Lots of different shapes: in the tropics and sub-tropics, countless clouds form in a belt where the trade winds prevail. These trade-wind clouds cool the climate by reflecting sunlight. They can take different shapes – the one shown here is called a flower.
In early 2020, climate researchers assembled an armada of ships and aircraft off the coast of Barbados, the likes of which had rarely been seen before: four research vessels, including the two German ships Meteor and Maria S. Merian, and five research aircraft, including the Halo jet of the German Aerospace Center (DLR), a French ATR-42, and a US Lockheed WP-3D Orion Hurricane Hunter, all went cloud-surveying in the tropics. DLR’s large-scale cloud radar Poldirad went into operation on Barbados. More than 300 researchers from 20 nations took part in this major operation. The object of study: small, low-lying trade-wind clouds.

The four-week campaign was called Eurec4a, which stands for “Elucidating the role of cloud-circulation coupling in climate.” Of course, the name also alludes to Archimedes, who is said to have discovered the law of buoyancy while bathing and exclaimed: “Eureka!” – “I found it!” As Bjorn Stevens points out: “Clouds are really about buoyancy!” As Director at the Max Planck Institute for Meteorology in Hamburg, Stevens conceived and led the Eurec4a campaign with his French colleague Sandrine Bony, Director at the Centre National de la Recherche Scientifique in Paris. They were joined on the ground by David Farrell, Director of the Caribbean Institute for Meteorology and Hydrology. Stevens also worked with Farrell to establish the Barbados Cloud Observatory at the easternmost point of the island, which became operational in 2010. But why are climate researchers focusing so closely on tiny clouds in the tropics? Trade-wind clouds are low-lying clouds that form at an altitude of about 700 meters and, usually, extend no higher than two kilometers. Yet they’re a heavy weight in the climate system because there are so many of them. They are as gregarious as a flock of geese and cover more than 30 percent of the total area of the trade-wind zone, which stretches like a belt across one-fifth of the Earth’s surface in the tropics and subtropics. Together, the clouds form a large mirror that reflects much of the Sun’s radiation back into space, effectively cooling the surface. Since trade-wind clouds cover a much larger area than the polar ice caps and are exposed to almost vertical solar radiation, their reflective effect on solar radiation is much more significant than that of the large areas of ice in the Arctic and Antarctic.
If the number of trade-wind clouds were to decrease as a result of climate change, this would have a crucial impact on the Earth’s climate. This concern was sparked by the results of several climate studies, most notably a scientific paper published in 2014 in the British journal Nature. To put it simply, the article showed that with warming the trade-wind layer would become dryer, leading to fewer clouds, and hence an increase in warming, which in turn would further increase the drying, reducing the clouds further, and so on. “Positive feedback” is the technical term for a vicious cycle of this kind.

That large, global climate models are effective in simulating global trends is not disputed, in addition, they provide one of several lines of evidence that underpin the scientific consensus that human greenhouse gas emissions are warming the planet. However, today’s climate models poorly represent cloud formation and the ways clouds respond to global warming. This leaves the magnitude of warming in doubt, as well as the regional impacts. Eurec’a was conceived to address this knowledge gap. The four-week campaign was designed to collect data on what factors influence cloud numbers, and in particular their response to variations in weather similar to what might be expected with general warming. To this end, several research activities ran in parallel and were closely coordinated.

### SUMMARY

The Eurec’a campaign used four research ships, five aircraft, and other instruments to study the tropical trade-wind clouds.

The density of the trade-wind clouds will not decrease in the foreseeable future due to climate change, as shallow mesoscale overturning circulation compensates for the moisture losses caused by global warming: the cooling effect of trade-wind clouds will remain for the foreseeable future.

A better understanding of how precipitation forms in trade-wind clouds, and why trade-wind clouds vary in shape, will help to improve climate models and their predictions.

The centerpiece of this cloud research was a cylindrical volume about 10 kilometers high and 220 kilometers in diameter. Within this volume, the team tried to record the air movements as completely as possible, particularly the subtle vertical motions that influence moisture transport. To put it in everyday language, cumulus clouds are produced from air that is warmer and moister than surrounding air, which makes the clouds buoyant and causes them to accelerate, something scientists call convection.

