to the refineries, power plants, and cement works, into which carbon dioxide from exhaust gases will be fed. The carbon dioxide will then be pumped down the pipeline into a depleted natural gas reservoir under the North Sea.

A controversial idea

The second climate engineering category, known as radiation management, includes methods that directly impact the Earth's heat balance. One particularly bold idea in this category is solar radiation management (SRM), shading the Earth in space with huge sunshades – a plan that is still considered to be in the realm of science fiction. But there are also options on a smaller scale: aircraft, for instance, could scatter particles into the atmosphere, which could then reflect some of the Sun's radiation back into space. This idea, however, exposed Paul Crutzen to a storm of indignation. It is always hubris, so the detractors, to try to alter the Earth's radiation budget using technology. Furthermore, the impact of such a massive climate intervention would be impossible to predict in the various regions of the world. After many years of research, Ulrike Niemeier agrees with this view. "While CDR only reduces carbon dioxide concentration in the atmosphere, radiation management influences the amount of solar energy reaching the whole of the world's surface."

Aerosols could slow down heating

All the same, Paul Crutzen's paper triggered considerable scientific interest in climate engineering. As experts in simulating sulfur clouds from volcanic eruptions and their impact on the climate, Ulrike Niemeier and her colleague Claudia Timmreck were also much in demand. At that time, they had just developed a unique simulation tool: a stratospheric aerosol model, which could be employed to calculate the impact of sulfur dioxide or sulfate particles in the stratosphere. Aerosols are particles of a few nanometers to several micrometers in size, which are so small and light that once they have been thrown up into the atmosphere, they almost never sink back to the ground. Sulfate particles in the stratosphere are also aerosols. Ulrike Niemeier was able to use her model to calculate how quickly and efficiently small sulfate particles form from sulfur dioxide, and how quickly they clear up once again by gradually clumping together and sinking down from the stratosphere.

"At the time, along with colleagues we tried to clarify whether climate change induced heating of the Earth could theoretically be compensated

SUMMARY

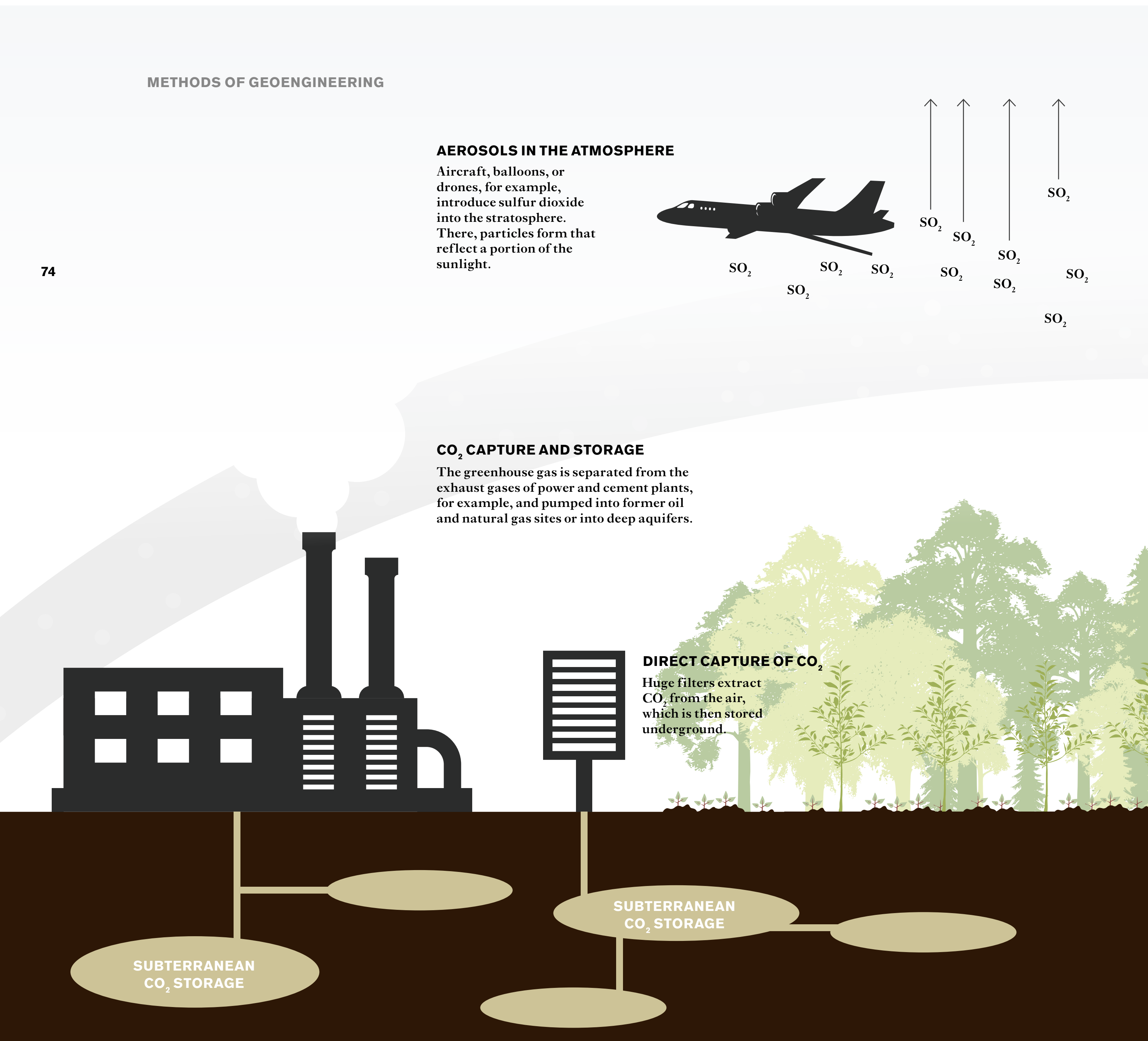
Geoengineering, or climate engineering, is viewed as one way of halting anthropogenic climate change – whether through reforestation, subterranean storage of carbon dioxide, iron fertilization of the ocean, or shading the Earth by means of sulfate particles produced from sulfur dioxide.

