Sometimes too little, sometimes too much: climate change brings both longer dry spells and more heavy rainfall. Water cannot seep away from parched or sealed surfaces, increasing the risk of flooding.

PHOTO: ADOBESTOCK

WATER ON A WAYWARD PATH

TEXT: JAN BERNDORFF

Drought and heavy rainfall – climate change is altering the planet's water cycles. That has considerable consequences for ecosystems and thus for our food supply. Max Planck researchers are refining climate models to better understand interrelationships, predict regional impacts, and enable adaptation to changing water availability.

In a good orchestra, all the parts – strings, wind, and percussion – harmonize to create a melodious experience. Research is no different, even if the result is more important than the experience. That is why nearly 50 research institutions from 11 countries have chosen this analogy for their major measurement campaign: Orcestra. The acronym stands for Organized Convection and Earthcare Studies over the Tropical Atlantic. In August and September, about 200 researchers and technicians collected data across the Atlantic Ocean between Cabo Verde off the coast of West Africa to Barbados just north of South America to find out how the climate and towering rain-bearing tropical clouds interact. It was an immense effort, spread over eight individual projects – the parts of the orchestra, so to speak – with acronyms named after musical instruments: Cello, Clarinet, Strings, and Percussion. The researchers use specially equipped research aircraft to make measurements above, in and around clouds; ships and ground stations to take measurements under them; and last but not least, the new Earthcare satellites to get a good overview from space. They make use of cameras, radar, lasers, autonomous probes, and everything else that technology has to offer.

SUMMARY

Climate change is altering the global water cycle. In particular, precipitation is being distributed differently: the Mediterranean region, for example, is experiencing longer and more intense droughts, as well as more and heavier downpours that cannot be absorbed by the soil.

Higher-resolution models make it possible to represent rain-forming processes much more physically and thereby simulate regional and local weather extremes missing from existing models. Measurement campaigns such as Orcestra are organized to help provide the data needed to fine tune these models.

The measurements and model predictions will enable societies to adapt to changes in water availability and prepare for extreme events.

A poorly understood climate driver

In addition to Max Planck Institutes, Helmholtz Centers, German University partners funded by the DFG, and Leibniz Institutes, the European Space Agency (Esa), the CNRS (France), and universities from various European countries and the US, as well as the Instituto Nacional de Meteorologia et Geofísica of Cabo Verde and the Caribbean Institute for Meteorology and Hydrology were all involved. “We are putting together a big orchestra to unravel the secrets of rain-bearing clouds,” says Ulrike Kirchner, Research Operations Coordinator at the Max Planck Institute for Meteorology in Hamburg, which co-initiated the campaign. The goal is to gain a clearer picture of how and where rain forms and develops in the Intertropical Convergence Zone (ITCZ); how it and the clouds that accompany it influence the regional, but also the global water cycle and ultimately the climate; and how climate change is altering these processes.

