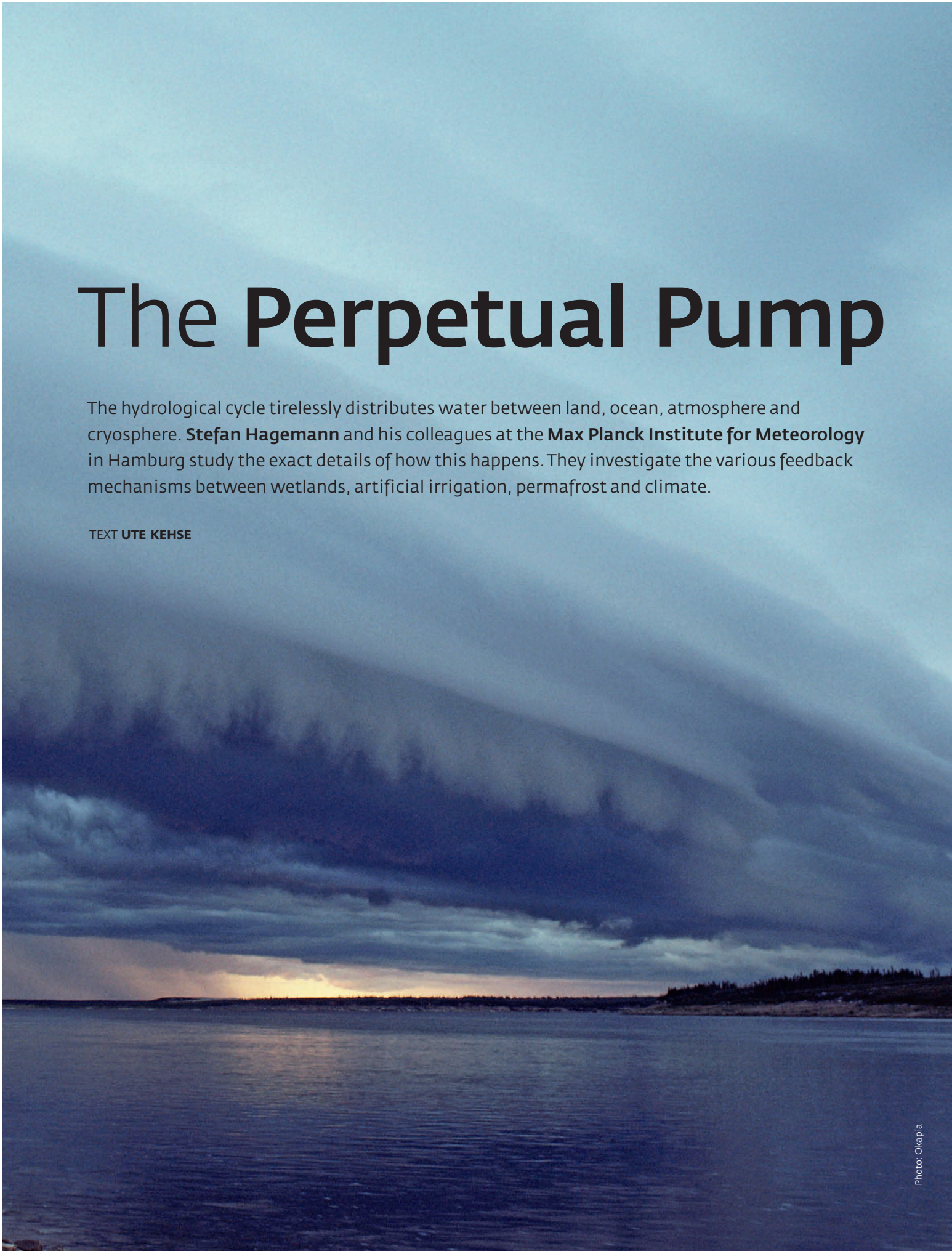


The **Perpetual Pump**

The hydrological cycle tirelessly distributes water between land, ocean, atmosphere and cryosphere. **Stefan Hagemann** and his colleagues at the **Max Planck Institute for Meteorology** in Hamburg study the exact details of how this happens. They investigate the various feedback mechanisms between wetlands, artificial irrigation, permafrost and climate.

