

Witness to past climate: Scientists such as those working at Grenoble's CNRS analyze the gases contained in Arctic and Antarctic ice cores. In this way, they can reconstruct what temperatures once held sway in the polar regions, and how much carbon dioxide was in the air. Victor Brovkin's team of researchers compare their simulations with this data.

Traveling in Time through Climate History

When climatologists look into the past, they intend to learn for the future. **Victor Brovkin** and his team at Hamburg's **Max Planck Institute for Meteorology** reconstruct historical climate changes and analyze what processes reinforce those changes. Their discoveries are helping to predict the future of the Blue Planet.

TEXT **PETER HERGERSBERG**

Victor Brovkin comes across as a reserved and patient interviewee, but on one subject he expresses himself in blunt and adamant terms: “According to all we know, man is responsible for the fact that Earth’s climate has been changing faster than ever before in recent decades. Human activity has pumped greenhouse gases into the atmosphere.” The level of carbon dioxide alone has increased by 40 percent since the advent of industrialization, to 0.35 per mil. This gas is generated by the burning of fossil fuels, and its concentration in the atmosphere rose very markedly during the last century. This is reflected more and more clearly by a rise in average global temperatures.

It is important to re-emphasize the connection at this point, as climate history can also be abbreviated as follows: Global warming, including sudden changes, belongs to the planet’s history just like meteorite impacts, the shifting of the continental plates and volcanic eruptions. Atmospheric carbon dioxide levels, too, have fluctuated greatly over millions of years, as well as over millennia and even centuries. This has often occurred to the same extent that industry, traffic and agriculture have emitted greenhouse gases into the atmosphere over the last 200 years.

This style of rudimentary telling of climate history quickly leads into a corner, and it is one that Victor Brovkin and his colleagues at the Max Planck Institute for Meteorology in Hamburg want nothing to do with: the corner of those who still doubt or even deny

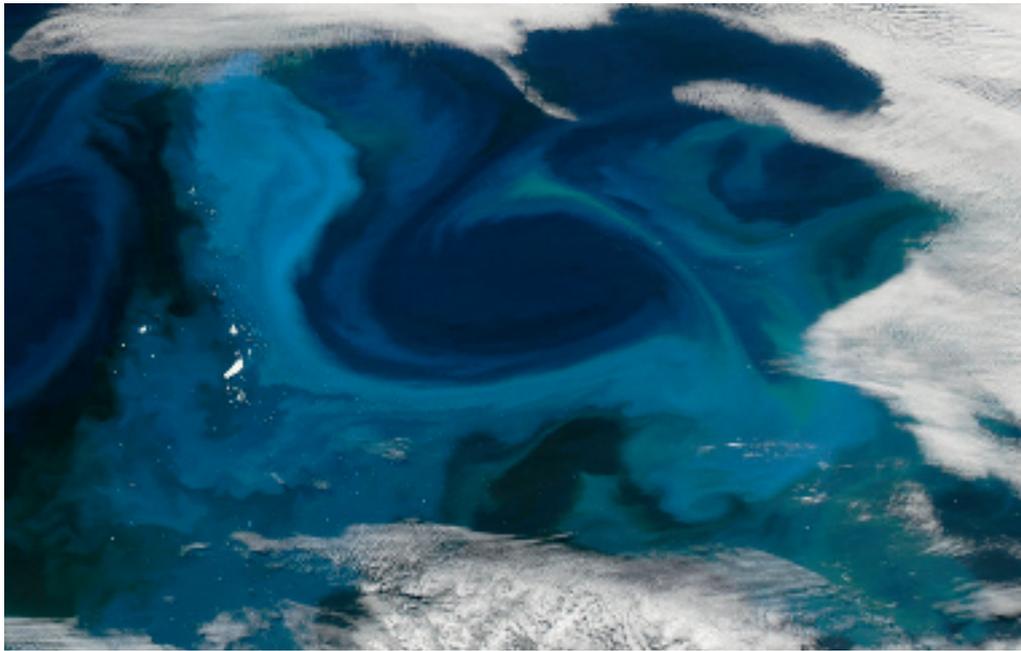
man-made climate change. This group loves to argue that there have always been climate developments such as the changes we are now experiencing. What they don’t say, however, is that, based on all the data scientists now have at their disposal, the carbon dioxide concentration has never risen as quickly as it has during the last two hundred years. Or that, throughout the last two million years, there has always been less carbon dioxide in the atmosphere than there is today.

