Bridge without a river: a drought in 2018 led to a drastic reduction in the water level of many bodies of water, such as the Rhine. As seen here in Duesseldorf, this also had a serious impact on inland navigation.

PHOTO: PICTURE ALLIANCE/DPA | CHRISTOPHE GATEAU

PREDICTABLE CLIMATE STRESS

TEXT: ANDREAS KNEBL

Droughts, heatwaves, and floods – climate change is likely to make extreme weather and climate events such as these more frequent and more intense. Markus Reichstein, Director at the Max Planck Institute for Biogeochemistry in Jena, and his team are working on predicting the impacts of such events. Reichstein uses large volumes of data in conjunction with artificial intelligence to carry out this research, which he hopes will make societies more resilient to extreme climate events.

The researcher Markus Reichstein is fond of rosemary and would ideally like to grow the Mediterranean herb in his garden in Jena, but it probably would not survive there for long. That is because there is a severe cold spell there every few years – such as that in the winter of 2020/2021 – that prevents a large rosemary bush from thriving. Nevertheless, Markus Reichstein, Director at the Max Planck Institute for Biogeochemistry, can still use rosemary to illustrate his research into extreme climate events. The sunny, warm, and dry climate in Jena is actually ideally suited to the Mediterranean plant, and the average winter temperatures are not a problem either. But just a few days at temperatures below minus 10 degrees Celsius can sound the death knell for the bush. Reichstein uses this fact to explain the different dimensions of extreme climate and weather events.

PHOTO: DAVID AUSSERHOFER

Alerted by extreme events: Markus Reichstein and his team combine meteorological measurements – such as from a weather station in Jena – with ecosystem data. Artificial intelligence helps them predict extreme climate events and their consequences for agriculture and forestry, for example.

The term "extreme climate event" is used to refer to prolonged, extraordinary events, such as droughts or heatwaves. "Extreme weather" refers to short and unusually intense events, such as storms or heavy hail showers, but there is no standard definition of what is classified as extreme: "For a start, you can look at the meteorological data and determine how frequently, or indeed infrequently, a specific event occurs at a given location – such as temperatures below minus 10 degrees Celsius," Reichstein explains. "But you can also look at an event like this differently and analyze how far the value deviates from the mean. It is even more compelling, however, to consider what effects the event has and whether its impacts are just as extreme – that is, unusually intense." After all, native plants can easily handle a few very cold winter days – and the effects are not extreme by their standards, but they certainly are extreme for rosemary.