TEXT **UTE KEHSE**

Photo: Okapia

Water molecules are always on the move. They migrate from the ocean into the atmosphere, disperse to all corners of the continents and eventually return to the oceans after days, months or even centuries. They have possibly the most varied life of all substances involved in the cycle of the elements on Earth. A water molecule on Earth can be in a solid, liquid or gaseous state. It can drift along in the sea, rise into the air, dance across the sky as a cloud, crawl slowly along Earth's surface in a river of ice, or babble quickly along a river bed. It can seep away in the soil, be absorbed by a plant and released again, or gradually find its way through the subsoil as groundwater.

The water cycle, driven by the Sun, is enormous: at any one time, the water molecules contained in the atmosphere would fill a volume of 12,900 cubic kilometers in their liquid state. This quantity is sufficient to cover Earth's surface to a height of 2.5 centimeters across the entire globe. Altogether, however, the hydrological cycle turns over many times this quantity of liquid. It's as if the total water content of the atmosphere were exchanged completely around 40 times per year.

Water's journey plays an important role in Earth's climate, but this role is a big challenge for climate researchers. It's not only the fact that water uses so many different travel routes and transport paths, but many hydrological processes also take place in a very small space. Local processes such as heavy rain during a storm, evaporation in wetlands or the runoff from glaciers fall through the usual grid that climate researchers span across the Earth in their models.

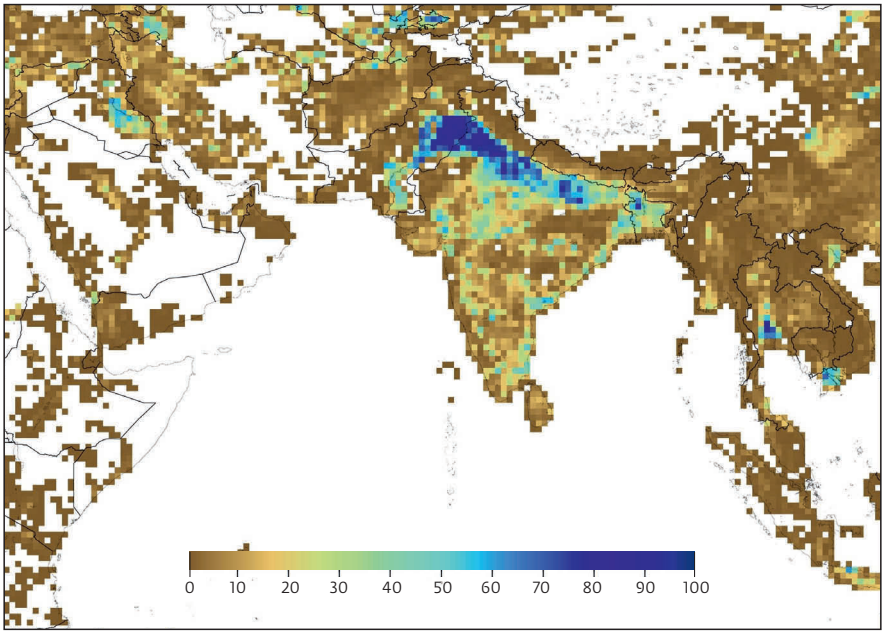
Always on the move: Water from the atmosphere enters the soil, rivers, lakes and oceans as rain – and evaporates again sooner or later.

Although the scientists' most important tools, the latest generation of Earth system models, are able to calculate the temperature on Earth quite well, they still have their weaknesses when it comes to estimating the precipitation in any particular region. "The error is sometimes between 50 and 100 percent," says Stefan Hagemann. A physicist with a German post-doctoral lecturing qualification, Hagemann is working very hard to change this at the Max Planck Institute for Meteorology in Hamburg: he heads the Terrestrial Hydrology research group. His team aims to gain a better understanding of those parts of the water cycle that take place on land – and to investigate how they feed back into the climate.

