Earth's **Breath**

The amounts of carbon dioxide and other trace gases that vegetation and soil exchange with the atmosphere affect the climate in a variety of ways. **Markus Reichstein** and his colleagues at the **Max Planck Institute for Biogeochemistry** in Jena are analyzing this complex structure – with the aid of a global network of measuring stations and new data analysis methods.

TEXT **UTE KEHSE**

A new generation is about to take over in climate research: When the first part of the fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) is published in fall 2013, the results will be based on computer simulations of Earth's climate, in which the life on Earth plays a much greater role than in the past. These latest models now include far more of the processes that take place in the biosphere on land and in the oceans than those of a few years ago. And they include the cycle of the element carbon, which heats the atmosphere when it is in the form of carbon dioxide or methane, but is the key building block of the biosphere when it is in the form of organic compounds. The climate researchers now call their computer programs Earth system models, in contrast to the earlier ocean-atmosphere general circulation models, which represented state of the art research in the fourth IPCC report in 2007.

Attempting to calculate the processes of life with computers is, of course, no easy undertaking. When attempting to illustrate the complex processes on Earth to his audience, Markus Reichstein likes to compare the planet to an organism. "This image is more fitting than that of a purely physical machine," says the Director of the Department of Biogeochemical Integration at the Max Planck Institute for Biogeochemistry in Jena. Like an organism, Earth has a metabolism in which such elements as carbon, nitrogen, phosphorus and water play an important role. The Earth system comprises various components that are coupled with one another, and this system is constantly evolving.

"But the individual parts of the Earth system – the atmosphere, oceans, areas of ice and snow, and terrestrial ecosystems – aren't as closely interrelated as the organs of an organism," he says. The lung is a vital organ for us humans, for example. What would happen if the rainforests, which are often

View across the Siberian taiga: The tower of the climate research station ZOTTO (Zotino Tall Tower Observatory) is equipped with high-precision measuring equipment. The image shows instruments the researchers use to determine the radiation balance.

Photo: MPI for Biogeochemistry

(inappropiately) called the lungs of the planet, were to disappear? "That would certainly be a critical event, but it is highly unlikely that life would completely disappear from Earth," says Reichstein.

The problem is that even the new Earth system models aren't yet particularly good at predicting how the biosphere reacts to changes in the climate – and conversely, how changes to the vegetation and soils affect the global climate. "At present, the terrestrial biosphere absorbs around a quarter of the anthropogenic carbon emissions, but it's uncertain whether this natural sink will remain as strong in the future as it is now," says Reichstein. His department focuses on how the atmosphere and biosphere affect each other.

In recent years, he and his colleagues discovered some unexpected facts about the biosphere as a climatic factor. In 2010, for example, they reported that the savanna vegetation is the second largest important photosynthetic carbon absorber on Earth, following closely on the heels of the rainforests. Previously, no one had expected that a quarter of the organic material that plants produce globally is created here.

