

A photograph of a desert landscape. In the foreground, a large, smooth sand dune curves across the frame, its surface a warm orange-brown color. Behind the dune, the terrain is covered with patches of green grass and small, dark green shrubs. In the far background, more sand dunes and a hazy horizon are visible under a clear blue sky.

The Greening Desert

Climate change will very likely result in southern Europe becoming much drier. Ironically, however, significant global warming could lead to an increase of vegetation in the Sahara – as has frequently occurred in the past. **Martin Claussen**, Director at the **Max Planck Institute for Meteorology** in Hamburg, simulates the interplay of climate and vegetation, and in doing so, explores the possibility of a greener future for northern Africa.

TEXT TIM SCHRÖDER

László Álmásy should have had better things to do than pursuing an interest in rocks. A secret agent of the German army, he smuggled German spies into Egypt. He knew the paths through the hostile sands and boulders of the southern Sahara better than almost any European. The novel *The English Patient* is a romantic literary memorial to him. Ultimately, however, Álmásy's military activities were of secondary importance. From today's perspective, the rocks Álmásy busied himself with – the cliffs of the Gilf el-Kebir plateau, dusty caves full of prehistoric wall paintings in the southwest corner of Egypt – are far more interesting.

Bedouins led Álmásy to the hidden murals in the 1930s, and he made them known to the Western world. They depict rhinos, hippos and tillage farmers, people of the Neolithic period on the cusp of transition from hunter-gatherers to settled small farmers. It occurred to Álmásy that the southern Sahara could not always have been so dry and hostile. There must have been times when cereal crops and prairie grass swayed in the wind, where now only dust and stones extend in all directions.

In the 1930s, people laughed at Álmásy and his crazy ideas about a green Sahara, but the adventurer and self-made discoverer has been proven right. It is now known that the Sahara has turned green and dried up again several times throughout its history. The last wet phase began in western Africa about 16,000 years ago, and in eastern Africa about 10,000 years ago. The whole region then dried up again some 5,500 years ago. >

Today, plants in the Sahara grow only in oases, although they extended over large parts of northern Africa during the Neolithic Age. The photo shows an oasis at M'hamid in Morocco, near the Algerian border. In the foreground: the dunes of Erg Chigaga.

- 1 Adding green to the climate model: While analyzing the interplay between climate and vegetation, Martin Claussen discovered that the Sahara sometimes adopts a bistable state. Depending on the initial situation, it can then turn either green or desert-like.
- 2 Forbidding beauty with a lively past: Sand dunes now dominate the landscape once occupied by a savannah some 6,000 years ago.
- 3 The rock paintings of Wadi Howar, south of Gilf el-Kebir, bear witness to the Sahara's fertile past. The Wadi stretches from Chad into Sudan and was an important tributary of the Nile during the Neolithic period.



In recent decades, archaeologists have found many indications of past civilizations in the once green desert – earthenware shards, pollen, seeds. During dry periods, people moved to the fertile lowlands of the Nile. During wetter times, they migrated into the wide plains of the south, far from the swampy, uninhabitable Nile area. For a good ten years now, researchers have been trying to understand this constant interchange of wet and dry phases, but they are no longer limited to looking at cave paintings and pollen. On the contrary, they now have the benefit of concentrated computer power. Claussen and his colleagues look into the past using models and simulations in the hope that they will also be able to predict the future of the desert region.

The computer systems required for this task are huge. One of them is located in Hamburg: the mainframe of the German Climate Computing Center, an ensemble of several dozen head-height grey cabinets packed into a room the size of a gymnasium. There, millions of electronic calculations are processed simultaneously. Martin Claussen is a reg-

ular user of this electronic super-brain. The meteorology professor and his colleagues from the Max Planck Institute for Meteorology in Hamburg feed it with information on the Sahara and climate.

INTERPLAY OF VEGETATION AND CLIMATE

For Claussen, climate simulation is like a game – and the climate computer gives him the chance to play one of the world's biggest computer games. Sometimes he pushes the simulation to the limits, causing rain to fall over Africa as it hasn't done for years, or deactivates evaporation for entire continents. This is no arbitrary game, however. Claussen wants to understand the big picture, because climate is hopelessly complex. It is all too easy to become lost in detail, with air streams and ocean currents, the reflectivity of wet surfaces, falling air masses and the color of topsoil – hundreds of variables that together determine climate. A broad perspective provides a first estimate.