PRECIPITATION INCREASES WITH GLOBAL WARMING

The most important relationship here is the interaction between precipitation and temperature. Not only do clouds, rain, hail and snow transport a vital substance across the globe, but they also carry along thermal energy in the process – albeit hidden, in latent form, as meteorologists say. Water vapor, for example, releases heat when it condenses into liquid water or freezes to form ice. Conversely, energy input is necessary for ice to melt or sublime, or for liquid water to evaporate. Water acquires this energy from its surroundings. It therefore becomes cooler where a lot of water evaporates. This is also the reason why rain feels cold to the skin, or why sweat cools the body.

So if climate researchers want to project the temperatures for the future correctly, they need to know how the precipitation is changing. "In general, one can say that the water cycle and the precipitation are intensifying due to global warming," says Stefan Hagemann, because a warmer atmosphere



top: A map of artificial irrigation: The colors indicate the proportion of irrigated areas. In the brown regions, the share is below 10 percent, and in dark blue ones, it is between 90 and 100 percent.

bottom: Artificial irrigation affects the climate: The simulations show the routes of low pressure areas over the Indian subcontinent for a few days during the months of July (a, c) and September (b, d). With irrigation (a, b) the lows penetrate inland; without (c, d) they don't. The colored lines represent an air pressure of 996 millibars, and the numbers give the days of the particular month.

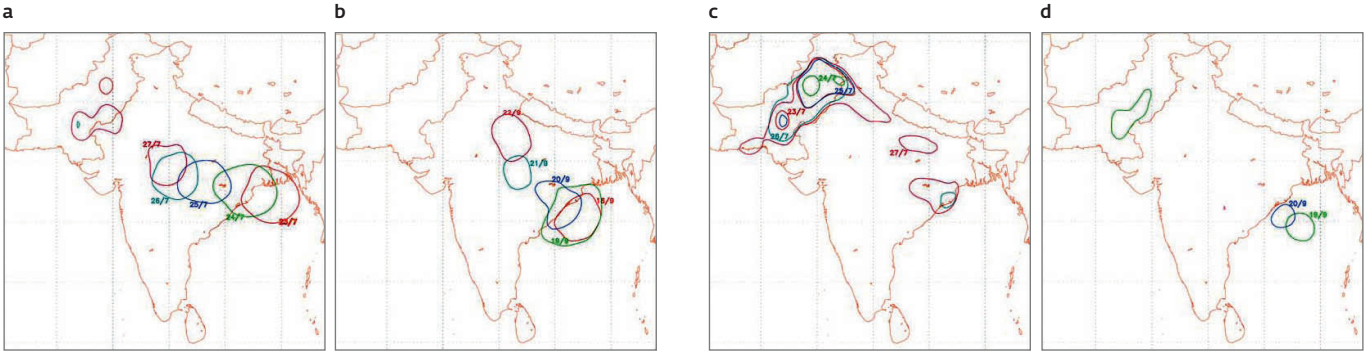
can store more water. But there are also regions that are getting drier. "If it rains even less in a predominantly dry region, evaporation can decrease there, and with it, also the cooling. It thus becomes even warmer there," explains the Hamburg-based researcher. Consequently, the decreasing precipitation aggravates the warming even more – a textbook example of positive feedback.

Hagemann and his six colleagues focus on three quite different hydrological processes that are currently not yet represented realistically in the current climate models, but that could possibly create strong feedback loops with the climate. Firstly, they investigate the consequences of artificial irrigation. Where water is released onto fields for agriculture, evaporation increases – an effect that can impact not only temperatures, but also large-scale air currents in the atmosphere.

