The Power **of Flames**

Fire has existed on earth ever since land plants colonized the continents. To date, however, surprisingly little is known about the role that fire plays in the global climate system – even though vegetation fires have always influenced the climate with their emissions. **Silvia Kloster** from the **Max Planck Institute for Meteorology** is looking to close this gap in our knowledge. She is researching the complex relationship between fire and climate. Humans also play a key role in this closely woven web.

TEXT **UTE KEHSE**

Playing with fire isn't Silvia Kloster's thing. "Actually, I've always kept well away from campfires," the scientist admits with a smile. Kloster had her most impressive encounter with the hot element in 2011 during a conference in South Africa. Along with other participants, she visited the Pilanesberg National Park northwest of Johannesburg, where spheres the size of ping-pong balls were being flung from helicopters into the head-high grassland.

These balls, filled with potassium permanganate and glycol, set the savanna ablaze at lightning speed. "It was terrifying to suddenly be standing in the middle of a fire," recalls Silvia Kloster. But it was also amazingly interesting for the meteorologist to experience her research topic first hand for once. "It was fascinating to see the real-life version of what I work with on my computer every day," she says.

RESEARCH INTO A NEGLECTED FIELD

Kloster's topic is the interactive relationship between fire and climate. The meteorologist focuses on two main questions: Does global warming intensify natural vegetation fires? And, conversely, how does fire act on the earth's climate? Surprisingly little is known about this. With the topic "Fire in the earth system," Silvia Kloster has chosen a field that hasn't had a lot of attention to date. "Although fire is an important process on the earth, it's not taken into consideration in the so-called earth system models," says the scientist, who

Fire-climate feedback: As the greenhouse effect increases, forest fires are becoming more common in some regions, and rarer in others. This alters the carbon dioxide balance and the albedo, which in turn has effects on the climate.

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heads an Emmy Noether Junior Research Group at the Hamburg-based Max Planck institute.

Earth system models are computer programs that document all important natural processes on our planet in formulas, particularly the water cycle and the cycles of trace gases, like carbon dioxide. They also describe the conversion of solar energy into heat, wind and biomass. The main purpose of earth system modeling is to simulate the climate. To do this, the models include not only processes in the atmosphere, but also on the ground, in the oceans and in the ice-covered regions, known as the cryosphere. All of them are linked to the mantle of air that surrounds us.

Thus, earth system models also simulate phenomena such as the build-up and melting of glaciers, changes in vegetation, the solar radiation reflected back from the earth's surface, and biological processes in the sea. But fire is missing from just about all of these models.

A WORLD WITHOUT FIRE WOULD LOOK TOTALLY DIFFERENT

The power of flames has been shaping life on earth since a good 400 million years ago. At that time, the first land plants conquered the continents. As they spread, so did fire: that cataclysmic chemical reaction that converts carbon into carbon dioxide, releasing energy in the form of heat and light. Only three ingredients are needed for a fire to start spontaneously: oxygen, fuel and an ignition source.

While oxygen levels in the air have fluctuated greatly over the course of the earth's history, for the past 540 million years or so, they have been high enough to ignite organic material. Later on, plants delivered the fuel needed for this to happen. But ignition sources must have been there all along too – most of all lightning, but also volcanic eruptions and meteorite impacts.

Fire is likely to have played an important role in evolution. For a long time, biologists assumed that it was mainly climate and soil that determined which ecosystems thrived at any specific location, but this idea is now regarded as too simplistic. “Fires also decisively influence how vegetation is distributed on the earth,” says Silvia Kloster. A world without fire would

Fire researchers: Silvia Kloster (far left) and her working group (Stiig Wilkenskjeld, Iryna Khlystova, Jessica Engels, Gitta Lasslop and Andreas Veira) standing on the roof of the Geomatikum building at the Max Planck Institute for Meteorology, next to a weather station.

Photo: Nina Lüth

Controlled vegetation fires in the woods: In the Pilanesberg National Park in South Africa, the grass is burned off once a year to prevent the build-up of excess flammable material and the possible outbreak of a fire that could also endanger the trees.

look totally different. "There would be more forest and probably no savannas." According to one theory, grasses that burned off readily were able to spread over large areas of the earth about eight million years ago because, in the forests, fires cleared the swaths that were needed for these grasses to grow.