“The decisive difference between the interplay of global warming and the carbon cycle today and in pre-industrial times is that cause and effect have been reversed,” says Brovkin. “Carbon cycle” is the term scientists use to describe the perpetual cycle by which carbon-containing compounds such as carbon dioxide and methane come into the atmosphere, are absorbed by the oceans and plants, escape into the air, and so on.

FEEDBACK AMPLIFIES GLOBAL WARMING

Until some 200 years ago, whenever carbon dioxide was released into the air, it was invariably the result of global warming and, probably, changes in continental vegetation. The greenhouse effect of carbon dioxide then caused further heating of the planet. In the present case, however, it is different: Today’s climate change has been caused by the drastically increased emissions of greenhouse gases.

As a result of current global warming, the oceans absorb less carbon dioxide, meaning that they remove less



greenhouse gas from the atmosphere. This feedback effect amplifies global warming. According to calculations carried out by Brovkin and his team, the impact is considerable: If Earth's temperature rises by 2 degrees, the warming releases so many additional greenhouse gases into the atmosphere that this alone heats the planet by about another 0.2 degrees.

For the sake of simplicity, the relationship between global warming and the carbon cycle may be represented as a play with a prologue and three acts that get progressively shorter in terms of world history as they come closer to the present day and become more relevant to today's climate. The play is still being written, and could end badly for many of Earth's creatures – in-

cluding many humans. The truly tragic thing is that those who will suffer most from climate change are the ones who are least to blame for it.

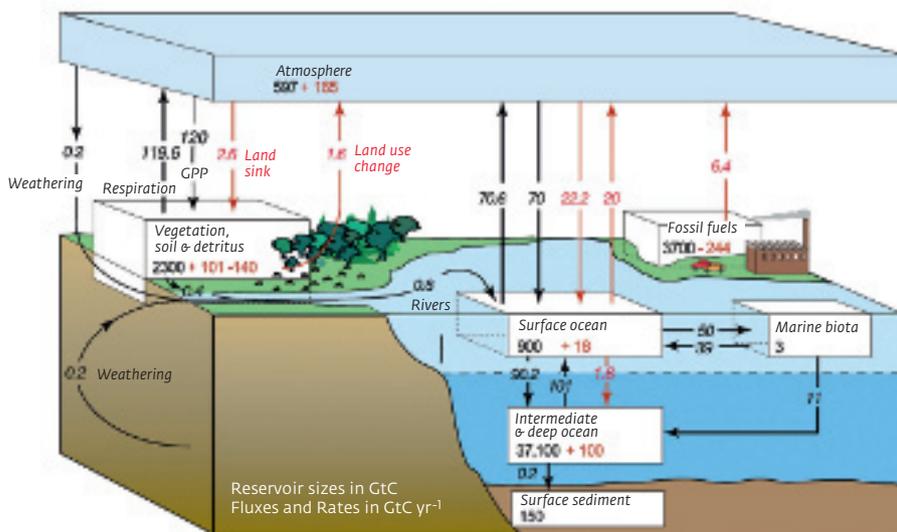
ICE AGE CYCLES: THE LONG-TERM DETERMINANTS OF CLIMATE

For now, it is unclear what the full cast of the play looks like. We do not know what role individual actors play or whether other players are pulling strings backstage. Climatologists like Victor Brovkin and his colleagues want to bring order to this confusion. They approach the issues analytically, simulating the history of climate and comparing their results with real measurements in order to untangle the individual storylines and reveal the often obscure

roles of the actors. Finally, they feed the information into their models to predict how the play will continue.

Their work could have an impact on the political stage, too, because Victor Brovkin is a co-author of the *Assessment Reports of the International Panel on Climate Change (IPCC)*. He and his colleagues from around the world integrate their findings in relation to the physical principles of climate into the reports – for example, if they have identified new actors and are able to describe their roles.