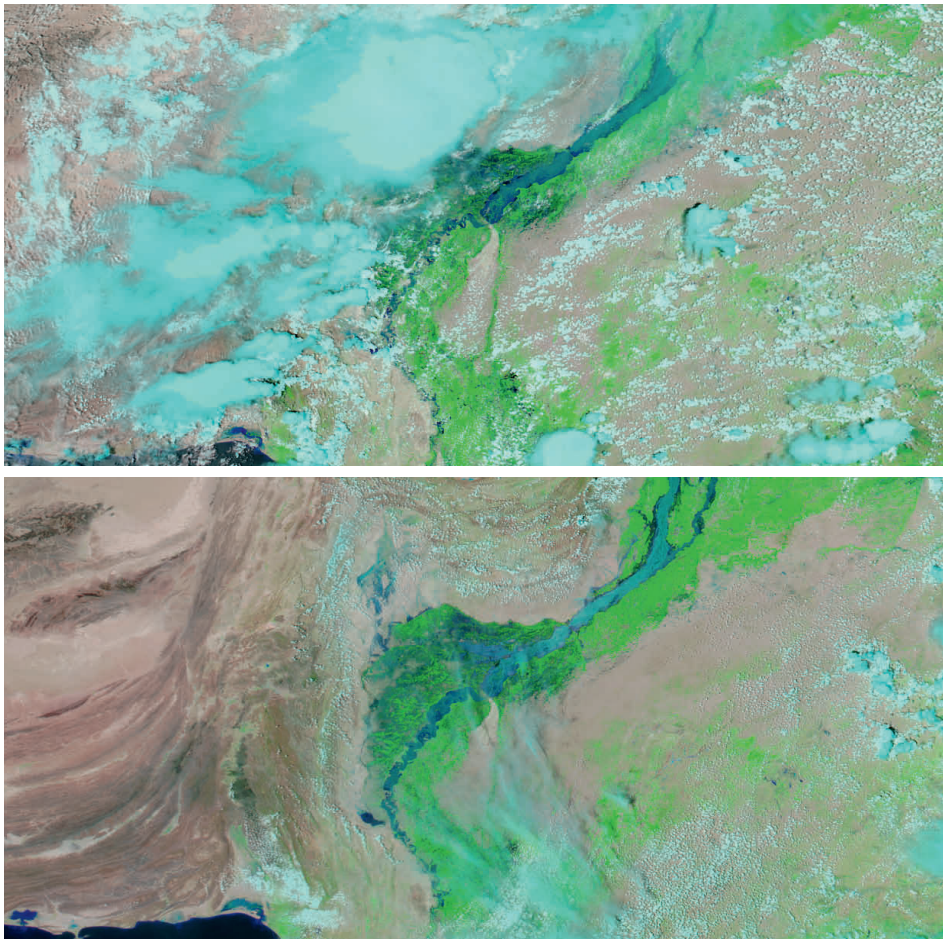
IRRIGATION AFFECTS THE REGIONAL TEMPERATURE

Secondly, the researchers in Hamburg model the growth and shrinking of wetlands as a function of the climate. Their third research focus is the permafrost. Quite a number of complicated hydrological processes occur in the permanently frozen regions of the high latitudes, and they determine how much the ground thaws in summer and how much water is stored there. Furthermore, the group wants to find out how large the errors are that different climate models are still making in the simulation of the terrestrial water cycle.

Fahad Saeed investigated a particularly impressive example of how important hydrological processes can be for the regional climate in his doctoral thesis. The physicist, who has since moved from the Hamburg-based Max Planck



Graphics: MPI for Meteorology – Saeed (top), MPI for Meteorology (bottom, 4)



Compared to its usual width (top), the Indus swells greatly during the monsoon (bottom). Its water is stored in reservoirs so that it can be used to supply the fields during the dry season.

Photos: NASA

Institute to the Climate Service Center, also in Hamburg, looked into irrigation in India and Pakistan.

"The Indian subcontinent is one of the most intensively irrigated regions on Earth," says Saeed, who himself originates from northern Pakistan. The climate is shaped by the monsoon: there is hardly any rain in winter, but in summer, humid maritime air is transported from the Arabian Sea and the Gulf of Bengal for several months and falls as rain on the slopes of the Himalayas. In some places, the annual average precipitation is 10,000 millimeters – more than ten times as much as in Germany.

The monsoon has its roots in the large temperature difference between land and sea. During the summer months, the land masses heat up much more than the ocean. The hot air above the subcontinent rises, thus drawing in humid air from the Indian Ocean, which releases its wet load over the land. Dams and reservoirs catch the plentiful summer rain so that the fields can be irrigated year-round.

An ingenious irrigation technique was probably the basis for the early advanced civilization on the Indus river as far back as more than 5,000 years ago. Even today, the waters of the mighty river in the northwest of the subcontinent are utilized intensively: the Indus catchment area is home to the largest continuous irrigated zone in the world, comprising countless reservoirs, dams and a huge network of channels and pipes. The experts estimate that only one-eighth of the precipitation in the Indus catchment area ever reaches the estuary in the Arabian Sea. The rest is first spread over the fields before evaporating again.