The realization that fires are a natural component of many ecosystems has slowly changed attitudes to them in many places. "For a long time, the policy in the US has been to suppress fires as much as possible," says Silvia Kloster, "but it now turns out that this isn't a smart idea at all." The reason is that regular fires are needed in savannas, Mediterranean scrubland and the coniferous forests of the northern taiga to thin out understory and rejuvenate the vegetation.

SCIENTISTS WERE RELUCTANT TO ACCEPT THE ROLE OF FIRES

Trees are protected from the heat of the flames by their thick bark, and usually withstand short and superficial fires unscathed. In Pilanesberg National Park in South Africa, controlled burning of the grass is carried out once a year. "This doesn't harm the trees," Kloster believes. "You could even jump over the flames."

However, if nothing burns for a long period of time, more fuel builds up. "And then there comes a time when you can no longer prevent a fire from breaking out," says the researcher. Since there is a lot more combustible material in the understory, the flames leap higher and build up higher temperatures. The consequences of these crown fires are much worse: they also engulf fire-resistant trees and destroy them.

For modelers like Silvia Kloster, fire is a challenge, as it influences many other processes on earth, and is influenced by them in turn. "I find these kinds of feedback mechanisms exciting," says Kloster. "Plus, I enjoy doing the math. I like modeling and find it fascinating to work with high performance computers."

The scientist was already focusing on feedback mechanisms during her doctoral work at the Max Planck Institute for Meteorology. At that time, it was all about whether marine algae could regulate climate like a kind of thermostat. However, her calculations showed that hypothesis to be wrong. For her achievement, she was distinguished with the renowned Otto Hahn Medal.

She got onto the subject of fire during her postdoc time at Cornell University in the US. "Fire models haven't been around very long," she reports. Climate researchers have been neglecting this part of the earth system, partly because there was little data about how often natural fires occur. But cultural reasons may also have played a part. Since fires are unwanted and have long been seen as unnatural, many researchers found it hard to accept their fundamental role.

Since then, the data has improved considerably. Among other things, satellites sent up by the space agencies ESA and NASA are keeping track of where things are burning in the world at any given time. The same satellites can also measure the visible solar radiation bouncing back from the surface of the earth, known as the albedo. This allows the area of a fire to be estimated. When combined with information about the predominant vegetation, emissions caused by the fire can be discerned.

KLOSTER'S GROUP IS GENERATING ONE OF THE FIRST FIRE MODELS

Silvia Kloster needs these variables for her model. Her group – consisting of two postdocs, two doctoral students and one programmer – is currently one of the first teams in the world to be working on producing a fire model that not only is a realistic representation of the distribution of natural fires on earth, but also calculates the influence of fire on the climate. The model is part of the Max Planck Institute for Meteorology's Earth System Model MPI-ESM. An atmospheric model feeds it with climate data, and the Earth System Model, in turn, produces its own data, such as carbon dioxide emissions and changes in albedo; these then flow back into the atmospheric model.

"Our fire model computes interactively within the Earth System Model," says Kloster. Since fire, with its emissions, is closely linked to the chemistry of the atmosphere, Kloster's team is working together with researchers from the Max Planck Institute for

Photos: MPI for Meteorology

» Humans have a big influence. They are a potential cause of fires, but they also fight them.

Chemistry in Mainz. The group also keeps in close contact with the Max Planck Institute for Biogeochemistry in Jena, where specialists collect a large amount of observational data for vegetation and fire models.

MORE FUEL GROWS WHEN CO_2 LEVELS RISE

"Basically, our model is really simple," says Kloster. According to it, fires occur if there is enough fuel available in the form of biomass at a given point on the earth's surface, if this biomass and the soil are dry enough, and if a thunderstorm or humans are present as an ignition source. In the model, fires unintentionally started by people are counted as natural vegetation fires.

All three fire factors depend on climate: for example, the warmer it is in a particular region, the more often the region will experience thunderstorms. At the same time, most plants grow better at higher atmospheric CO_2 concentrations. With higher future CO_2 levels, more fuel could collect in many parts of the world. While dry conditions produced by climate change favor fires, they can also prevent them – namely when there is so little water that nothing can grow any more. "In dry regions, there's simply less stuff to burn," says Kloster.