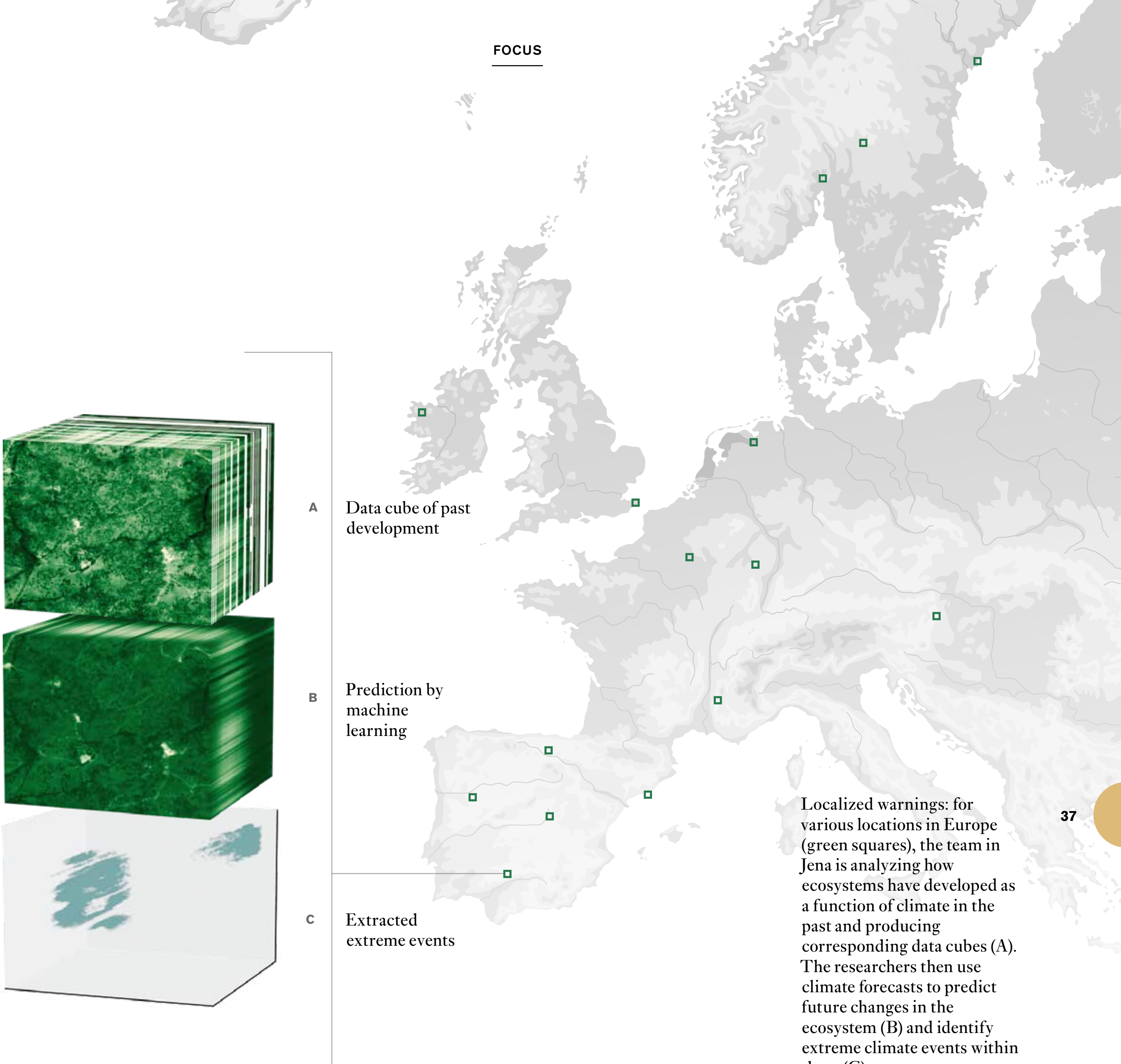
In the last few years, it has been hard to overlook the far-reaching consequences of extreme climate events in Germany – some of which were quite unexpected. The hot and very dry summer of 2018 created serious problems for foresters and farmers alike, and caused increasingly visible damage to German forests. In some parts of Germany, the extreme drought even led to extensive forest fires. These direct consequences were to be expected. What was more surprising, however, was that a low water level in the Rhine would lead to bottlenecks in supply and that power plants would run out of cooling water. The extreme climate conditions therefore had a serious impact not only on humans but also on the natural world – and were an area of intense public interest.

But for many ecosystem researchers, including Markus Reichstein, the wake-up call had already come in the form of another extreme event – namely the heatwave that hit Europe in the summer of 2003. Back then, the high temperatures and increased air pollution due to various climatic effects led to several tens of thousands of deaths. As well as affecting humans and the economy, the heatwave also had a serious impact on the natural world. Based on extensive data from measuring stations and remote-sensing satellites, researchers were able to conduct a detailed analysis of the heatwave's effects on ecosystems. At that time, Markus Reichstein's research focused on the carbon cycle and particularly on the carbon balance between the biogeosphere and the atmosphere. In other words, the researcher was trying to work out how much carbon dioxide was being absorbed from and emitted into the air by plants and soils, for example. The data from the 2003 heatwave also clearly demonstrated the profound influence of extreme climate events on the global carbon cycle: normally, the plants on the European landmass absorb large quantities of CO_2 during their growing season over the summer period. This is described as a "carbon sink" – as opposed to a "carbon source." But the effects of high temperatures, and especially of a shortage of water, meant that the plants grew significantly less in 2003. As a result, not only were the car-

"The aim must be a society that is resilient to extreme climate events."

MARKUS REICHSTEIN

GRAPHICS: GCO, BASED ON A TEMPLATE BY VITUS BENSON, CHRISTIAN REQUENA-MESA, WWW.EARTHNET.TECH (2021)



Localized warnings: for various locations in Europe (green squares), the team in Jena is analyzing how ecosystems have developed as a function of climate in the past and producing corresponding data cubes (A). The researchers then use climate forecasts to predict future changes in the ecosystem (B) and identify extreme climate events within them (C).

bon sinks across Europe much weaker, but European ecosystems even became sources of carbon dioxide.