According to simulations, the average global temperature could be maintained at the level of 2020 without reducing greenhouse gas emissions if five to eight times more sulfur dioxide were released into the atmosphere each year than from the 1991 Pinatubo eruption.

According to the calculations, the reduction in energy input from the Sun would disrupt large air currents in the tropics, for example, with unforeseeable consequences for the global climate. Aerosols formed from sulfur dioxide would also likely reduce average global rainfall. This could trigger conflicts between nations, some choosing unilaterally to go on releasing the gas and others suffering from the reduction in rainfall.

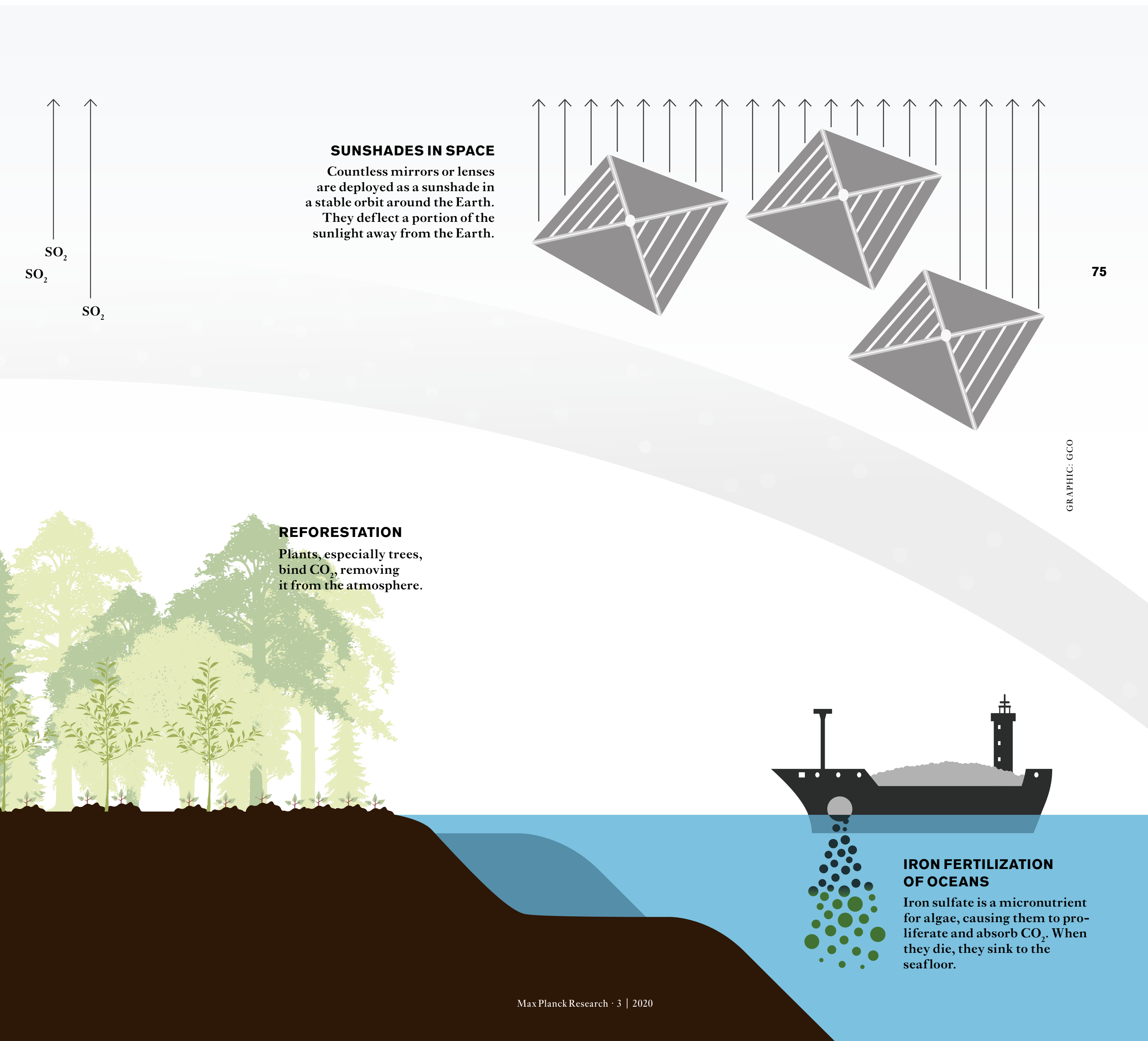
for by sulfur dioxide," explains Niemeier. Their investigations were part of Implicc, a large EU project led by her colleague Hauke Schmidt, which examined "Implications and risks of engineering solar radiation to limit climate change." The findings were clear and – much like Crutzen's article – controversial: yes, global warming could indeed be compensated for, even in the worst-case scenario outlined by RCP8.5, the Intergovernmental Panel on Climate Change. In this "business-as-usual" scenario, CO_2 emissions would continue to rise in the coming years. The Implicc partners calculated that the temperature level of 2020 could be maintained by means of large-scale sulfur dioxide injections into the atmosphere. "On average, the climate would remain milder worldwide," says Ulrike Niemeier. "However, average global rainfall would slightly decrease."