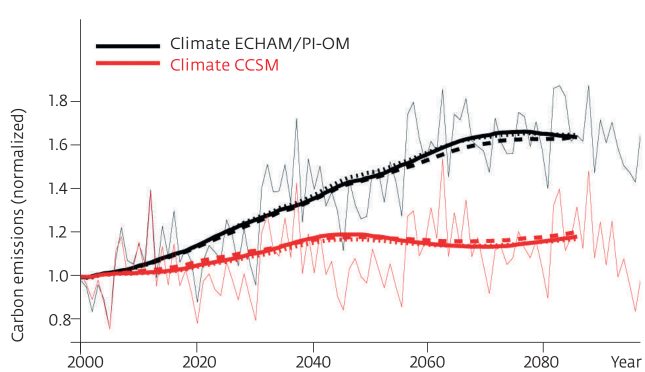
In its first study, the team simulated the frequency of fires during the 20th century. Their aim was to test whether their fire model accurately projects the actual distribution of forest fires on earth – whether forest fires occur in the model where they also happen in real life. "We've also included fire clearing, although this is not modeled using mathematical equations. Instead, it goes into the model through externally prescribed land use data, based on information from the Food and Agriculture Organization FAO, among others," says Silvia Kloster.

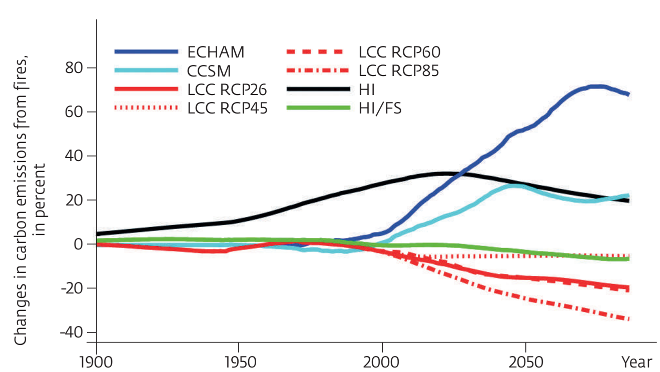
The test confirmed that the model reproduces real life really well. However, the researchers found that humans have a big influence. According to Kloster, people themselves are a potential cause of fires, but they also fight them. The higher the population density in a particular location, the more is done for fire protection – the local population is told not to throw away cigarette butts in the woods, and planes quickly extinguish any fires that do flare up. Areas used for agriculture are another important factor. Since cultivated fields hardly ever catch fire, and since they also prevent the spread of forest fires, an increase in agricultural area means fewer fires.

THE NUMBER OF FIRES WILL RISE IN THE 21ST CENTURY

Kloster and her colleagues got the right result only when they incorporated the population density factor into their program. "The west coast of the US, for example, would burn much more often if it weren't for the active steps that are taken against forest fires," she says. The study also showed that the number of fires worldwide decreased between 1860 and 1960. "This is very interesting, because it was previously assumed that fires started by people had increased during this time," says Silvia Kloster.

But the model's calculations confirm that rising population numbers and forest management eventually led to fewer fires. Since 1960, though, there has been an upward trend. "The cause for this is global warming," says Silvia





Many factors make predicting fire uncertain: Depending on the underlying climate scenario, carbon dioxide emissions from fires (left), when compared with average emissions in the years 1990 to 2009, increase by about 20 percent, or even up to 60 percent. What both calculations take into account is that, as the world's population grows, forests will need to give up more and more area to agricultural usage, and will be burned more often. However, these fires will also be suppressed to a greater extent. The individual factors have a very different effect in this system (right graph): depending on its scale, climate change (blue – ECHAM; pale blue – CCSM) leads to a greater or lesser increase. As land cover changes (LCC), there is also a trend toward fewer fires (red curves), with the greatest decrease in forest area also causing the biggest drop. The number of fires ignited by humans (HI) rises, but this will also be more than compensated for by fire suppression (FS) in the future.

Graphics: MPI for Meteorology

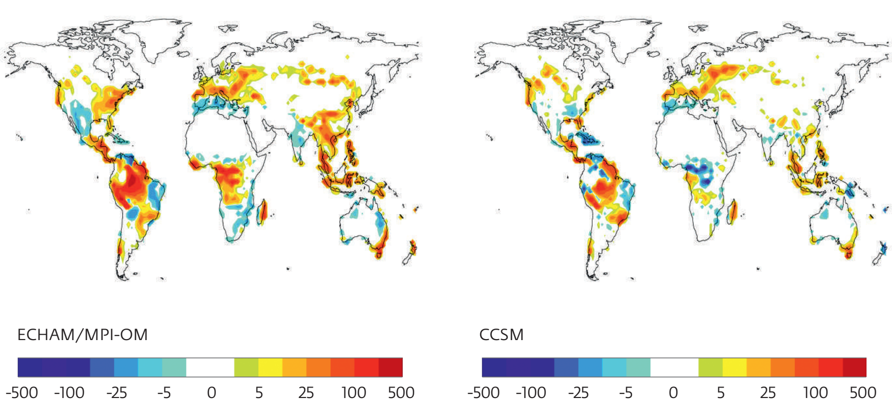
How can individual causes of fire be expressed in mathematical terms? On the whiteboard, Silvia Kloster is developing an approach to enable her to feed lightning rates, which will be altered by climate change, into her fire model.