This finding sent shock waves through the research community. Until then, researchers had assumed that anthropogenic climate change would cause plants at middle and high latitudes to absorb more CO_2 in the future. The theory was that warming and the increased level of carbon dioxide in the atmosphere would cause plants to grow earlier in the year and more vigorously – and that this would slow down not only the rise in carbon dioxide levels due to anthropogenic emissions, but therefore also the process of climate change itself. "However, the 2003 heatwave was an eye-opener," says Markus Reichstein. Even then, everything scientists had learned thus far suggested that climate change would lead to more extreme events, such as droughts and heatwaves, in the future – and it turned out that an event of this kind was capable of temporarily converting a carbon sink into a carbon source. Indeed, if vegetation dies off or experiences permanent damage, this effect can even intensify over the years. Reichstein's team discovered that extreme climate events exert approximately the same degree of influence on the global carbon cycle as that of all carbon sinks on the Earth's landmasses combined. And if extreme climate events become more frequent, the CO_2 content of the atmosphere could continue to rise – creating a feedback loop between the atmosphere and the biogeosphere that would further accelerate climate change.

PHOTO: SHUTTERSTOCK/HIKRCN

At the mercy of climate change: a heatwave in 2011 forced a million people in East Africa to flee their homes and land. Forecasts of these events could allow people to take precautions against disasters of this kind.

Of course, the degree to which extreme events affect humans and nature also depends on their frequency and intensity. Accordingly, predictions as to whether climate change will lead to more extremes help us to assess what is coming our way. For a long time, these kinds of forecasts were based on abstract considerations. It wasn't possible to make detailed forecasts, because insufficient data was available on rare extreme events in the complex system of climate and weather. However, fundamental thermodynamic considerations led researchers to conclude that climate change would make extremes more likely and therefore more frequent. The reason for this is that the global rise in temperatures means there is more energy in the Earth system. More water evaporates, and the atmosphere can also hold more water. This means that the generation of weather events gains momentum – and results in more extreme events such as heatwaves, heavy rain, or storms.

SUMMARY

As our climate changes, extreme meteorological events such as heatwaves, droughts, storms, and heavy rain look set to become more common. In some cases, this interrelationship has already been proven.

Researchers from the Max Planck Institute for Biogeochemistry are using meteorological and ecological data in conjunction with artificial intelligence to improve their understanding of – and ability to predict – extreme climate events and their impacts.

By adopting this approach, they have been able to demonstrate that the heatwave and drought that affected Russia in 2010 led to a collapse in plant growth in agricultural regions, as expected, but was also linked to increase in biomass production at latitudes dominated by woodland.

Predictions of extreme climate events and their consequences could help societies to be better prepared.

Over the last few years, climate scientists have been proven correct in their reasoning, as they have actually succeeded in attributing the increase in extreme events to climate change. Their analysis is based on improved global and regional climate models that run on powerful computers. At present, the attribution works best for heatwaves, while the statements are less reliable for other extreme events such as droughts, heavy rain, or floods. Rather than establishing a causal relationship between climate change and a specific event, the researchers calculate how much more likely an extreme event of this kind has become due to climate change. This involves comparing the probability of an extreme event in a world without anthropogenic climate change with the probability in a world with climate change. This is rather like throwing two dice numerous times to compare how often a certain number occurs. Climate change has loaded one of the dice – the one from our real world. In the case of the devastating bush fires in Australia in 2019 and 2020, for example, an analysis by the World Weather Attribution research initiative found that climate change has increased the risk of an event of this kind by at least 30 percent.