The prologue of the play is relatively unimportant for these reports and for understanding current climate change, and scientists working with Victor Brovkin are not concerned with that period of history – although it repre-



The global carbon cycle for the 1990s, showing the main annual fluxes in GtC yr⁻¹: pre-industrial 'natural' fluxes in black and 'anthropogenic' fluxes in red. Gross fluxes generally have uncertainties of more than ±20 percent, but fractional amounts have been retained to achieve overall balance when including estimates in fractions of GtC yr⁻¹ for riverine transport, weathering, deep ocean burial, etc. The net terrestrial loss of -39 GtC is inferred from cumulative fossil fuel emissions minus atmospheric increase minus ocean storage. The loss of -140 GtC from the 'vegetation, soil and detritus' compartment represents the cumulative emissions from land use change and requires a terrestrial biosphere sink of 101 GtC. 'GPP' is annual gross (terrestrial) primary production.



Actors in the interplay of climate and carbon cycle: The most important factor is the capacity of the oceans to store carbon dioxide. Even algae have a part to play: A satellite image of an algal bloom (left). It is not yet clear how much greenhouse gas is released when permafrost thaws (middle). Wetland microorganisms that produce methane also contribute to rising carbon dioxide levels. Frozen methane bubbles (right).

sents the longest period by far, at almost 4.6 billion years. It is necessary to give a brief overview of the period in order to demonstrate the complexity of climate history.

The main climate developments of the first billion years were shaped by the movements of the Earth's tectonic plates. The breakup of the supercontinent Gondwana, which contained all of today's continents, opened up pathways for new ocean currents – and the climate changed. Of course, this process is still ongoing today, but it takes much too long to play a role in today's climate events. By way of summarizing the prologue, it must be stated that the Earth cooled down over the very long term, achieving a reduction of 5 to 10 degrees in the last 65 million years.

The first act comprises the last 800,000 years, and in it begins a phase that, in principle, still determines long-term climate trends today: the constant alternation of cold and warm periods. The causes of ice age cycles are cosmic in nature, because they are determined by Earth's orbit around the Sun. "The tilt of Earth's axis to the orbit is probably the most important factor," explains Victor Brovkin. When the axis approaches perpendicular, the differences between the seasons become blurred. Particularly in the high northern latitudes, summers are no longer warm enough to melt the win-

ter snow. Another factor that affects global climate is that the Earth teeters a little on its orbit, which is sometimes more like an ellipse and sometimes more like a circle.

These factors explain why ice spreads over the northern hemisphere at regular intervals. However, they do not explain why the ice then retreats, and climatologists have yet to fully understand the process. "It seems to be that the ice masses become so swollen at some point that the stronger solar radiation of summer renders them unstable," says Victor Brovkin.

IRON FERTILIZATION INCREASES ALGAL GROWTH

Once it has started, the warming amplifies itself as greenhouse gases escape into the atmosphere. This feedback interests the Hamburg-based scientist: "The reasons behind it have not been fully explained," he muses. Climatologists do, however, know a few mechanisms that come into play at the end of an ice age. The warming oceans store less carbon dioxide, because it is less soluble in warmer water; and the acidity of the oceans increases in warm periods, which again reduces their capacity to absorb greenhouse gases.

In order to determine the strength of these feedback mechanisms and identify further effects, climate histori-

ans use computer simulations to understand the relationship between global warming and the increase in greenhouse gases. Victor Brovkin and his colleagues have gained their insights with a model called Climber-2 (short for Climate-Biosphere Version 2) which they use as a kind of virtual time machine. They then compare the results of their calculations with carbon dioxide values obtained from ice cores by Jérôme Chappellaz' team at the CNRS Laboratory for Glaciology and Environmental Geophysics in Grenoble.

Ice contains the air of the past in dissolved form or in tiny gas bubbles. Consequently, where ice has accumulated over thousands of years, climatologists can access an archive of historical greenhouse gas values. By analyzing the carbon dioxide content of Antarctic ice, scientists can see back up to one million years into the history of Earth's climate.