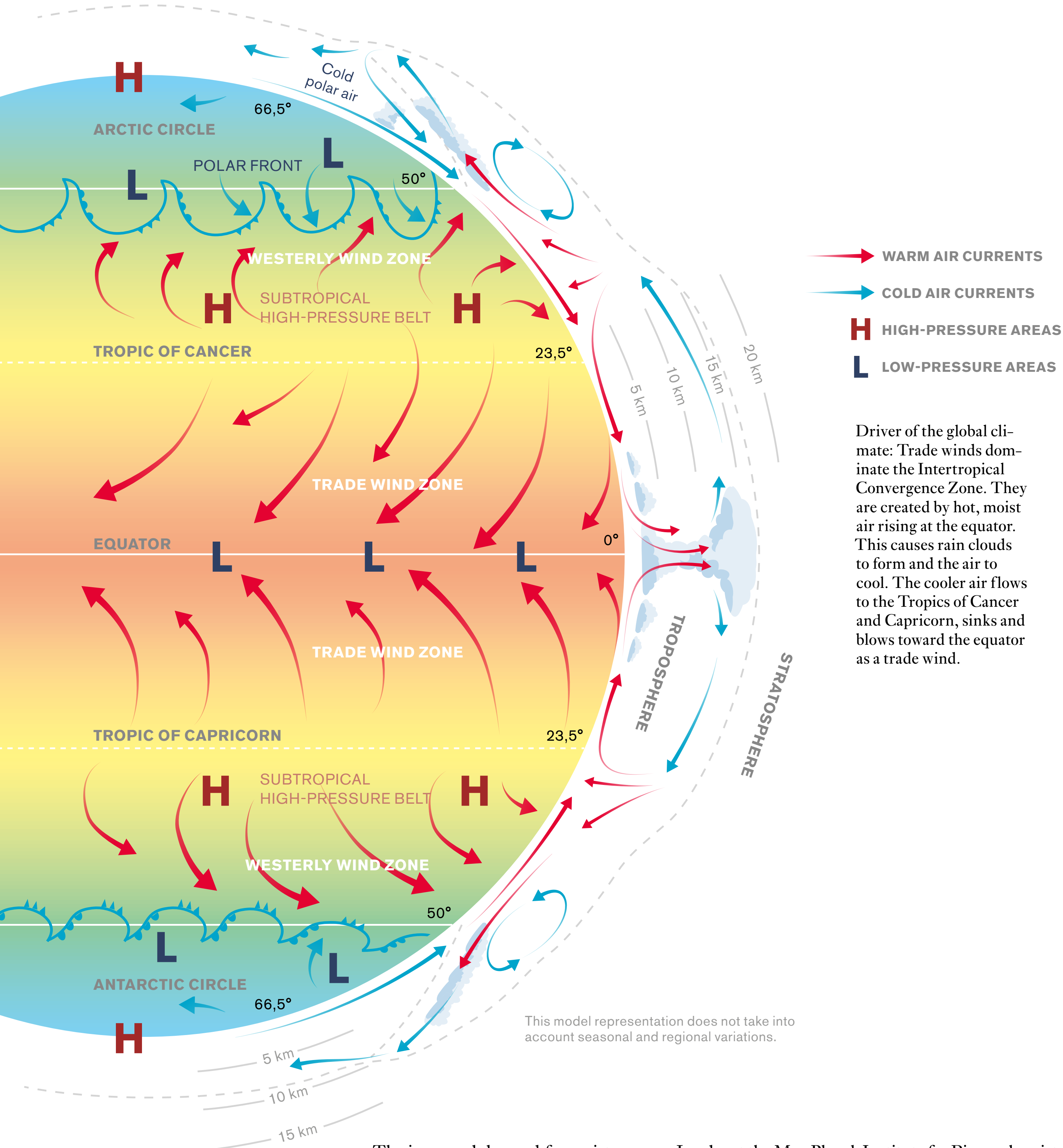
The ITCZ is the zone near the equator where the trade winds from the north and south meet. They are part of a cycle that is important for the entire global climate: where the sun is highest, the air heats up the most and rises. As it rises, it cools to form towering clouds that gather and tower above the ocean in ferocious bands of rain. Above, the cooled, now dry air flows toward the edges of the tropical zone. There it sinks again, forming an area of high pressure, which usually means dry, hot weather: this is why there are so many deserts along the Tropics of Cancer and Capricorn. At ground level, the air flows back toward the equator as a trade wind.

This pattern is known as the Hadley cell. It influences other cycles of air and water in the atmosphere that occur closer to the poles and determine weather around the globe. The driver of this process is in the ITCZ. “It’s startling,” says Bjorn Stevens, Director at the Max Planck Institute for Meteorology, “how little we understand this circulation system.” The Orcestra campaign aims to change that and contribute to a better understanding of how the global climate changes.