Fahad Saeed discovered that the huge amounts of water vapor that rise from the floor of the Indus basin have a great impact on the whole monsoon climate in India. "Without irrigation, the areas of low pressure from the Gulf of Bengal wouldn't penetrate very deeply into the interior," says the physicist. Saeed compared two different versions of the regional climate model REMO from the Max Planck Institute for Meteorology. He incorporated the effect of irrigation into one, but not the other. As he found out, a too-strong westerly wind from the Arabian Sea toward the Gulf of Bengal always developed in the model without irrigation, which prevented the monsoon lows from migrating to the east. The interfering wind was less pronounced in the model with irrigation, so that the modeled route of the low pressure areas agreed better with observations.

By taking irrigation into account, it was also possible to remove a further deficit of the regional climate model: a so-called heat low above northwest India and northern Pakistan could be represented more realistically with the changed water balance. In earlier climate models, this heat low, a stationary area of low pressure that forms above the Thar desert on the border between India and Pakistan due to the extreme heat in summer, was too pronounced. The temperatures calculated from models were sometimes 5 degrees Celsius above the actual values here, and the air pressure modeled was also significantly lower than that observed.

IF GLACIERS MELT, THE INDUS RIVER WILL HOLD LESS WATER

In Saeed's model with irrigation, this systematic error disappeared, the heat low was less intense. "Irrigation must obviously be taken into account in order to realistically simulate the monsoon climate," says Stefan Hagemann. At present, the human impact in the region has an overall positive effect on the climate: without the gigantic irrigation region along the Indus, it wouldn't only be hotter in large parts of India, but also significantly drier.

But the source that feeds the irrigation installations may well begin gradually to dry up with climate change, because a large part of the Indus water originates from the glaciers of the Himalayas. If the glaciers melt, the

amount of water available for irrigation will decrease. The evaporation in the irrigation region could then decrease, and its positive effect diminish. Future climate models must therefore also take into account changes in land use, says Hagemann.

The impact of wetlands on the climate system is at least as important as that of irrigation. Swamps, moors, riverside meadows and marshlands store not only water, but carbon as well. Since organic material is slow to decay in wetlands, the carbon accumulates over the years and millennia. Moors, for example, are deemed to be the most effective carbon stores on land.

Overall, wetlands contain roughly as much carbon as the atmosphere. The problem is that they also release greenhouse gases: if the organic material decomposes aerobically, they release carbon dioxide. If no oxygen is present, the much more powerful greenhouse gas methane is produced. Whether a marshland stores carbon or releases it, and in which form it does so, depends primarily on the water level. Some researchers suspect that global warming could transform wetlands from carbon sinks into carbon sources, given that the methane bacteria become more active in oxygen-starved sludges at higher temperatures.

In order for Earth system models to be able to compute these relationships in the future, Tobias Stacke from the Hamburg research group developed a model in his doctoral thesis that simulates the growth and shrinking of wetlands. At higher latitudes, for example, relatively small lakes increase in size in spring after the snowmelt, forming entire lakeland areas. If the climate in a region changes in the long term, this also has implications for the wetlands there.

THE MODEL COMPUTES LAKES IN THE RIGHT PLACES

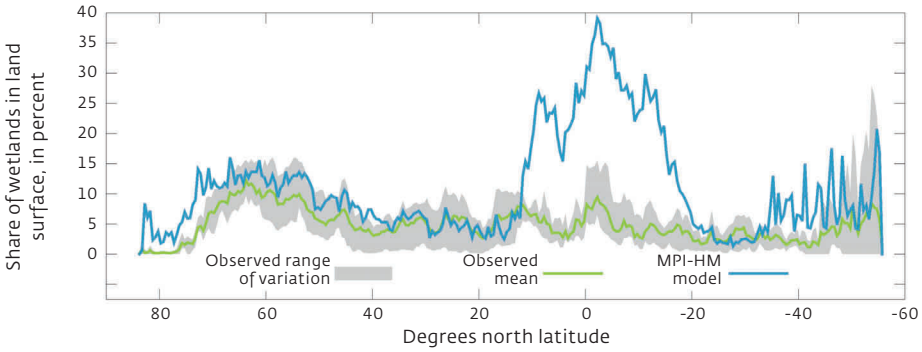
Stacke first integrated these processes into a specific hydrology model developed at the institute, a program called MPI-HM. "This model is relatively simple, but it provides results that are just as good as those of other, significantly more complicated hydrology models," emphasizes Stefan Hagemann. It is therefore an excellent tool to test new program components such as the wetland module. MPI-HM uses either observed or modeled precipitation data as input. The model then computes the evaporation, the runoff and the soil moisture, for example – either for a specific region or for Earth as a whole.