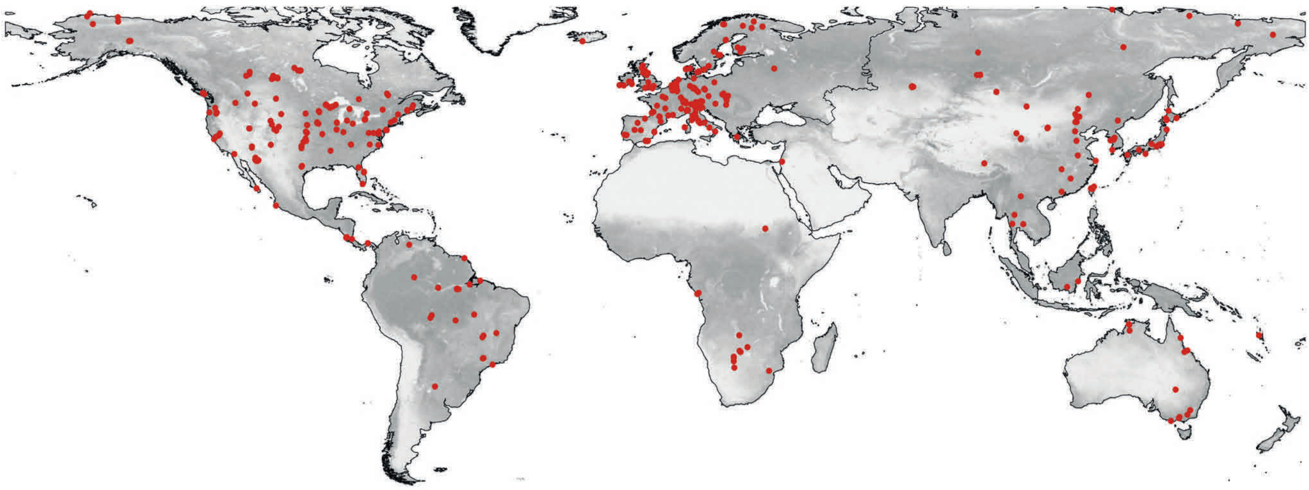
In a different study, the researchers in Jena showed that the plant growth in many regions of the world depends mainly on how much water is available to the plants in the form of soil moisture – and less on temperature. "At first glance, this sounds relatively trivial, but it isn't described adequately in the current Earth system models," says Reichstein. It isn't yet possible to accurately predict how the precipitation will be distributed, nor how terrestrial ecosystems will react to it.

Sönke Zaehle, head of the Terrestrial Biosphere Modelling research group in Reichstein's department, and his team made another surprising discovery. In 2011, he and his colleagues investigated the climatic effect of anthropogenic reactive nitrogen. On the one hand, this man-made 'fertilizer' counteracts global warming: plants grow better when they have a good supply of nutrients, and they therefore absorb more carbon dioxide (CO_2) from the atmosphere. But fertilizer also has a damaging impact on the climate, because fertilized soil releases more nitrogen oxides, including the potent greenhouse gas nitrous oxide. The researchers' model calculations showed that the nitrous oxide emissions nearly cancel out the positive effect of the plant growth.

It is presumed that there are still many other, as yet unknown, relationships or feedback effects in the biosphere that impact the climate. "Whenever biology is involved, the system

On the roof of the institute in Jena, the researchers test different instruments that are later used in the field at the Fluxnet locations. They measure wind speeds and trace gas concentrations, as well as radiation, temperature and air humidity.

Photo: MPI for Biogeochemistry



Global monitoring: More than 500 Fluxnet measuring stations (red dots) record the exchange of carbon dioxide and water in different ecosystems around the globe.

becomes significantly more difficult to predict," says Miguel Mahecha, head of the Global Empirical Inference research group. While it's possible to provide a good description of the processes in the atmosphere with physical equations, we currently know little about the mathematical rules that govern the biosphere.

The soil represents a further large element of uncertainty. To date, researchers aren't sure how much carbon is stored in the global soils, or how long it remains there (cf. MaxPlanckResearch 1/10). For example, they now think that the amount of carbon in Earth's top layer is twice as much as they estimated 20 years ago. "We also call the soil the 'dark matter' of Earth system research," jokes Markus Reichstein.

He and his colleagues are therefore pursuing a new line of inquiry to discover the rules of the biosphere. "The motto here is: Data first," says Miguel Mahecha. The Jena-based researchers use satellites and measuring stations to monitor the condition of the ecosystems as accurately as possible. They then use innovative methods from the field of machine learning to analyze the data and search for patterns and unknown relationships.