These predictions are already alarming, as the reports of the Intergovernmental Panel on Climate Change (IPCC) make clear: by the end of this century, the global climate will have warmed by an average of 1.6 to 4.7 °C compared to pre-industrial times, depending on the amount of greenhouse gases humans continue to emit. These estimates seem conservative, as the world is already on track to be over 1.5 °C warmer in the present year. Warming intensifies the hydrological cycle as anyone who has experienced the difference between a tropical deluge and a northern European rain shower can attest. This will bring with it intensified heat waves, drought, and fire, but on other hand, storms, and floods too. Overall precipitation will increase, but it will be distributed differently.

“Soils will tend to become drier, even though there is no reduction in rainfall.”

RENÉ ORTH



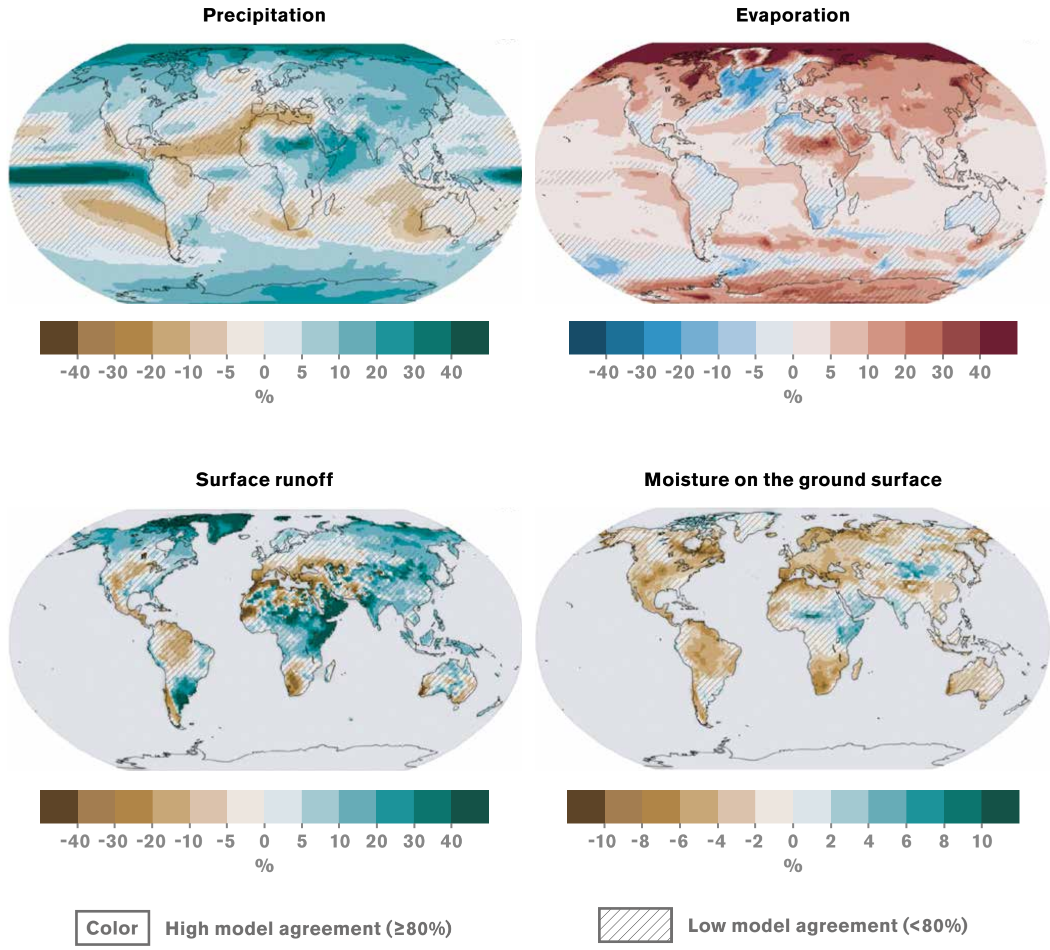
Driver of the global climate: Trade winds dominate the Intertropical Convergence Zone. They are created by hot, moist air rising at the equator. This causes rain clouds to form and the air to cool. The cooler air flows to the Tropics of Cancer and Capricorn, sinks and blows toward the equator as a trade wind.