This was the case back in the mid-1990s, when Claussen developed the Sahara simulation. The scientific consensus at the time was that climate alone determines which plants grow where: “vegetation follows climate.” However, in the light of the destruction of tropical rain forests, the idea occurred to Claussen that vegetation, in turn, affects climate; that each has a direct influence on the other. He checked his hypothesis, initially using an extreme comparison: In one simulation, he changed the continents to completely green zones with parts covered in dark forests. For the comparison, however, he made the entire Earth very bright. The computer calculated air streams, ocean currents, and the transport of heat and moisture around the globe.

Claussen had not yet turned his attention to the Sahara. He simply wanted to know what our world would look like today if he started a simulation with different vegetation. The results were baffling: When he started out with a densely forested Earth, plant life around the world developed as we know it today – except that the Sahara remained fairly green, with extensive savannahs covering the region. When he started with a bright Earth, however, the Sahara remained a bright, dry desert. “That was a strong indication that there is interplay between vegetation and climate, and that they must be considered in combination. Vegetation

The average amount of solar energy, or to be more accurate, solar energy flux density (measured in watts per square meter) in the Northern Hemisphere in the summer months of June, July, August has fallen gradually over the last 9,000 years (top graph). In contrast, the vegetation coverage in the Sahara, which was very high in the Neolithic Age according to a relatively crude simulation, falls to zero in just 1,000 years (middle graph). At the same time, the volume of desert sand deposited as sediment in the Atlantic has risen (measured as a proportion of sediment and in grams per square centimeter per thousand years; bottom graph).

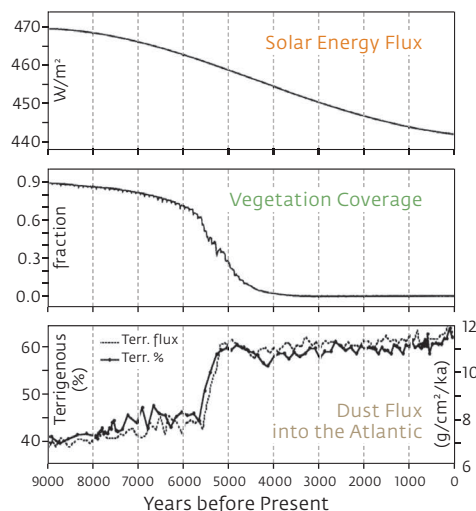
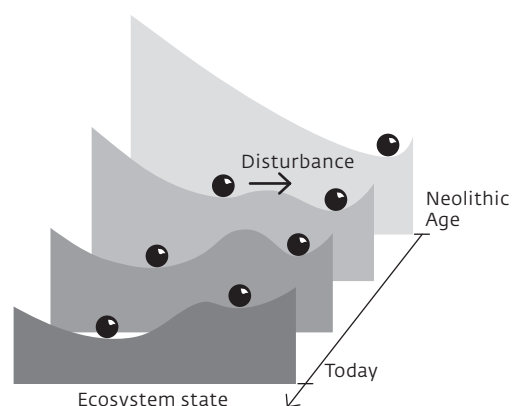


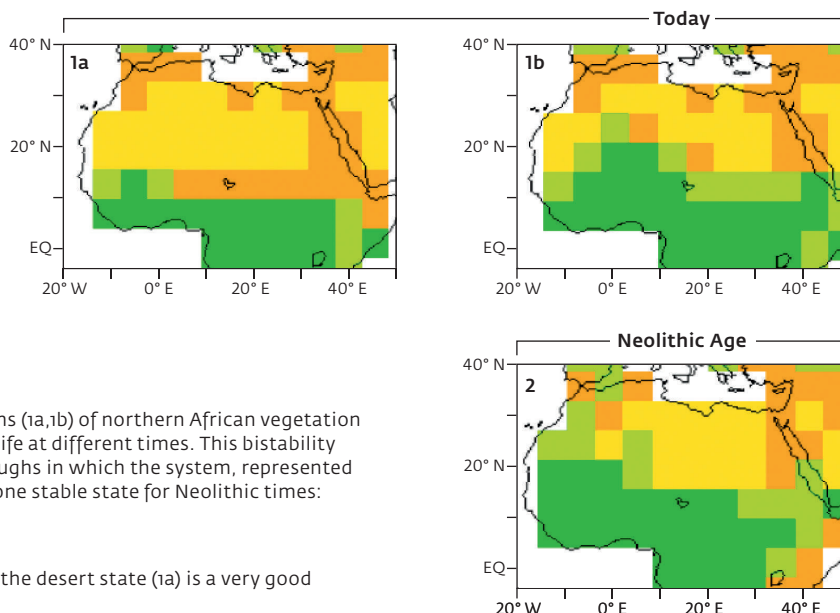
Photo: David Ausserhofer





The Sahara can now exist in two states. Both simulations (1a,1b) of northern African vegetation show that it can have a higher or lower degree of plant life at different times. This bistability is represented on the diagram at top left by the two troughs in which the system, represented by a ball, lies in a stable state. Simulation 2 shows only one stable state for Neolithic times: the green one.