MEASURING INSTRUMENTS ABOVE THE HIGHEST TREE TOPS

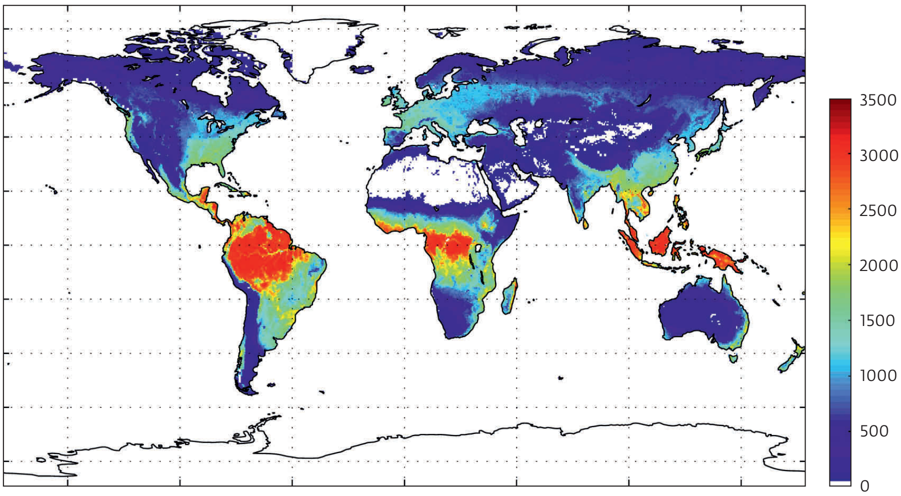
Their most important tool apart from the satellite data is Fluxnet, a global network of more than 500 measuring stations. Every half hour, these micro-meteorological stations monitor the exchange of various trace gases between the biosphere and the atmosphere, directly in the transition zone between these two parts of the Earth system.

The measuring instruments are located on towers a few meters above the highest treetops, where the airflow splits up into a large number of turbulent vortices. The instruments measure how much carbon dioxide an area of, for example, forest, bog land or grassland absorbs or releases, how much water vapor, methane and nitrogen oxides the ecosystems release, and also how high the temperature, precipitation and insolation are. Like a doctor who uses numerous electrodes to monitor a patient in the intensive care unit, the geo-ecologists in Reichstein's department use these measuring towers to record the vital signs of the biosphere.

These stations use the so-called eddy covariance method: The measuring instruments measure the wind velocity in

The Fluxnet measurements also provide the researchers with information about how much of various nitrogen oxides, and how much water vapor or methane the plants release in forests (left) or bog land (right).

Graphic: MPI for Biogeochemistry – Ulrich Weber (top); photos: 123RF (bottom left), fotolia (bottom right)



World map of ecosystem productivity: The different colors indicate the absorption rates of carbon dioxide (in grams of carbon per square meter per year). Red regions are particularly productive. The map is based partially on Fluxnet data.

the vertical direction, on the one hand, and the concentration of various trace gases on the other, both ten times per second. Since the air becomes turbulent just above the vegetation, the measuring equipment sometimes records a gust of air going up, and sometimes one going down. If the airflows toward the atmosphere contain a higher CO_2 concentration over a certain period of time than those going down, the result is an overall flow of CO_2 from the biosphere to the atmosphere.

SEARCHING FOR UNKNOWN PATTERNS

"Until a few years ago, there were some technological limits to this method, but now it's gaining great momentum," reports Markus Reichstein. He was one of the researchers who were instrumental in the existing regional networks in Europe, North America, Asia and Australia joining forces to form the global Fluxnet network. The data is stored centrally and processed uniformly, and is freely accessible to all participating researchers.

In conjunction with the satellite measurements, the Fluxnet data provides a relatively good overview of the condition of the various ecosystems on Earth. "The only places where the network is still spread too thinly is in the tropics and the very high latitudes," says Reichstein. Of course it isn't possible to observe everything at every point in time at every point on Earth, but the researchers in Jena are working on using the Fluxnet locations and the satellite data to calibrate their statistical models in such a way that they can describe any spot on Earth, including those between the measurement points. "This provides us with a kind of diagnosis: we are describing Earth's present condition," explains Reichstein.

He and his colleagues trawl through this data for unknown patterns and relationships, collaborating closely with researchers in Bernhard Schölkopf's group at the Max Planck Institute for Intelligent Systems in Tübingen. The mathematicians are experts on machine learning and develop, for example, algorithms for facial recognition. The researchers in Markus Reichstein's department use these same algorithms to search for patterns in their climate and vegetation data; one doctoral student works with both groups. "The collaboration works very well, and we have already published a joint article and are working on further studies," says Miguel Mahecha.