The increased demand for moisture as a result of a warmer atmosphere means soil moisture is likely to decrease in many regions of the world, including Europe, especially in the Mediterranean region. This effect may be compounded by soils that have been dried out by prolonged hot spells and are unable to absorb the heavy rainfall, leading to more run-off and less replenishment. "Soils will tend to become drier, even though there is no reduction in rainfall," says climate researcher René Orth, former Research Group Leader at the Max Planck Institute for Biogeochemistry and now a professor at the University of Freiburg.

Various weather-related disasters in recent years have shown what this can mean. Although individual events cannot be clearly attributed to climate change, some researchers are attempting to quantify how much more likely a particular heat wave or heavy rainfall has become as a result of global warming. The crux of the matter is that to be prepared, people naturally want to know ex-

⟶

Climate change: by the end of the century, the global water cycle will have changed, in some cases drastically, compared to the average of the years 1995 to 2014, according to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. This will affect amounts of precipitation, evaporation, surface runoff, and soil moisture (scenarios of global warming 3 °C above pre-industrial levels).



GRAPHIC: GCO BASED ON BOX TS.6, FIGURE 1 IN IPCC, 2021: TECHNICAL

actly where and when such natural disasters are likely to occur and how much water will be available. And not just when a storm or drought is approaching. But that's not something attribution science, or today's climate models can deliver.

The specific consequences of these climate impacts vary greatly from place to place. Global climate models typically have a resolution of only 100 to 150 kilometers. And this means that many essential processes in climate models must be calculated empirically, rather than through the use of basic physical principles. Much finer computations are possible, allowing a more physical representation of the climate system, but climate researchers have not had the dedicated access to the most powerful computers needed to perform much finer computations. But things are changing thanks to new supercomputers and artificial intelligence: global models with a resolution of a few kilometers are beginning to be developed and used – by many of the same people participating in Orcestra. What they are missing is the data needed for their evaluation and fine-tuning – this is where Orcestra comes in.

Eurec4a, a similarly complex measurement campaign that took place in Barbados in 2020 and which demonstrated new measurement approaches on which Orcestra is based, has already delivered a surprise (see MaxPlanckResearch 1/2024): until now, models showed that global warming should lead to a decrease in trade wind clouds – the typical low, fleecy clouds that populate the trade winds. Because these clouds reflect much of the Sun's energy back into space, their decline would heat the Earth even more. But Eurec4a has shown that there has not been a reduction in cloud formation.

Thunderstorms in climate models

Orcestra will now study the high, dark thunderclouds of the ITCZ. How and where do they cluster? This process, which is crucial for understanding how they influence rain formation and attract winds, is not only central to understanding the climate in the tropics, but worldwide. Nonetheless it's a process entirely neglected by the types of climate models on which international assessment are made. It's quite an amazing fact considering that 30 percent of all the rain on Earth falls from these clouds, and that they form the seeds tropical cyclones (hurricanes and typhoons), which cause enormous damage in temperate zones as well.

Atmospheric scientist Cathy Hohenegger's research group at the Max Planck Institute for Meteorology specializes in thunderstorms. She notes that it is still unclear how they will change in our latitudes as a result of global warming. Current models predict that they will become more frequent and severe. "But we don't have a clear idea because we can't simulate thunderstorms in a global context with existing models. The resolution of these models isn't high enough. So far, the models can only guess where thunderstorms will occur based on rules of thumb." However, the researchers have now developed a new model that can simulate the climate globally with a resolution of five kilometers or even finer: "This finally makes it possible to study individual thunderstorms and their interaction with large-scale circulation." With these more detailed models, the team hopes to answer questions such as whether thunderstorms get their moisture primarily from evaporation from soil, water, and plants or from larger-scale atmospheric circulation. Previous models suggest the former, but the new model suggests the latter. "This has implications for the importance of land use," says Hohenegger. "It would mean that changes in surface conditions, such as deforestation, do not affect the frequency and intensity of thunderstorms as much as previously thought." Conversely, of course, changes in the frequency and intensity of thunderstorms have direct consequences for our land use – especially in the world's arid regions. "The dry seasons there are already getting longer and the rainfall more intense," says Hohenegger. This is disastrous for agriculture, on which many people in these regions depend. The soil dries out more, and when it rains heavily, the masses of water wash everything away.