right: A satellite image of the Sahara: The simulation of the desert state (1a) is a very good reflection of actual vegetation in the Sahara.



is a variable of the climate system, just like temperature and air pressure,” says Claussen. An underlying reason is that dark continents absorb more heat, while bright surfaces reflect sunlight. This influences evaporation and air streams, for example.

Then Claussen remembered reading that the Sahara had been green some 10,000 years ago. He reasoned that the gradual changes in the Sun’s radiation could have been a major influence. After all, the Earth totters around the Sun like a wobbly spinning top. This means that Earth’s position in relation to the Sun, the length of the seasons and the tilt of the Earth’s axis vary almost cyclically, every 20,000, 40,000 and 100,000 years. Consequently, the northern hemisphere receives more sunlight in summer and less in winter during some periods, resulting in hotter summers and colder winters.

Claussen changed the solar radiation in his model, setting it as it would have been on Earth 6,000 years ago. He was surprised to find that his climate model yielded, not two, but just one single solution, no matter whether he fed the calculation with an initially green or bright, dry Sahara: the

green Sahara. His explanation? Depending on the distribution of solar radiation, the climate and vegetation system moves toward just one or two stable states. Claussen concluded that if two solutions arise through the course of time, the system can jump from one to the other. Thus, Saharan vegetation can tip in one direction or the other – aridity or a life-supporting savannah.

THE SAHARA CAN CHANGE ABRUPTLY

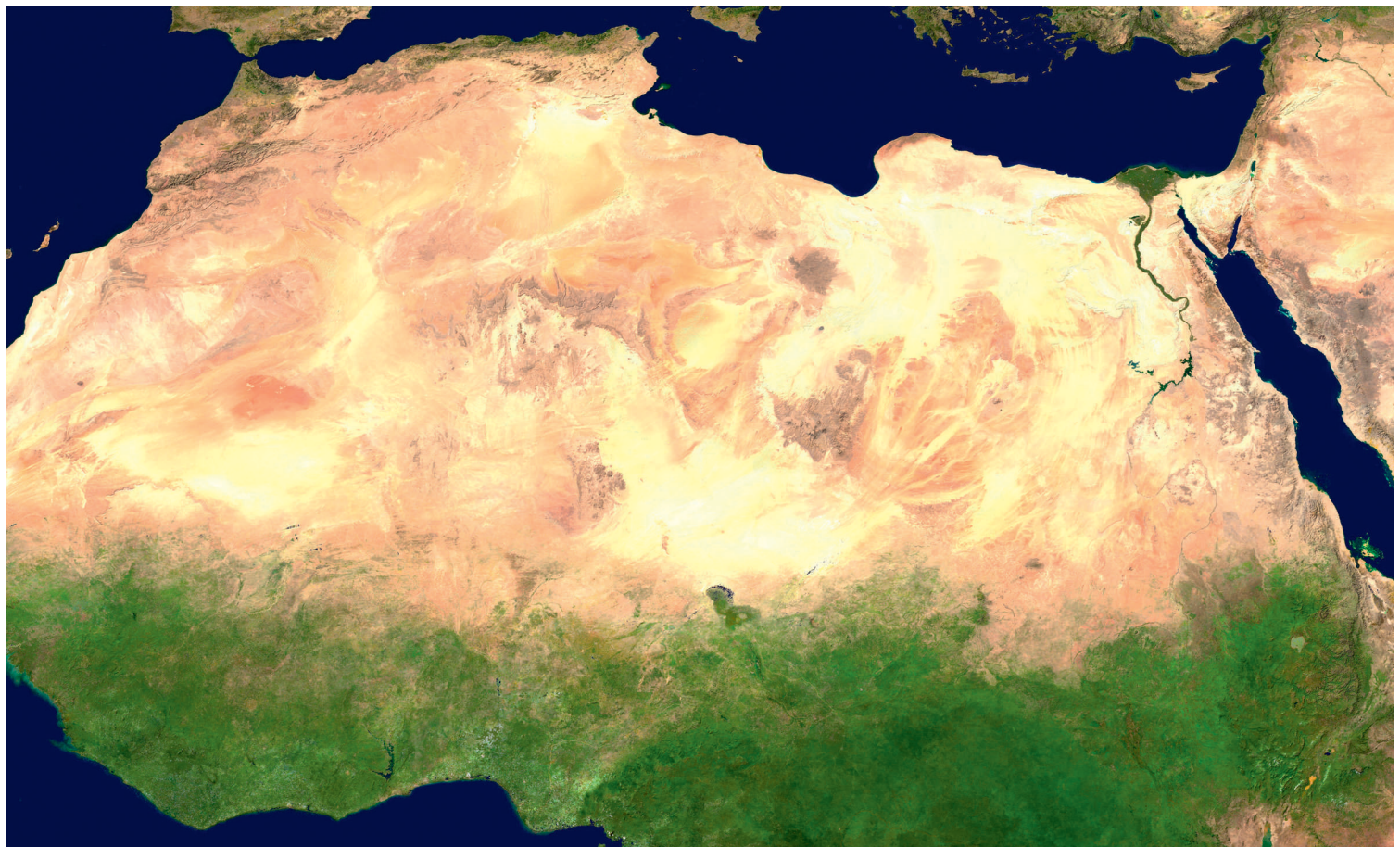
This juxtaposition of several stable states is called multistability or bistability, and is also known in other fields of mathematics, such as macroeconomics, which is concerned with variables that can lead to economic crises. In biology, too, some nutrient-rich lakes remain clean and clear, while others tip in response to some trigger and are transformed into putrid, algae-filled waters in record time.