The collaboration also enables the developers in Tübingen, particularly those in Stefan Harmeling's research group on Computational Imaging, to make progress with their work, because ecological data poses new challenges. For instance, ecological measurement data is always fraught with very high uncertainties, it is sometimes recorded in different units, and there are systematic gaps in the data, as well as cyclic events such as the seasons, periodic climate changes with long-term cycles, and trends such as climate change.

Moreover, the volumes of data in Earth system research can quickly take on huge dimensions. In the Jena-based group's simplest datasets, there is one data point every 0.5 degrees, yielding more than 75,000 points for each time interval for the entire land surface of Earth. The necessary calculations are already a challenge for the developers. In the future, the spatial resolution will be significantly higher, and they can expect to have hundreds of millions of data points.

A DIAGNOSIS OF EARTH'S PRESENT CONDITION

But it's worth the effort: "This is enabling us to find relationships that can't be explained with the current Earth system models," says Markus Reichstein. The study on the dependence of plant growth on soil moisture, for example, which was published in the journal SCIENCE in 2010, was based on the new method. The researchers were thus also able to create a statistical model that can be used to predict, among other things, how much organic matter the various ecosystems produce around the globe under specific climate conditions.

When Reichstein and his colleagues find a previously unknown relationship in their data, they search for a physical or biological explanation. The process can then, in turn, be described in equations and be incorporated into the MPI-ESM Earth system model of the three Max Planck Institutes for Meteorology in Hamburg, for Biogeochemistry in Jena, and for Chemistry in Mainz. Together with some 20 additional Earth system models from other institutions, the Max Planck model has computed

Graphic: NATURE/MPI for Biogeochemistry

the scenarios that will be published in the fifth IPCC report.

While Markus Reichstein's department concentrates on deriving the carbon footprint of the terrestrial ecosystems from the point measurements from the Fluxnet stations – that is, working from the bottom up, so to speak – the researchers in the Biogeochemical Systems Department of the Max Planck Institute in Jena pursue the opposite approach: they work from the top down, as Director Martin Heimann says.

"We measure the CO_2 concentration in the atmosphere at different heights, for example with the Zotino Tall Tower Observatory, a 300-meter high measurement tower in West Siberia," explains the physicist. These measurements provide an average of the CO_2 concentration, similar to the one that can be seen in the famous Mauna Loa curve. The values are representative for a larger region: they show how the plants within a radius of many hundreds of kilometers take up carbon dioxide and release it again over the course of a year.

Both methods provide a picture of the carbon footprint of the vegetation, but from different points of view – like in a library, where it's possible to monitor the overall holdings, or to record the incoming and outgoing books. In Sönke Zaehle's research group, which belongs to both Markus Reichstein's and Martin Heimann's department, researchers are currently working on the challenge of linking up the two methods in a joint model.

The aim is to reduce the uncertainties in the data. "Ultimately, we expect it to result in better datasets," says Heimann. The uncertainties owe to the fact that Earth's material budget is much more difficult to monitor than the holdings of a library. This is why there are discrepancies between the measurements taken directly above the vegetation and the observations made in higher layers of the atmosphere. >

Markus Reichstein in front of the institute: In one hand he holds a core sampler for taking soil samples, in the other a young fir that will later be used in drought experiments.

Photo: MPI for Biogeochemistry

The researchers will soon have formed a consistent picture from the results of both measurement methods. They then plan to apply the model produced by combining the two methods to current research issues for the first time, says Heimann. This will give them a much clearer idea of how much carbon the terrestrial biosphere absorbs and releases, and when and where it does so.

ALGORITHMS HUNT FOR EXTREME EVENTS

An important new research field for the institute in Jena involves extreme climate events, such as droughts, storms or weeks of persistent rain. In CARBO-Extreme, the EU project coordinated by Markus Reichstein, an international team of researchers is investigating what effects such extreme events have on the carbon balance of the terrestrial vegetation. Many researchers suspect that extreme events cause more turmoil in the carbon cycle than was previously assumed. But how strongly they change the balance is still unclear – one reason being that not all extreme events are detected in the first place.