"We need to take action if we don't want to destroy our livelihoods."

SUSAN TRUMBORE

A correlation between land use and rainfall distribution can be seen in the Amazon rainforest in Brazil. Experts from the Max Planck Institute for Biogeochemistry in Jena are measuring the water and carbon cycles both in the middle of the remaining, still intact rainforest and in a region where slash-and-burn agriculture and deforestation have already destroyed large parts of the rainforest. The latter is now home, at best, to secondary forests, but mostly to soybean farms and other plantations or livestock farms (see MaxPlanckResearch 4/2019). This is the case of the Tanguro Ranch in the state of Mato Grosso, where we can clearly see the impact of human intervention. "Tanguro is the place where we first tested the prediction that the rainforest will gradually turn into savanna as a result of global warming and overexploitation," says Susan Trumbore, Director at the Max Planck Institute for Biogeochemistry in Jena. Mato Grosso is a heavily agricultural state, and much of the forest has been cleared to make way for cattle pastures and plantations. But because crops and grasses allow less rain to evaporate from their surfaces and do not draw water from deeper underground, they produce much less evaporative cooling than trees. This causes the temperature to rise in addition to general global warming. "In fact, this thermal effect of land use in the region is as strong as the global greenhouse effect," says Trumbore.

More fires in the Amazon

Less evaporation on cultivated land also reduces rainfall, with consequences for the remaining forest and for agriculture itself, which is exposed to higher risks and faces economic losses. In addition, more water runs off the surface and heats up because there are no trees to provide shade. The warmer water affects fish and other animals in the rivers. "We originally identified the impact of agricultural fertilizers in bodies of water, but it turns out that the warming and increased risk of flooding are much more serious," says Trumbore.

At the edges of the remaining forests, the added heat and lower humidity are leading to greater drought stress. "The least drought-tolerant tree species will die out and be replaced by generalists," says Trumbore. However, some functions of the former forest, such as cooling, remain largely intact even in a damaged forest. "That means that a damaged forest is better than no forest at all," she says. However, drier conditions increase the likelihood that fires will break out and destroy sensitive forests. For example, especially devastating fires raged in the Amazon rainforest in 2023 and 2024 and will continue to do so as the increasing drought caused by climate change is exacerbated by the El Niño phenomenon. "The big question is what will happen to the damaged forests," says Trumbore. "Under what conditions can they recover, and how long will it take? And if their condition continues to deteriorate, what does that mean for agriculture and the climate in the region?"

The interplay between vegetation and the water cycle is the subject of another project involving the Max Planck Institute for Biogeochemistry, this one focusing on the effects of climate change in Germany. At the edge of the

⟶

Hainich beech forest in Thuringia, researchers led by the University of Jena are investigating the extent to which water, soluble solids, and gases such as CO_2 are exchanged between vegetation, differently managed soils, and groundwater. For example, plant compounds predominate in the water at the top of the soil, while microbial compounds dominate in the groundwater. "This shows the breakdown of substances by the many microorganisms as they seep downward," explains Susan Trumbore. However, the difference between near-surface and deep water has become significantly smaller over the 12 years that measurements have been taken at this site. "This shows that the filtering effect is diminishing," says Trumbore. The researchers attribute this in part to more frequent heavy rains: large amounts of water seep through more quickly, and the microbes do not have enough time to do their work. As a result, not only do more plant substances get into the groundwater, but pollutants such as pesticides and nitrates from agriculture too. Due to increased evaporation rates and changes in the distribution of precipitation, groundwater levels do not simply sink, as can be seen in many parts of Germany and elsewhere in the world, water purity also suffers. And with it, the quality of our drinking water, some 70 percent of which in Germany comes from groundwater.