With colleagues from the Potsdam Institute for Climate Impact Research, the University of Chicago and the University of Liège, Victor Brovkin has calculated how the volume of greenhouse gases in the atmosphere developed during the last ice age, which began some 120,000 years ago. In doing so, they gradually introduced more and more geophysical and biogeochemical processes into Climber-2, as the protagonists in the climate system. >



Of particular interest to the scientists is the transition from a cold to a warm period some 12,000 years ago, because in just a few millennia, carbon dioxide levels increased by almost a third, climbing from 0.19 per mil to 0.27 per mil. Brovkin and his team managed to simulate this change fairly closely by integrating not only ocean circulation and carbonate chemistry, but also another two effects that they summarize using the keywords iron fertilization and land.

Iron fertilization means that, during the dry glacial periods, more iron-bearing dust gets blown from the land into the oceans, where it increases algal growth. Consequently, some researchers have constantly brought the iron fertilization of the oceans into play as a mechanism for removing carbon dioxide from the atmosphere. However, its effect is too limited to counteract the 0.1 per mil increase caused by humans to date.

Nevertheless, iron fertilization is important for understanding the relationship between global warming and atmospheric carbon dioxide, particularly when there is less iron fertilization of the oceans during a warm, moist period. This means that algae do not thrive and hence absorb less carbon dioxide. According to calculations by Brovkin's team, this translates into an increase of 0.04 per mil in atmospheric carbon dioxide.

In the same way, land-based processes release carbon dioxide during warm periods, albeit in more limited quantities. However, many mechanisms

are at work here, some of them mutually conflicting. One mechanism that contributes to increasing CO₂ levels is that microorganisms in the ground break down organic material such as leaves faster in warmer temperatures, allowing more greenhouse gases to escape. In addition, the north became wetter after the warm period, but the subtropics dried out, again releasing carbon dioxide. On the other hand, the higher the carbon dioxide concentration in the air, the more efficiently and productively plants build biomass, thus mitigating the strength of the greenhouse effect.

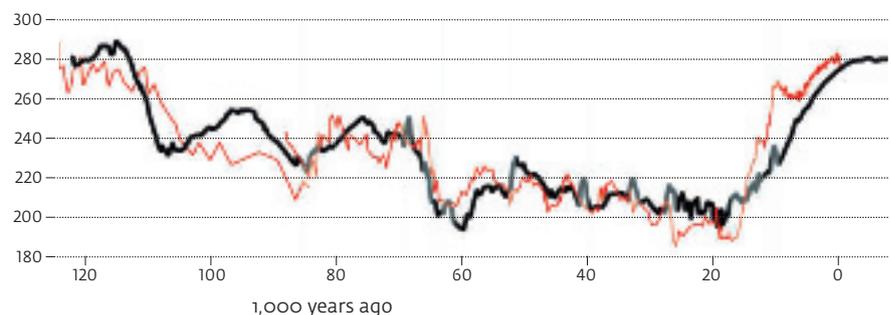
Compared with the oceans and their miniscule inhabitants, the land masses play only a secondary role in influencing climate. Still, it is important for climatologists to understand their reaction to global warming, not least in order to

estimate how current climate change will impact agriculture and forestry.

In an attempt to identify other actors in the interplay between climate and carbon cycles, Victor Brovkin and his colleagues are applying themselves to the current warm period with particular intensity. This epoch, which began almost exactly 11,700 years ago and is known as the Holocene, merits the second act of the climate play all to itself for at least two reasons.

For one thing, world climate was unusually stable through the last 11,700 years. When the last remaining skeptics of man-made climate change point out that turbulent fluctuations have always formed part of climate history, they are right. However, it may well be that human civilization was able to develop only in the relatively more settled climate of the Holocene.

Atmospheric CO₂ levels in ppm



Reconstructing the carbon balance: The Hamburg group simulated the development of greenhouse gas levels in the atmosphere during the last ice age (black line). Their calculations corresponded very closely to the results their research partners found in ice cores (red curve). (ppm - parts per million; 100 ppm = 0.1 per mil)



Corals release CO₂ from the ocean into the atmosphere during warm periods, when they build more reefs (left). This reduces the oceans' capacity to store carbon dioxide. Peat bogs also grow in warmer climates, removing carbon dioxide from the atmosphere, because organic material hardly decays in the marshy ground (middle). Volcanic eruptions also play a role in determining climate, although it is probably only a small one.