Bistability for the desert was a completely new concept. The simulation made it clear that a desert’s state could change abruptly, with catastrophic consequences for the peoples who had

settled there. The main climate factor of solar radiation has changed slowly and constantly over the last 20,000 years. Bistability, however, means that vegetation and climate can change much faster than the steady pace of orbital forcing.

With his early simulation in the mid-1990s, Claussen had, for the first time, linked a model of the atmosphere with a vegetation model, creating a simulation in which climate and vegetation influenced each other. This caused a small sensation at the time. However, those early simulations had the disadvantage that they could calculate climate for only one target date – today or 6,000 years ago, for instance. They were unable to deliver a progression through time, over millennia, to reveal gradual climate change.

Together with his Russian research partners Victor Brovkin, Andrey Ganopolski and Vladimir Petoukhov, Claussen forged ahead in 1999. The four met at that time at the Potsdam Institute for Climate Impact Research, where Claussen worked for more than ten years after starting his scientific career. They developed a fast climate model that not only fully linked the at-



mosphere, oceans and vegetation, but also processed long periods of time rapidly. They started their simulations in the more distant past – about 9,000 years ago, when lions and rhinos roamed the central Sahara, and the giant “Lake Mega-Chad” was hundreds of kilometers wide.

The computer was cranked up again, rearranging enormous volumes of data. The simulation program calculated the ocean currents and air streams for each day and the state of vegetation for each year – according to the wetness or dryness at each stage – all the way up to the present day. The results confirmed their assumption that, sometime around 5,500 years ago, the Sahara began to dry up, surprisingly abruptly. Within a few centuries or even decades, life must have disappeared over large expanses of the Sahara.

Initially, this was not much more than mere theory, just ugly numbers generated by a computer in Germany, some 5,000 kilometers distant from the Sahara. Then, in 2000, just one year later, geologist Peter deMenocal of New York’s Columbia University published the results of an expedition to the western African coast. He had drilled deep

into the sediment of the sea floor, through layers dating back thousands of years.