Hainich also shows that forests depend on groundwater – especially in dry periods. Even then, deep-rooted trees can still draw water from intact groundwater reservoirs. The researchers are investigating how deep the root system can reach. They can then estimate how far the water table can drop before the forest canopy is affected. In other words, the planet's vegetation, and thus the cultivation of crops, can adapt to some extent to the changes brought about by climate change. But the balance is becoming increasingly fragile. This has been confirmed by studies conducted by René Orth during his time at the Max Planck Institute for Biogeochemistry: with his group, he used 40 years of satellite data to investigate the extent to which vegetation activity – expressed as leaf area – is related to near-surface soil moisture, which can also be measured by satellite. In other words, he looked at how tolerant plants are to changes in water availability. "The result was that plants are becoming increasingly sensitive," says Orth. Although many species are extremely adaptable, certain species are simply replaced by others. But the climate is apparently changing so much, or so fast, that at some point it will exceed their tolerance – with implications for our drinking water and food supplies.

More accurate predictions of extreme events

A group led by Markus Reichstein, another Director at the Max Planck Institute for Biogeochemistry, is also working on better predicting the consequences of climate change, especially extreme events such as droughts and heavy rainfall (see MaxPlanckResearch

An eye for clouds: the Earthcare satellite, launched by the European and Japanese space agencies in late May 2024, monitors the extent to which clouds and aerosols reflect sunlight back into space or contribute to the greenhouse effect.