Kloster. One example of how the model provides a good reflection of reality is that it correctly reproduced the extreme fires of the El Niño year of 1997/98 in Southeast Asia.

In a second study, published in 2012, the team worked out how the situation would develop further in the 21st century. Their results showed that the number of fires is set to rise even more. Carbon emissions due to fire will increase by one- to three-fifths compared to the last 25 years. However, this result depends on various developments – such as the rate of population growth and whether more areas will be used for agriculture. It is highly likely that these opposing trends will balance each other out, report Kloster and her colleagues in the journal BIOGEOSCIENCES.

According to the model, forest fires in South America are on the increase, because it is becoming drier there. Tropical rainforests like those of the Amazon are actually regarded as being pretty much immune to forest fires. Even if it doesn't rain there for a long period, the humidity of the air beneath the canopy of leaves remains high, as the water evaporating from the trees can't escape. But forest clearing and the construction of highways is causing the rainforest to fragment into smaller and smaller plots. These wooded patches are more susceptible to wind and dryness than an enclosed area of forest.

These days, only single trees are often felled for tropical timber production. But even this selective clearing endangers the rainforest. The remains left behind by saws and heavy machinery make for good fuel. And fire can spread more easily in thinned rows of trees. In addition, fires in tropical forests cause more damage than in ecosystems adapted to fire, such as the savanna. Rainforest trees have thin bark that offers them little protection. >



The climate scenarios ECHAM/MPI-OM (left) and CCSM (right) provide a different picture of where fires will release more or less carbon dioxide (grams per square meter and year) at the end of the 21st century. Both simulations, however, show a decline in fires in the Mediterranean region, as fewer plants will be growing there.

Photo: Nina Lüth

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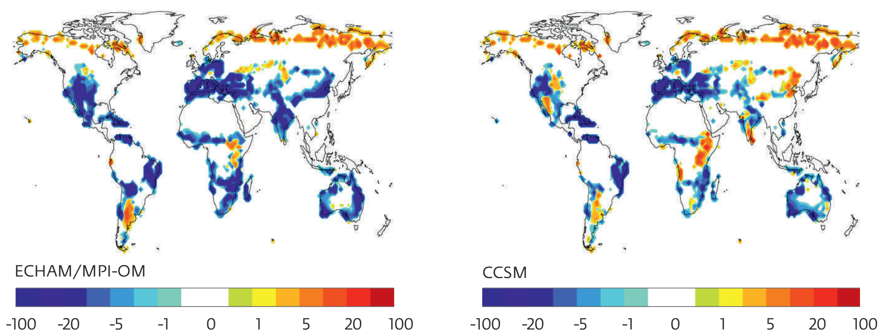
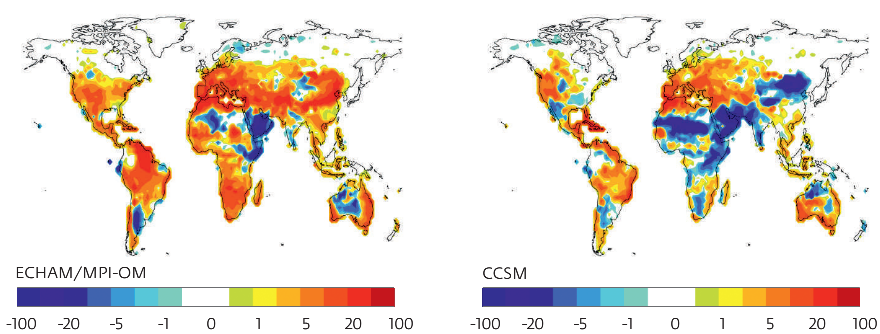
Changes in the probability of fire due to available biomass, in percent



Changes in the probability of fire due to soil moisture, in percent



Two factors that influence the probability of fire for the years 2075 to 2099 show changes in the ECHAM/MPI-OM and CCSM climate scenarios: the quantity of available biomass (above) and soil moisture (below). In general, dry areas burn more often, but they also grow less flammable material.