In addition, scientists have a particularly accurate and detailed picture of the Earth's temperature for this epoch. Pollen has been obtained in practically all wetlands and in ocean sediments, and these can be reliably dated for at least the last 20,000 years using the radiocarbon method, based on the radioactive decay of a carbon isotope. By studying the pollen quantities and composition, scientists can reconstruct the vegetation of a given period, in turn enabling them to accurately deduce the temperatures to which the plants were exposed.

The precise data generated by mathematical and statistical analysis enables

climatologists to better evaluate their simulations and to calibrate them more finely. The relatively short period that makes up the Holocene also requires less computing power than a full ice age cycle, so the Earth's carbon dioxide cycle during this epoch can be reconstructed with higher spatial resolution and for smaller time intervals.

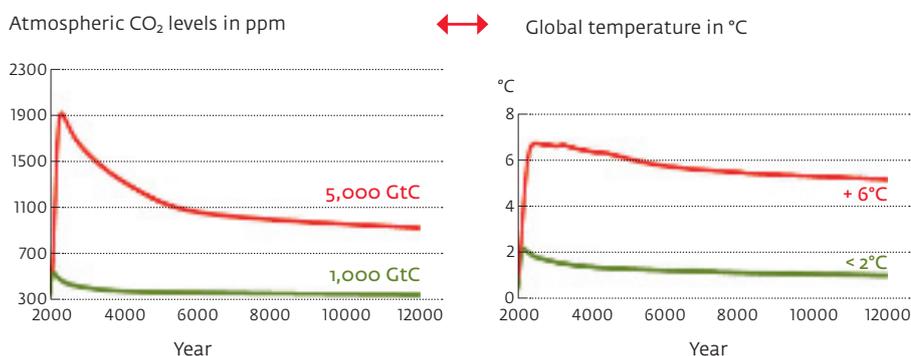
CORAL REEFS AND PEAT BOGS COME INTO PLAY

As shown in simulations, corals come into play as a factor during warm periods like the Holocene. Reefs practically spring out of the ocean floor in

warmer shallow waters. In the process of coral formation, CO₂ is emitted into the atmosphere. Scientists have also integrated peat bogs into their model. Organic materials hardly decay at all in marshlands, so they store carbon. However, calculations show that, on balance, coral reefs have a greater impact.

The building activity of these sea creatures helps researchers absolve humankind of blame in the dispute over climate history, because in the 8,000 years before industrialization, the volume of carbon dioxide in the air increased slightly, by 0.02 per mil. Some scientists explain this increase by saying that the human population of the Earth was growing in this period, and that humans began to clear the forests. Some even go so far as to say that, by doing so, *Homo sapiens* delayed the next ice age. "However, our calculations show that the impact of coral reefs in this period was large enough to explain the increase," says Thomas Kleinen, who simulated the scenario at the Max Planck Institute for Meteorology.

The third and, for now, final act of the climate play began with the advent of industrialization, some 200 years ago. In this act, humans took on a leading role, driving atmospheric carbon dioxide levels up to about 0.38 per mil to date. If coal, gas and oil were to



Atmospheric carbon dioxide levels and global temperatures for two long-term scenarios: Humans continue to burn the remaining reserve of fossil fuels at the current pace (red) or limit this exchange to 1,000 gigatons (green). In either case, CO₂ levels will fall to half only after 10,000 years.



Researching climate history takes teamwork: Victor Brovkin (middle) with Tim Brücher and Lena Boysen, two members of his group. Together, they are studying the feedback mechanisms of climate change.

continue to be burned unchecked, this concentration would rise to 1.9 per mil, heating the global greenhouse by more than 6 degrees.

If the warming effect is to be kept to 2 degrees as agreed in December 2009 by world heads of state at the climate conference in Copenhagen, greenhouse gas levels must not rise above 0.5 per mil. Even this level of warming is dangerous, because it occurs quickly and is amplified just as fast.

GREENHOUSE GASES PERSIST FOR THOUSANDS OF YEARS

Mechanisms that remove carbon dioxide from the atmosphere work much more slowly. Rocks weather faster on a warmer Earth, giving rise to silicon and calcium carbonates, which bind the gas. But it does not take mere centuries for the released carbon dioxide to be eliminated from the atmosphere, as some climatologists suppose. Victor Brovkin and David Archer of the University of Chicago have calculated that, although half of greenhouse gas

emissions disappear within the first 1,000 years, some 10,000 years must pass before only a fifth remains. And it could take as long as several hundred thousand years for amounts to fall to pre-industrial levels.