This would however be problematic to put into practice. "If, despite rising CO_2 emissions, we were aiming to maintain 2020's climate through to 2100 with the help of sulfur dioxide alone, humanity would have to release five to eight times as much sulfur dioxide into the stratosphere each year than that from the 1991 Pinatubo eruption," says Niemeier. That would be absurd. A Japanese research team arrived at similar conclusions, calculating that 6,700 airplanes would have to distribute sulfur dioxide in the stratosphere every day to reduce global warming by one single degree Celsius. For comparison, at London's



Heathrow Airport, 1,200 aircraft take off every day at peak times. Ulrike Niemeier also stresses that such sulfur dioxide releases would have significant side effects. Bright blue skies would be likely to take on a milky appearance. Worldwide, rainfall would decrease on average, and the monsoon and large air currents in the atmosphere would change due to our efforts to reduce solar energy input. Solar radiation would drop more steeply in the tropics than at the poles, thereby reducing the temperature gradient between the two regions, which could weaken air currents. The quasi-biennial oscillation (QBO), one of the large stratospheric air currents in the tropics, would be affected. Every two years it changes its direction – from west to east and then back again. Coupling her aerosol model with the MPI-ESM, the large climate model of the Max Planck Institute for Meteorology, Ulrike Niemeier investigated what would happen to the QBO. "The calculations clearly show that a large-scale sulfur dioxide injection would lead to the collapse of the QBO," says Niemeier. "We have no way of predicting what impact this would have on the global climate."