The study also had an unexpected result: “There will be fewer fires in the Mediterranean region. It will become so dry there that less biomass will be available as fuel,” explains Silvia Kloster.

NATURAL FIRES ARE THE SECOND LARGEST CO_2 SOURCE

It isn’t yet possible to definitively assess the effects that fires will have on the climate. In any case, the formula “warmer climate = more fire = even greater warming” is too simple, says Silvia Kloster. “Fire has many different effects. Some of them also cause global cooling.” Carbon emissions are viewed as the most important climatic factor. In a fire, the carbon stored in plants burns to form carbon dioxide. This greenhouse gas then escapes into the atmosphere. A single fire that burned for many weeks in the summer of 2007 near the Anaktuvuk River in Alaska, transforming thousands of square kilometers of tundra into a blackened moonscape, released 2.1 million tons of carbon, equivalent to the annual emissions of 1.4 million cars.

After mankind, natural fires are the world’s second largest source of the greenhouse gas carbon dioxide. They release half as much CO_2 as humans do by burning fossil fuels. A total area averaging 400 million hectares is affected by fires throughout the world every year. This is more than the area of India. But this figure varies greatly. “We also need to take into account the fact that vegetation grows back after a fire, reabsorbing part of the carbon dioxide it emitted,” says Silvia Kloster.

But a fire also generates other greenhouse gases. The most important of these is the hydrocarbon methane, which has a greenhouse effect 20 times more powerful than that of CO_2. Nitric oxides and highly reactive trace gases like ozone are also formed and cause their own changes to the atmosphere’s chemistry. In addition, fires generate various aerosols, specifically airborne liquid droplets and solid particles. Dark aerosols, like black carbon, have a warming effect. Others, like sulfate aerosols, have a cooling effect and reflect sunlight back into space. Aerosols also influence the formation of clouds.

BLACK AREAS CONTRIBUTE TO GLOBAL WARMING

Forest fires have a further climatic effect in that they temporarily change the color of the land surface from green to black. Since black areas absorb more sunlight than a green wood or yellow grassland, they heat up more intensely and thus contribute to global warming (the albedo effect). “In high latitudes, however, a fire can also make the earth’s surface brighter,” explains Kloster. “When a forest is burned away, the area is whiter in winter, because the snow is not hidden by the trees.” What role this mechanism plays is currently the subject of a doctorale research project in her group.

She and her fellow researchers want to incorporate other feedback processes into their model. They are thus working on correctly modeling the transport of ash into the atmosphere. “It makes a difference if aerosols stay close to the surface or if they go higher up and reach all the way into the stratosphere,” explains Kloster. Another thing that the scientists in Hamburg

Graphics: MPI for Meteorology

have not yet taken into account are peat fires, as it can take millions of years to build up a layer of peat, and vegetation models have not yet provided a satisfactory simulation of this. "Only vegetation burns in our model," says Kloster. "Peat is a major source that we have had to overlook."

FIRES HAVE BEEN RARE IN THE TUNDRA SO FAR

The scientist also wants to include fires in permafrost regions in the model, like the Anaktuvuk River fire of 2007. While only a thin layer of moss is usually combusted by fires in the tundra, this destruction can have long-term consequences. The reason is that the thin plant cover on the surface insulates the permanently frozen deep permafrost soil from the heat of the summer. If that protective layer is destroyed by fire, the permafrost could begin to melt more widely, forming bogs. This risks releasing large amounts of the climate-altering methane that has been stored there for millennia.

Thus, global warming in the high north could potentially set off an overlooked vicious circle. Fires have been rare in the tundra: a blaze like the one in 2007 at the Anaktuvuk River had not been seen in northern Alaska for at least 5,000 years. But the summer of 2007 was hotter and drier than ever before. This heat brought thunderstorms to the Arctic for the first time. The trigger for this devastating fire, which raged through the tundra from July to October 2007, was a lightning strike. ◂

TO THE POINT

- **Fire has always influenced the earth's climate. Conversely, global warming also affects the frequency of fires.**
- **The number of fires has been rising since 1960 due to global warming. According to model projections, they will continue to increase. While people are a potential cause of fires, they also fight them.**
- **Although fire is an important climatic factor, it has not been considered in earth system models to date. Researchers at the Max Planck Institute for Meteorology are therefore studying the complex interactions between fire and climate.**