THE REGIONS OF NORTHERN AFRICA REACT DIFFERENTLY

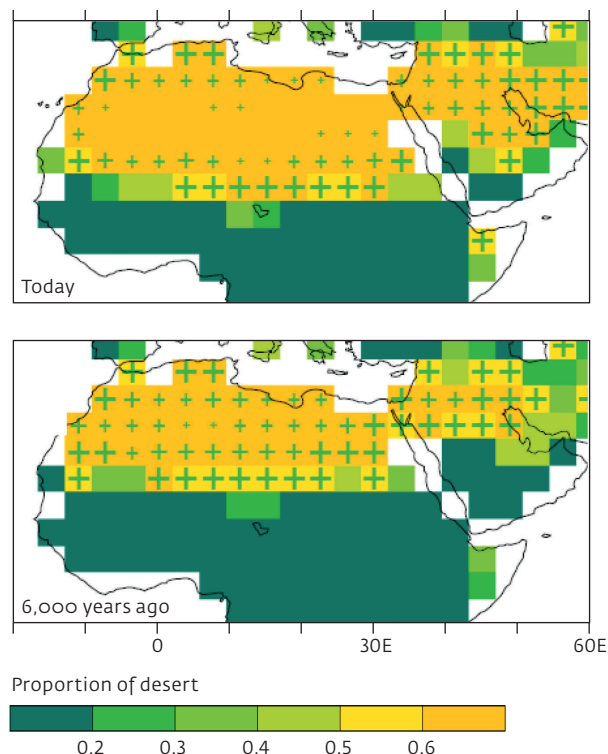
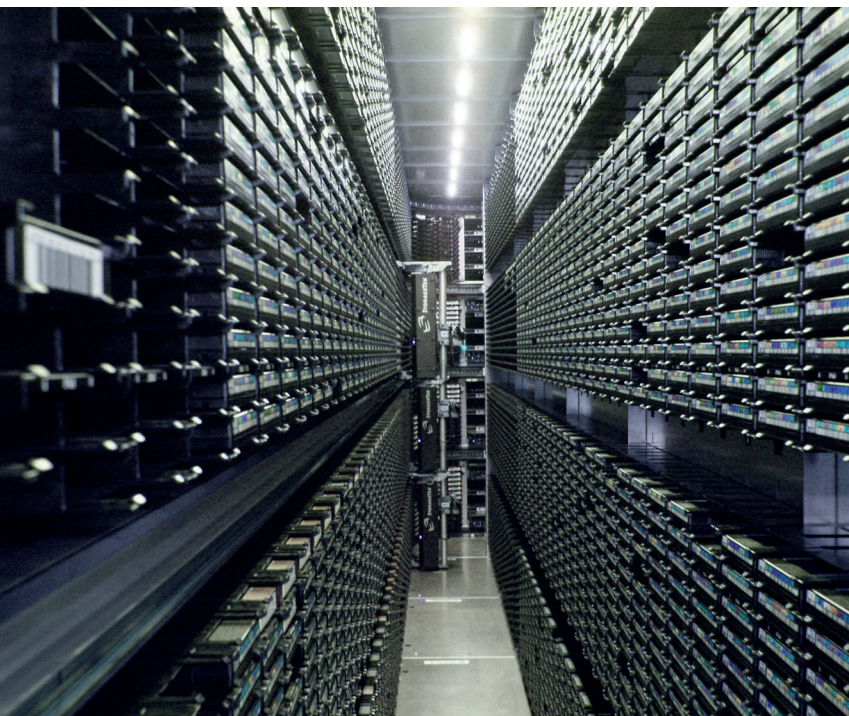
The analysis of the drill cores took the climatologists completely by surprise: until about 6,000 years ago, the sediment on the sea floor consisted of coarse, solid grains that are commonly washed into the sea by rivers. This means that there must have been abundant rain in the Sahara at that time. However, more recent layers of sediment told a different story. Starting around 5,500 years ago, only dust was found, leaving room for just one conclusion: winds must have blown dust into the sea from the fast-drying Sahara. Claussen and his colleagues were delighted, as hard geological facts now seemed to corroborate their calculations.

Still, Claussen was not really happy with his climate model. It was able to generate very fast calculations, but its continental resolution was too low. “We wanted a new model that would look at the whole world in detail, taking regional differences into account.” At the time,

a higher-resolution climate model such as they were looking for was available at the Max Planck Institute for Meteorology. For their purposes, however, Claussen – back in Hamburg once more – and his colleagues needed to supplement it with vegetation so that the model could include green growth in its calculations, integrating the migration of prairie grass, brushwood and trees through the course of time.

This comprehensive climate model has been running for some years and divides the world, and the Sahara, into small squares of up to 120 km in length. In addition, new knowledge about the reflectivity of the soil and evaporation in different areas is constantly fed into the model. All this allows Claussen to obtain high temporal and spatial resolution. This combination would usually bring a computer to its knees, and even Hamburg’s large climate computer needs a whole day to simulate a hundred years. Consequently, despite the huge computing power available to them, the researchers need patience for a journey 5,000 years back in time.