Andreas Oschlies from the GEOMAR research center in Kiel considers research such as Ulrike Niemeier's to be groundbreaking. "She's one of the very first to have analyzed in detail the chemical-physical processes in the stratosphere," says Oschlies, who is an expert in climate engineering. "She has supplied quantitative, robust



GRAPHIC: GCO

data, which can be used to correctly calculate the climate in the future if we implement such climate engineering." The discovery, for example, that sulfate particles clump together over time has been pivotal. In other words, it won't help to pump ever more sulfate into the stratosphere, because the aerosols will just clump and sink at a higher rate. Saturation is bound to occur at some point, no matter how much sulfate airplanes spray. "Niemeier's findings have been essential in enabling us to assess how effective such radiation management methods might be," says Oschlies. Ulrike Niemeier has also analyzed the effect of different sulfur dioxide release methods, for example, whether daily releases of the gas or releases at other particular intervals would be more effective. She discovered that releasing large quantities into the stratosphere over a period of one month would result in far less particle clumping than daily releases. Not only that, the cooling effect was highly dependent on where on Earth the sulfur dioxide was released. The models suggest that injections at several points around the tropics would have the greatest impact.

Such findings make it sound like Niemeier and other experts have already worked out a climate-engineering master plan. But, according to Ulrike Niemeier, nothing could be further from the truth. "I believe there's only one way to halt climate change: reduce CO_2 emissions as quickly as possible. Because one thing's clear: radiation management would only be treating the symptoms. It wouldn't do anything to solve the real problem, carbon dioxide." Nevertheless, investigating climate engineering is important. If the climate were to change extremely rapidly, climate management measures could at some point be placed on the political agenda as an emergency option – the lesser of two evils in comparison to massive climate impacts. "If it ever came to that, we would need to know precisely what we would be getting into." Nor can it be ruled out that at some point in this century, individual countries may embark on climate engineering on their own initiative – without consulting the worldwide community of nations. Politically, that would be a fiasco, as it would affect the whole world. A solo initiative by individual nations or a small group of nations could therefore lead to conflicts, for example if rainfall decreased in other countries. Hence, for Ulrike Niemeier, the Ceibral project

GRAPHIC: GCO FROM MICHAEL BÖTTINGER/DKRZ

Historical cooling effect: Ulrike Niemeier has calculated how the sulfur dioxide cloud that formed after the eruption of the Yellowstone volcano about two million years ago is likely to have spread over the Earth. Her results indicate that after eleven days, it covered large areas of the northern hemisphere. After about a month, it covered almost the entire northern hemisphere.

has been one of the most interesting she has worked on. Together with Hauke Schmidt, lawyers, political scientists, economists, and philosophers, she helped investigate whether and how climate engineering could be uniformly regulated internationally. The focus was on whether individual nations could be held liable for damage caused by their climate engineering activities.

In her work for Ceibral, Ulrike Niemeier attempted to deduce from models where the world's winners and losers of climate engineering measures would be. "However, it's incredibly difficult to causally link damage to a particular climate engineering measure," she says. "As an example, a five-week drought in Poland led us to ask whether climate engineering measures in Australia were to blame." She couldn't give a definitive answer. "But it was enormously exciting working with experts from the other disciplines, while developing a common language and mutual understanding of each other." It became clear that, at present, it would be difficult to prosecute a nation for climate engineering activities. No court in the world has ever tried such a case. Which institution would be responsible? "And in this respect, I think climate engineering also represents a crucial political issue," says Ulrike Niemeier. "Should we ever actually consider climate engineering, humanity will have to be extremely vigilant not to stumble into starting wars. At any rate, an international agreement regarding the matter of liability should be ratified beforehand."

Her collaboration in the Ceibral project and also her long-standing cooperation with other climate researchers as an expert in aerosols have shown Ulrike Niemeier how important academic exchange between disciplines is. "We have no idea whether we'll ever employ climate engineering," says Niemeier. "But we still need to prepare ourselves for it and, above all, be aware of the risks."

GLOSSARY

AEROSOLS
are particles dispersed in the atmosphere, ranging in diameter from a few nanometers to several micrometers. They reflect solar radiation but also play a role in the formation of cloud droplets.

RADIATION MANAGEMENT
is a method of climate engineering which would shield the Earth from a portion of the Sun's light by means, for example, of sulfate aerosols.