At an altitude of about 700 meters, the rising air has expanded and cooled to a point that it becomes saturated, and water vapor condenses into cloud droplets, explains Raphaela Vogel. She participated in Eurec’a and is now a scientific research assistant at the University of Hamburg. “That is why these cumulus clouds have such a razor-sharp edge at the base,” she explains. This can also be seen in Europe during good summer weather. Vogel received her PhD from the Max Planck Institute for Meteorology and joined Bony’s group in Paris as a postdoc. Her job at that time was to coordinate the flight program as lead scientist. She flew mostly on the French
ATR-42 and occasionally on the German Halo. It was a very exciting time, she says enthusiastically, and the campaign helped the international team to bond.

**Aircraft for every cloud level**

The German Halo jet was responsible for the highest level. It flew the upper section of the cylinder 72 times over the four weeks, in addition to 13 such flights with the American WP-3D. And each time, Geet George, then a graduate student in Stevens’ group and now an assistant professor at Delft University of Technology, sat in the back making a crucial measurement: At exactly 12 points on the 360-degree circle, like the five-minute markers on a clock face, he shot probes out of the plane. These then floated on parachutes 10 kilometers down to the surface of the ocean. Their cardboard tubes contained a transmitter, three sensors for pressure, temperature, and relative humidity, and a GPS receiver. During their 12-minute descent, they transmitted their measurements and positions to Halo 2 to 4 times per second. The GPS data was particularly important because it provided information about how far the winds at each altitude blew the probes laterally. George used this data to calculate which air masses flowed through the imaginary wall into – or out of – the circumscribed measurement volume. Since the conservation laws of physics prohibit air from simply disappearing or being added, this makes it possible to calculate how convection behaves within the cylinder.

The French ATR-42 had the task of flying much lower inside the measurement cylinder, at the height of the cloud base. Instruments that scanned the clouds laterally with radar and lidar, a type of laser scanner, were particularly important. They provided information about the cloud droplets and their movements. To ensure that these instruments were aimed as horizontally as possible, the aircraft itself had to be aligned horizontally while flying straight and level. The ATR-42 therefore repeatedly flew a course consisting of two tight turns and long straight sections, not unlike an ancient Roman chariot race. Discipline was needed, even when there were hardly any clouds, in order to obtain an overall picture in all weather conditions over the four weeks. “It wasn’t always easy to pull through,” says Raphaela Vogel with a laugh, “when there was a nice thunderstorm a little further away.” Looking back, she is particularly impressed by the reliability of the Eurec'a data. But what were the results?

First, the researcher explains what generally happens during cloud formation: moist air heated by the Sun rises above the water, while cooler, drier air descends between the clouds. This convective flow has been known for a long time. In the Eurec'a project, researchers have now discovered mesoscale air circulation over an area spanning 100 to 200 kilometers that brings moisture to where clouds form. There is therefore no reason to fear that trade-wind clouds will dry out as a result of global warming.

A previously unknown moisture cycle in the atmosphere: cumulus clouds form where warm, moist air rises; cooler, dry air descends between the clouds. This convective flow has been known for a long time. In the Eurec'a project, researchers have now discovered mesoscale air circulation over an area spanning 100 to 200 kilometers that brings moisture to where clouds form. There is therefore no reason to fear that trade-wind clouds will dry out as a result of global warming.
from higher up must sink to compensate. As the moist air rises in this convective lifting, its temperature drops and some of the water vapor condenses into cloud droplets. These moist air masses containing droplets mix with the drier air masses descending from above. This causes some of the droplets to evaporate once again. The water doesn't disappear; it simply becomes gaseous and does not contribute to the cloud. In a warmer climate, however, it is possible that fewer cloud droplets would form since global warming would mean that the air descending from above would be able to absorb more water vapor. As a result, fewer and fewer trade-wind clouds would form, which in turn would accelerate global warming due to the decreasing reflective effect. This would mark the positive feedback loop mentioned above.

According to the findings of the Eurec4a campaign, this feedback is nowhere near as strong as some climate models would have us believe. This was shown by a team led by Raphaela Vogel, including Bjorn Stevens and Sandrine Bony, in a publication on the main finding of the field study in the December 2022 issue of the journal Nature. “This is good news for us humans,” says Raphaela Vogel. Geet George explains why. He played a key role in a second major publication on the results, which appeared in Nature Geoscience in July 2023. The scientist explains that atmospheric circulations so small that they fall through the cracks of previous global climate models are crucial.