Still, a look at the details is worth it. “We used to consider the Sahara as one big box,” says Claussen, “which would



Only a very powerful computer, such as Blizzard in the German Climate Computing Center (above), can simulate Saharan vegetation with good spatial and temporal resolution. The green crosses symbolize the probability of short green periods: the bigger the cross, the stronger the greening. The Sahel stretched further north 6,000 years ago, and plants repeatedly sprouted throughout the Sahara.

mean that the entire desert dried out.” Now he knows that it’s not that simple. There are, apparently, marked differences between the regions. Every now and then, greener and drier strips of land would occur, and the western Sahara seemed to dry out more quickly than the eastern part. Some areas seem to have changed their appearance quite abruptly. “Plus it seems that some regions pull others along with them. If the desert expands in one part, neighboring areas follow suit.”

The findings are consistent with studies by a Cologne-based group led by Stefan Kröpelin, who took sediment samples from the ancient saline Lake Yoa in northern Chad a few years ago. Based on pollen and spore findings, the scientists deduced that tropical plants and ferns suddenly vanished 5,000 years ago. Yet plants native to the savannahs, Mediterranean region and desert are still found today at Lake Yoa, in the eastern Sahara. This rules out a

sudden aridification. The loss and destruction of life was abrupt for some species, but insidious for others.

THE SOUTHERN SAHARA MAY SOON BE GREEN AGAIN

The team in Cologne combined their sediment samples with knowledge about prehistoric settlements, bones and pottery shards, concluding that the region enjoyed a warm, humid climate 8,500 years ago – the period when Álmásy’s rock paintings were made. The fertile Sahel region stretched much further north. As the eastern part slowly dried out some 5,300 years ago, people retreated further to the south, or to the north, where the Nile became a new lifeline. While the fertile steppes of the Sahara sank into dust, the era of the Pharaohs began on the Nile. “Our fast climate model treated the Sahara as a uniform area,” says Claussen. “But we now know that it has many facets.”

The Sahara is a complex habitat – that much is clear. Claussen thus believes that predicting its future will be complicated. Nonetheless, he has used his climate models to look into the future and attempt to answer the question of whether climate change could cause plants to grow in the Sahara again in the near future. If humankind continues to blow carbon dioxide into the air unabated, the planet will heat up swiftly. Global warming will increase evaporation like water in a saucepan, raising precipitation levels. This could lead to greening of particularly the southern Sahara as early as this century, while dry areas expand in other regions, such as the Mediterranean basin – at least that is what the simulations show.

Without human intervention, the picture would be quite different: With the slow, steady changes in solar radiation, the Sahara would stay dry for about another 10,000 years. Then heavy monsoon rains would move in

over Africa as they last did 6,000 years ago. The possibility of green growth extending into the Sahara in the coming decades can already be seen as a trend from satellite measurements, with increasing vegetation perceptible in the south. "However, overgrazing and poor land management could quickly destroy that plant cover," cautions Claussen.

In any event, it seems that the greening would not last long. "Our new, more complex model shows an initial greening of the Sahara, but that further warming would cause a marked reversal of that trend." Still, no one can say with certainty just what the future of the Sahara will be, as the results generated by different climate models currently vary too much.

For this very reason, Claussen goes a step further, feeding his powerful climate model with more details. "If trees

lose their leaves, if moist humus is formed, how much soil is visible between plants – all this influences climate and vegetation," he explains. He is collaborating with colleagues from the Max Planck Institute for Biogeochemistry in Jena who know biomass conversion under different climatic conditions like the back of their hands. Claussen's hope is that the more closely he can reconstruct reality, the more accurate the predictions will be.

The climate computer in Hamburg needs even longer to crack these more realistic simulations, so Claussen often goes back to the fast model that can run even on a standard PC. Its calculations are not as detailed, but its geographical resolution is quite acceptable. "It allows us to check major trends fast," says Claussen. Calculating 10,000 years in one day is a great advantage here. But ultimately, the detailed simulation is

crucial for, say, an accurate prediction of the next one hundred years in the Sahara. And that is of burning interest to more than just climatologists. ◀

GLOSSARY

Bistability

Describes the circumstance that a system can exist in two states. The state in which the system is actually found at a given time depends in part on the background history. However, as soon as an external factor changes to even a small degree, the system can switch from one state to the other. In the case of the Sahara, this means that, if the world as a whole is relatively greener or more barren, plant life or desert extends over northern Africa. A slight change in solar radiation can change the landscape abruptly, making it either dry or fertile.

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