"We identify such events with, among other things, the algorithms of our partners in Tübingen," says Miguel Mahecha. Using only satellite data that describes how green the plant cover is, Mahecha and his colleagues searched, for example, for periods of extremely low vegetation activity that have occurred during the last 30 years. The researchers then correlated the anomalies in the vegetation with the climate.

As expected, the algorithms found known droughts, such as the summer heat waves in Europe in 2003 and in Russia in 2010. A dry spell in the Amazon in 2005, however, remained hidden, probably because the many clouds often render the rainforest invisible to satellites. The program also detected previously unknown droughts, primarily in remote regions of the world.

At eye level with the Eiffel Tower: At a height of 300 meters, ZOTTO permits measurements in air layers that aren't affected by local conditions.

Photo: MPI for Biogeochemistry

When they compared the model with the climate data, the researchers found that most vegetation anomalies were triggered by water stress. But not always: for about 9 percent of the events, the climate data provided no apparent reason as to why the vegetation suffered. “Perhaps it is a lag effect,” suspects Miguel Mahecha. Although some trees succeed in surviving a drought, they are then so stressed that they fall victim to even insignificant climate fluctuations or insect infestations in the following year.

Overall, says Mahecha, extreme events are more likely to have a negative effect on the carbon balance: “A strong meteorological anomaly often causes the ecosystems to lose CO_2.” In the summer heat wave of 2003, for example, the drought resulted in as much carbon dioxide being lost in Europe as the plants store in five normal years. It also turned out that it is primarily the most extreme events that are important for the CO_2 balance. “These findings will now be integrated into the models of the Earth system,” says Markus Reichstein.

He and his colleagues test the quality of the various Earth system models by comparing the calculations of the programs with their data on the actual condition of the biosphere. In this way, they investigated, for example, how well the models describe the impact of temperature on soil respiration. In other words, they want to know whether roots and soil microbes breathe out more carbon dioxide when it becomes warmer. The Earth system models use different hypotheses for this purpose. “We analyze whether the patterns we see are described correctly by the models,” explains Reichstein.

The studies from Jena show that, like the growth of vegetation, the CO_2 evolution from the soil really depends primarily on the precipitation and the water balance. However, the most important driving force in the current Earth system models is temperature. “Our work shows that the water cycle often plays a more important role for the biogeosphere than temperature. More attention must be paid to this in the future,” says Reichstein.

Martin Heimann, Director at the Max Planck Institute for Biogeochemistry, collects data on CO_2 concentrations in the atmosphere. The measuring stations also include ZOTTO.

The processes of life will probably play a much greater role in the climate models of the future than has so far been the case. The invasion of foreign species or the question as to the effect roots have on the soil aren’t yet something that Earth system models address, for example. So the geo-ecologists from Jena still have a lot to do before they have completely understood the organism we call Earth. ◄

TO THE POINT

- **The ocean-atmosphere models on which the forecasts of the Intergovernmental Panel on Climate Change (IPCC) are currently based are being replaced by Earth system models. Here, processes in the land biosphere, such as the carbon cycle, play a much more important role in predicting the future evolution of the climate.**
- **The material cycles between the biogeosphere and the atmosphere impact the climate and vice versa in a complex way. The distribution of the precipitation is at least as important as the temperature.**
- **Geoscientists and climate researchers must acquire a better understanding of how the carbon cycle depends on the water cycle, and incorporate this in their models. Extreme climate events such as droughts and floods have a great impact on the CO_2 balance: over just one summer, a drought can release as much CO_2 as was stored in vegetation and soil over the course of five years.**

GLOSSARY

Earth system: The complex system that is our Earth can be understood as a whole only if the diverse interactions between atmosphere, hydrosphere (mainly oceans, but also lakes and rivers), geosphere and lithosphere (solid terrestrial surface), biosphere (ecosystems), cryosphere (regions covered in ice and snow) and, as long as humans have existed, also the anthroposphere are taken into account.

Machine learning: Computer programs that identify patterns from sets of data and create appropriate models that can be applied to new, but similar data.

Photo: MPI for Biogeochemistry