To find out how realistic the results of his model are, Stacke used it to simulate the distribution of the wetlands during the mid-Holocene, 6,000 years ago. At that time, there was significantly more precipitation in the Sahara than today, and in southern Asia, the climate was also wetter. There were expansive lakes in Africa, such as Lake Chad at the southern edge of the Sahara. The lake covered 400,000 square kilometers – more than the Caspian Sea today. Such mega-lakes also formed in the right places in the model, and it also provided the correct distribution and extent of the wetlands in today's climate. Since it proved to be correct, Tobias Stacke is currently working on integrating his model into the JSBACH land model developed by the Max Planck Institute in Hamburg. This model, in turn, is part of the current Earth system model. He collaborates closely with researchers from Victor Brovkin's Climate-Biogeosphere Interactions research group, which is interested mainly in the methane production of the wetlands.

The most northern terrestrial regions on Earth are also feared to be sources of the greenhouse gas methane – those regions in North America or Siberia where the ground is permanently frozen. Permafrost regions store

Photo: Still Pictures – images.de

Wetlands such as those in Scotland (left) store large amounts of carbon that would otherwise amplify the greenhouse effect as carbon dioxide or methane in the atmosphere. The MPI-HM model of the Hamburg-based researchers provides a good simulation of how much of the land surface is covered by wetlands (bottom). Only in the tropics does the model calculate too large a proportion.



large quantities of carbon in organic matter, just like wetlands; they are deep-frozen swamps, as it were. If the ground thaws there, the accumulated carbon could be released rapidly. Additional quantities of methane and carbon dioxide would get into the atmosphere and aggravate the warming effect. Climate researchers have therefore long been asking themselves how the permafrost will react to global warming – where, how rapidly, and to what depth the ground will thaw.

However, these questions aren't so easy to answer, because the hydrology of the permafrost is much more complicated than that of normal soil. This is due to the thin, active layer that thaws in summer and then lies on top of the largely water-impermeable frozen layer. The top layer is often quite swampy, even in areas of low precipitation. Only extremely small quantities of water run off in winter, but in spring, during snowmelt, there is significantly greater runoff.

Since the melt water can't penetrate very deeply into the ground, it runs off much more rapidly than at moderate latitudes. In addition, meter-high ice wedges often form in permafrost soils, which can suddenly collapse after heavy rain, for example. This gives rise to so-called thermokarst lakes, which, in turn, aggravate the soil erosion.

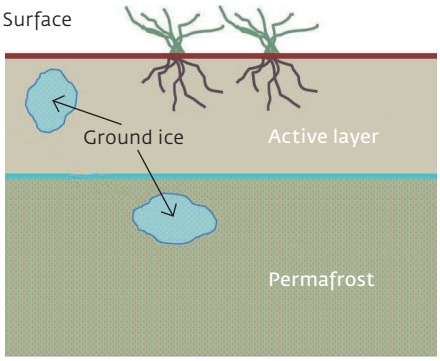
THE SOIL ACTS LIKE A MEMORY

As comparative tests show, the current Earth system models still fail to correctly reproduce the specific hydrological behavior of permafrost soils in today's climate. "Most Earth system models don't take into account even the simplest processes that take place in the permafrost, such as the freezing or thawing of the soil water," criticizes Stefan Hagemann. His group wants to change this: the researchers are involved in the PAGE21 EU project, which is investigating the vulnerability of the permafrost regions due to climate change. >

Tobias Stacke, Stefan Hagemann and Tanja Blome (from left) research the interplay between water cycle and climate.