The Hamburg group uses such calculations to try to predict the future development of the interplay between global warming and the carbon cycle. In doing so, they also foretell what would happen if methane were to bubble forth from the oceans, where it is currently bound as hydrate. This could happen if ocean temperatures were to rise by 3 degrees, and would lead to a further rise of up to 0.5 degrees in global temperatures.

“To enable us to predict such developments more accurately and reliably, we are now using the MPI Earth System Model, which was developed at our institute and integrates the JS-BACH model for land surface,” explains Brovkin. The Earth System Model simulates events in the global greenhouse with a spatial resolution of some 100 kilometers and in inter-

vals of 20 minutes. Climber-2 covers the Earth with a mesh size of thousands of kilometers and calculates climate processes in intervals of one day – too large to take differences between night and day into account.

“Bit by bit, we and other groups will integrate additional processes,” affirms Brovkin. One of the aspects scientists want to include in the future is the relationship between the carbon cycle on the one hand and the nitrogen and phosphate cycles on the other. Ultimately, plants do better if there are high levels of nitrogen and phosphorus in the ground, but nitrogen escapes from the ground into the atmosphere in the form of nitrous oxide – and then has a much stronger greenhouse effect than carbon dioxide.

The researchers also plan to include Arctic permafrost in their model. These soils store large volumes of organic materials, as long as they remain frozen. If the permafrost melts, microorganisms will break down the organic material, releasing carbon dioxide and methane. Like nitrous oxide, methane has a much stronger greenhouse effect than carbon dioxide.

Climatologists are also using the MPI Earth System Model to reconstruct the history of climate and carbon cycles more accurately. “We will come to fully understand the processes only when our models correctly reproduce even small variations in the carbon balance,” says Brovkin. Some details still need clearing up, because the curves that represent Earth’s temperature and the atmospheric carbon dioxide levels are like a mountain range: seen from afar, only the major peaks stand out against the horizon, but the closer one looks, the more secondary peaks and spikes appear. The curves associated with climate are similarly ragged.

Once more, the scientists are mainly concerned with gaining a basic understanding of the carbon cycle and its interplay with climate. “Our findings can’t be applied directly to industrial-

ization, because man-made emissions of greenhouse gases have switched cause and effect in climate development,” laments Brovkin. “But they do teach us many things about the relationship between climate and carbon cycles, enabling us to refine our models for prognostic purposes.”

In the medium term, the future course of the great climate play depends mainly on humankind. Then, in the long term, cosmic developments will again take over. And in the very long term, tectonic plates will come into the mix once more ... but that future is far beyond the time-frame relevant to us now, and the one that climatologists are contemplating through their models. ◀

GLOSSARY

Climber-2

A model of intermediate complexity for simulating climate. It works with a spatial resolution of 5,000 kilometers longitude and 1,000 kilometers latitude and calculates climate in intervals of one day.

JSBACH

Land surface model in the MPI-ESM. JSBACH simulates processes on land and contemplates the exchange of heat, moisture and greenhouse gases between the continents and the atmosphere.

Carbon cycle

Describes the path of carbon-containing compounds such as carbon dioxide and methane through the atmosphere, bodies of water (especially oceans) and continents. Chemical transformations involving life forms such as microorganisms and plants play an important role in this cycle.

MPI Earth System Model (MPI-ESM)

Climate model of high complexity that works with a spatial resolution of about 100 kilometers and a temporal resolution of 20 minutes. It allows more detailed, reliable analysis and prognosis than Climber-2.

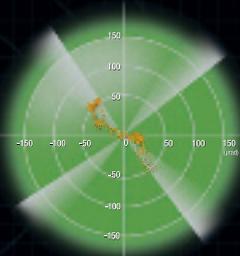
Radiocarbon method

Enables dating of organic material such as pollen and wood, exploiting the fact that carbon exists in different isotopes. These differ in terms of mass, and the isotope of mass 14 is subject to radioactive decay. The atmospheric isotope ratios remain constant because cosmic radiation produces carbon 14. In plant material, however, the ratio changes with time as a result of radioactive decay.

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