Sufficient moisture supply

These “shallow mesoscale overturning circulations” extend over areas about the size of that flown around by Halo and reach up to about 1.5 kilometers in height. “Mesoscale” means that we are talking about processes in the middle regions of the climate system, with an area of about 100 to 200 kilometers. This circulation mixes moist and dry air masses more vigorously than some global climate models would lead us to expect. Basically, it works like the convection that creates clouds, except that in this case, it takes place in these middle regions that were flown around near Barbados. It provides enough moisture to largely compensate for the drying of cloud droplets in a warmer environment. The rising, moist air and the falling, dry air together form the ascending and descending parts of the shallow, mesoscale circulation – like an old-fashioned paternoster elevator that goes up one side and down the other, with differently occupied cabins.

“We have identified a new circulation system that is strongly associated with the variability of cloud cover,” concludes Bjorn Stevens. “And this is a mechanism that doesn’t exist in our current climate models!” Eurec4a’s most significant finding was discovering how important this shallow circulation is in areas spanning between 100 to 200 kilometers for the present...
and future existence of trade-wind clouds. In addition, there were other new insights into cloud activity, such as how the movement and organization of trade-wind clouds affect the precipitation that they release. Climate scientists are not yet able to explain the conditions under which cloud droplets become rain, snow, or hail. Yet, being able to do so is important for weather forecasting and simulations of regional climate change. To better understand how precipitation forms in trade-wind clouds, Jule Radtke, a doctoral researcher at the Max Planck Institute for Meteorology, analyzed measurements from Poldirad in Barbados. Poldirad stands for Polarization Diversity Doppler Radar. This technical term essentially means that the large device can track the movements of droplets in a cloud very precisely via radar echo. Poldirad is normally located at the DLR site in Oberpfaffenhofen. With financial support from the Max Planck Foundation, the system was dismantled for Eurec4a and sent across the Atlantic by ship. It arrived in Barbados several months later and initially got stuck due to customs formalities. But despite all the obstacles they ran up against, the team managed to get the radar up and running near the Barbados Cloud Observatory just in time.

Radtke used the data from Poldirad to study the influence of the herding behavior of trade-wind clouds on their precipitation. “It used to be said that these small trade-wind clouds are fair-weather clouds that don’t grow particularly tall and therefore don’t rain,” says the climate researcher, “and that they tend to spread out randomly.” Even before Eurec4a, however, it was clear that this picture was not correct. Radtke concluded that the herd instinct has a clear influence on the rainfall behavior of clouds. When clouds herd together, they rain more often. This is because they seem to protect each other from the sun. This creates a more humid atmosphere and prevents raindrops from evaporating before they reach the ground. On the other hand, less rain falls from clouds in the herd because less rain is formed in them. “This could be because there are also younger or older clouds hanging around,” says Radtke with a laugh, “which either have yet to or no longer contribute to precipitation.”

Flowers and fish in the sky

During the preparations for Eurec4a, Bjorn Stevens’ team discovered that clouds’ ability to self-organize is very complex. Using machine learning and pattern recognition, the Hamburg team identified four different herd patterns in satellite images, which they named “sugar,” “gravel,” “flowers,” and “fish.” The latter structure does indeed resemble a fish skeleton. Together with Hauke Schulz, now a researcher at the University of Washington in Seattle, Stevens investigated whether a high-resolution climate model, which is limited to a smaller area to save computing power, could simulate these patterns with the Eurec4a data. The simulation was quite successful for “fish” and “gravel,” but not for “flowers.” The importance of being able to simulate these structures to a high degree of accuracy for future climate models remains to be seen, Stevens emphasizes. At the very least, the models need to calculate the average cloud cover as precisely as possible, and the shape of the clouds could be a relevant factor. The lesson from Eurec4a is that climate models need to be much more fine-tuned to simulate such mesoscale processes in a future warmer climate.

Bjorn Stevens is optimistic that the high-resolution climate models of the future will allow much more accurate predictions of small-scale processes. Only if climate models can better capture the processes in the atmosphere will they be able to predict phenomena such as regional changes in climate more accurately. The fact that more and more powerful supercomputers are becoming available for use in climate research will certainly help. However, even these computers will not be able to replace field research. A follow-up field study, Orcestra, will take place in August and September 2024, and Barbados will once again serve as its base.

GLOSSARY

SHALLOW MESOSCALE OVERTURNING CIRCULATION
is the name of an air movement discovered as part of the Eurec4a campaign, in which warm, moist air rises and cold, dry air sinks in areas of 100 to 200 kilometers. The circulation compensates for the loss of moisture in the tradewind clouds caused by global warming.