IMAGE: ESA / P. CARRIL, 2013

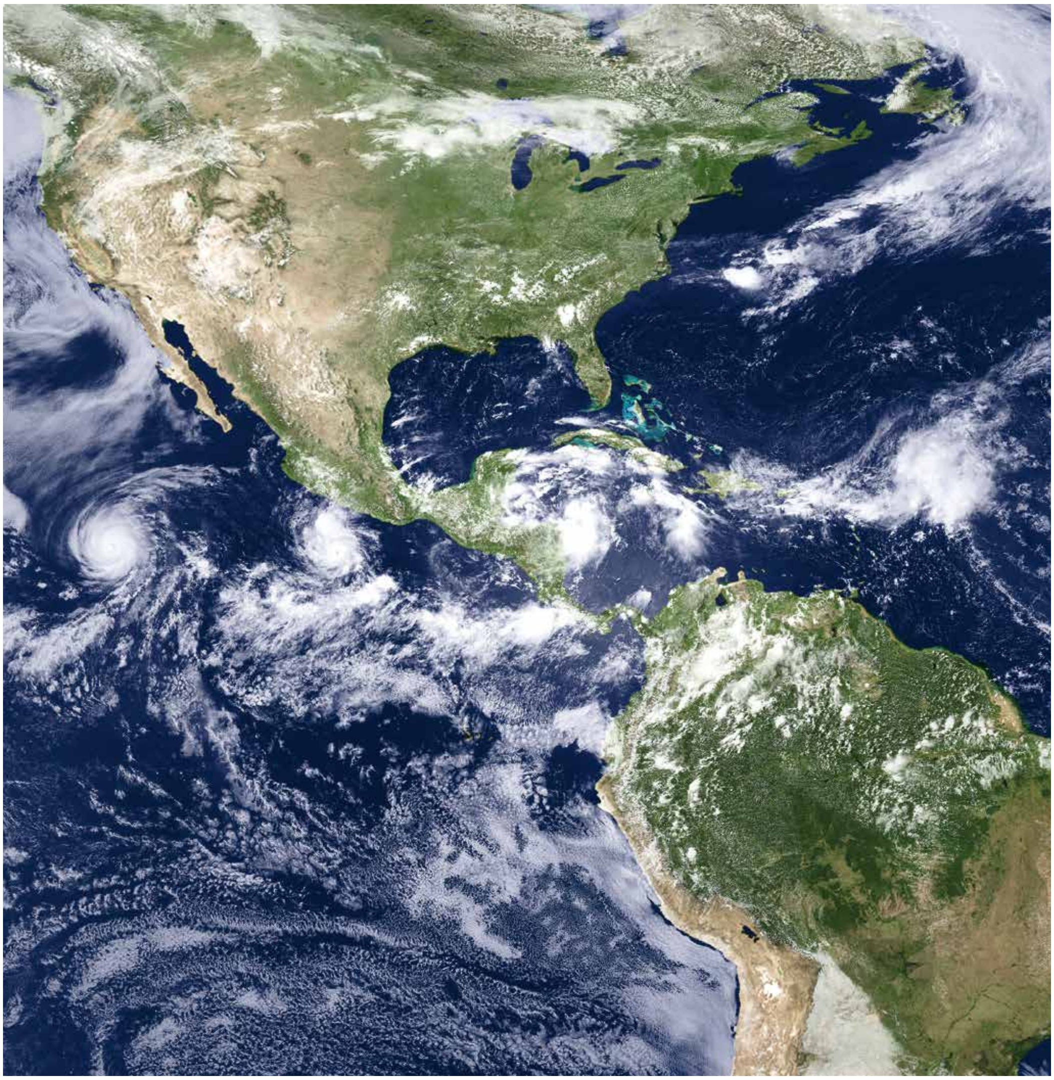


PHOTO: NOAA

A hotbed of hurricanes: this image from the EWS-G1 satellite shows two hurricanes west of Central America and a disturbance in the Caribbean that could develop into a tropical storm.

GLOSSARY

INTERTROPICAL CONVERGENCE ZONE (ITCZ)
is the name of a zone near the equator where trade winds from the north and south meet and influence the global climate. The trade winds are part of a cycle called the Hadley cell: at the equator, air heats up, rises, cools, and forms rain clouds. Up above, the cooled, dry air flows to the northern and southern edges of the tropics. There it sinks again and flows back to the equator as a trade wind.

ORCESTRA
is a measurement campaign involving nearly 50 research institutions from 11 countries. They use methods including ships, aircraft, and remote sensing to investigate how thunderclouds form in the ITCZ, from which about 30 percent of the world's rain falls, and how climate change affects their formation.

1/2021). "With data such as that from the ESA's Sentinel satellites, which provide measurements of the atmosphere and the Earth's surface with an accuracy of 10 to 20 meters, increasingly precise forecasts will be possible – for individual cities, forest areas, agricultural fields, and even your own yard," the geoecologist promises. His department is also researching the interplay between climate extremes and societies, combining high-resolution models and AI. One objective is to allow organizations such as the Red Cross to prepare international relief missions based on forecasts of storms, droughts, and floods even before the disasters show up on weather radar. "In regions that the models identify as particularly vulnerable, they can send a team in advance to set up relief infrastructure," says Reichstein. Based on past experience, this approach also produces false alarms, but ultimately saves a lot of damage costs. The goal now is to make the models more reliable and accurate. "We are currently training our AI with landscape data and climate conditions from the past to develop scenarios of the problems that certain regions can expect with warming of one or two degrees."

Ideally, humanity will not let it get that far and will curb both global warming and the active destruction of forests. While the links between climate change, water cycles, ecosystems, and society are not yet fully understood, says Trumbore, it is clear that evolution has not prepared our ecosystems for changes like these. "Our research is a clear indication that we need to take action if we don't want to destroy our livelihoods. If you are heading toward a precipice, you should at least slow down."

www.mpg.de/podcasts/lebensgrundlagen (in German)