Photo: Michael Zapf; graphic: MPI for Meteorology

A possible source of greenhouse gases: Permafrost soils in Siberia and in central Iceland (shown here) contain a large amount of undecomposed organic matter (top). The active layer thaws in summer. The soil deeper below the surface remains frozen (bottom), with the result that melt water runs off faster. The water also feeds the river Thjorsa in central Iceland.



Tanja Blome is currently working on the hydrological processes typical of permafrost areas. During this project, she is cooperating closely with colleagues from the Max Planck Institute for Biogeochemistry in Jena, who have incorporated these processes into the Max Planck land surface model JSBACH in order to simulate the methane production of the permafrost soils more reliably.

Be it in permafrost soils, in wetlands or in the artificially irrigated agricultural landscapes of the Indian subcontinent, the water balance on land, and thus the soil moisture, can play a key role regionally in medium-term forecasts. Stefan Hagemann's group is therefore also working in the BMBF project known as MiKlip (medium-term climate forecasts). This involves improving climate forecasts for the next years through to the next decade.

A detailed understanding of the hydrological processes on land could help here: since the soil can store water for a long time, it acts like a memory. A dry period or a flood can affect temperatures and precipitation for months. How strongly plants grow and how much water they release from their pores also depends on the soil moisture.

To date, soil moisture has gone into the Earth system model of the Max Planck Institute for Meteorology only in a greatly simplified form: "The soil was represented as a single layer," reports Hagemann. Model plants and evaporation gradually extracted the rain water from the soil. During dry pe-

Photo: SPL-Agentur Focus; graphic: MPI for Meteorology

riods, the soil moisture in the models rapidly decreased to zero, with the result that water could no longer evaporate. “But this isn’t realistic,” says Hagemann. This error is evident in certain regions, for example along the Danube or the Amazon, where the model regularly computes higher summer temperatures than occur in reality.

HOW WET IS THE SOIL AT GREATER DEPTHS?

In order to remedy the problem, Stefan Hagemann represents the soil as five stacked layers in his latest version of the model. “Especially in moderately dry regions, where part of the ground isn’t covered by vegetation, this yields a better description,” says the researcher.

Since it’s difficult to measure the soil moisture everywhere, Hagemann is also working on adjusting the model data with satellite data. “The satellite sees only the top few centimeters of the soil,” he reports. Therefore, it hasn’t yet really been possible to say how wet the soil is at greater depths. Hagemann’s goal now is to compute this from the satellite data with the aid of his new model. The European Space Agency, ESA, is also interested in this research work, the physicist explains: “They want to use the model to evaluate the satellite data.”

The collaboration with other researchers within and outside of the Max Planck Society is very important for Hagemann’s research group, especially since the team is financed wholly from third-party funds. In addition to the BMBF project MiKlip and the EU project PAGE21, the researchers are currently also participating in the EU project EMBRACE (Earth system Model Bias Reduction and assessing Abrupt Climate changE), which is concerned with improving Earth system models. In these comprehensive research projects, the Hamburg-based meteorologists contribute knowledge that has scarcely been taken into account so far: detailed knowledge of the perpetual pump that moves water through the Earth system. ◂

TO THE POINT

- **Gigantic amounts of moisture are constantly being moved between land, oceans, atmosphere and cryosphere – as much as if the total water in the atmosphere were exchanged 40 times per year. The water cycle on land is closely coupled with the regional and global climate.**
- **As simulations done by the researchers at the Max Planck Institute for Meteorology show, the massive extent of irrigation on the Indian subcontinent causes it to be less hot and dry in the region than in a climate without irrigation. Global warming could reduce the amount of water available for this process.**
- **Whether wetlands release carbon dioxide or methane depends on the water level in the ecosystems. Simulations of the water balance of swamps, moors, river meadows and marshlands thus help provide a more accurate determination of their role in the climate system.**
- **Forecasts of whether permafrost soils release more greenhouse gases during climate change also require knowledge of the water balance in these regions. The reason is that the soils that have so far been frozen all year round could emit more carbon dioxide and methane the more they thaw.**