Markus Reichstein hopes to go one step further: he not only wants to attribute extreme climate events to climate change retrospectively, but also to predict these events for a region or location as accurately as possible. For this, his group uses large quantities of data in conjunction with artificial intelligence to develop a better understanding of extreme climate events. By doing so, they hope to pave the way for forecasts of extreme climate events – and above all of their effects – with high spatial resolution and therefore to contribute to the development of an early warning system. To this end, the scientists gather large volumes of data that allow them to correlate a wide variety of information, such as meteorological measurement data and data that describes ecosystems. Artificial intelligence techniques help them to process and combine the data, allowing them to compare, for example, temperature and precipitation values with the plant activity determined from satellite images, as well as analyze the carbon dioxide concentration measured near the Earth's surface. This enables the researchers to produce a world map for all variables that characterize the state of an ecosystem. For example, this results in a drought stress map that covers many previous points in time – in other words, it has high temporal resolution. Along with the degrees of longitude and latitude, the slices of time form the third dimension of this "data cube." This ultimately allows the researchers to assess, for example, the extent to which the drought has damaged – and will damage – the vegetation as time goes by. The key strength of this approach is that it reveals spatial relationships and illustrates the development over time, allowing the scientists to detect anomalies. For these deviations from the norm, which indicate an extreme event, they then analyze a range of variables and volumes in order to obtain a multidimensional picture of the complex interactions.

An extreme climate event with ambivalent consequences

To examine how various factors contribute to the occurrence of an extreme climate event and influence its effects, the scientists studied one extreme event in particular: a heatwave that took place in Russia in 2010. The prolonged period of abnormally hot weather saw temperatures rise to over 38 degrees Celsius and exceed average temperatures by more than 10 degrees Celsius for a period of several weeks. This was accompanied by a period of severe drought – producing a devastating combination that resulted in crop failures, forest fires, and peat fires. The heatwave also led to tens of thousands of deaths, not only because of the high temperatures but also because of the air pollution caused by the drought, heat, and fires. However, in the data cube analysis, Reichstein's team discovered that the consequences were not as unequivocally negative for the natural world, because the time and location of →

the extreme meteorological event did not quite match up with the development of plant productivity. The anticipated effect appeared at the middle latitudes, which are dominated by agriculture: here, the hot and dry summer caused the plants to stop growing and wither. Plant productivity collapsed. At the higher latitudes with extensive forest cover, however, the mild spring and unusually hot summer triggered early and vigorous plant growth. In other words, the extreme meteorological event had very different effects on the ecosystems in different regions.

Accurate to the nearest 20 meters

In order to predict extreme climate events reliably, the key thing is to learn from as many different examples of these events as possible. Indeed, it is only by analyzing a large volume of data in detail that researchers can produce a clear and generally applicable picture of these complex relationships. That is precisely the strength of artificial intelligence – and specifically of methods based on machine learning, which can spot patterns in unfamiliar data. To this end, Reichstein's research group is working with Bernhard Schölkopf, Director at the Max Planck Institute for Intelligent Systems, as well as other researchers from the European Lab for Learning & Intelligent Systems (ELLIS), to refine machine learning algorithms and apply them to Earth system research. With the help of artificial intelligence, the researchers in Jena are not only analyzing the effects of extreme events, but also aim to achieve a better understanding of the causal relationships through which ecosystems and the climate influence one another. The data cubes are now accumulating increasing numbers of extreme climate events that have taken place around the world in recent decades – and the scientists hope to detect informative patterns in this data with the help of artificial intelligence. Moreover, it may also be possible to link risk factors or indirect consequences to an extreme climate event in an association that other approaches probably wouldn't have identified. "If we combine the results of these analyses with models and established climate knowledge, it may one day be possible to predict the risk of an extreme climate event – and above all its effects – down to the nearest 20 meters," explains Reichstein.

With the findings that the geoscientist and his colleagues around the world have obtained in relation to extreme climate events, Reichstein now wants to put his case to the general public and the world of politics. He is being supported in these efforts by Dorothea Frank at the Max Planck Institute for Biogeochemistry: "We want to raise awareness of the dangers caused by the fact that climate change is making extreme weather and climate events increasingly likely," says Frank, who is jointly responsible for numerous projects and initiatives in this context. After all, it is clear that even if efforts aimed at slowing down and stopping climate change are successful, the occurrence of extreme climate events worldwide will initially intensify. At the same time, the forces of nature are colliding with social conditions that are in a constant state of flux. The researchers in Jena therefore want to use findings from various scientific disciplines in order to better prepare society for the challenges associated with climate change. "Particularly in the case of systemic risks that arise from the interaction of natural systems with the economy, politics, and individuals, our understanding of these risks relies on our ability to consider developments from scientific, economic, psychological, sociological, and historical perspectives," says Reichstein.

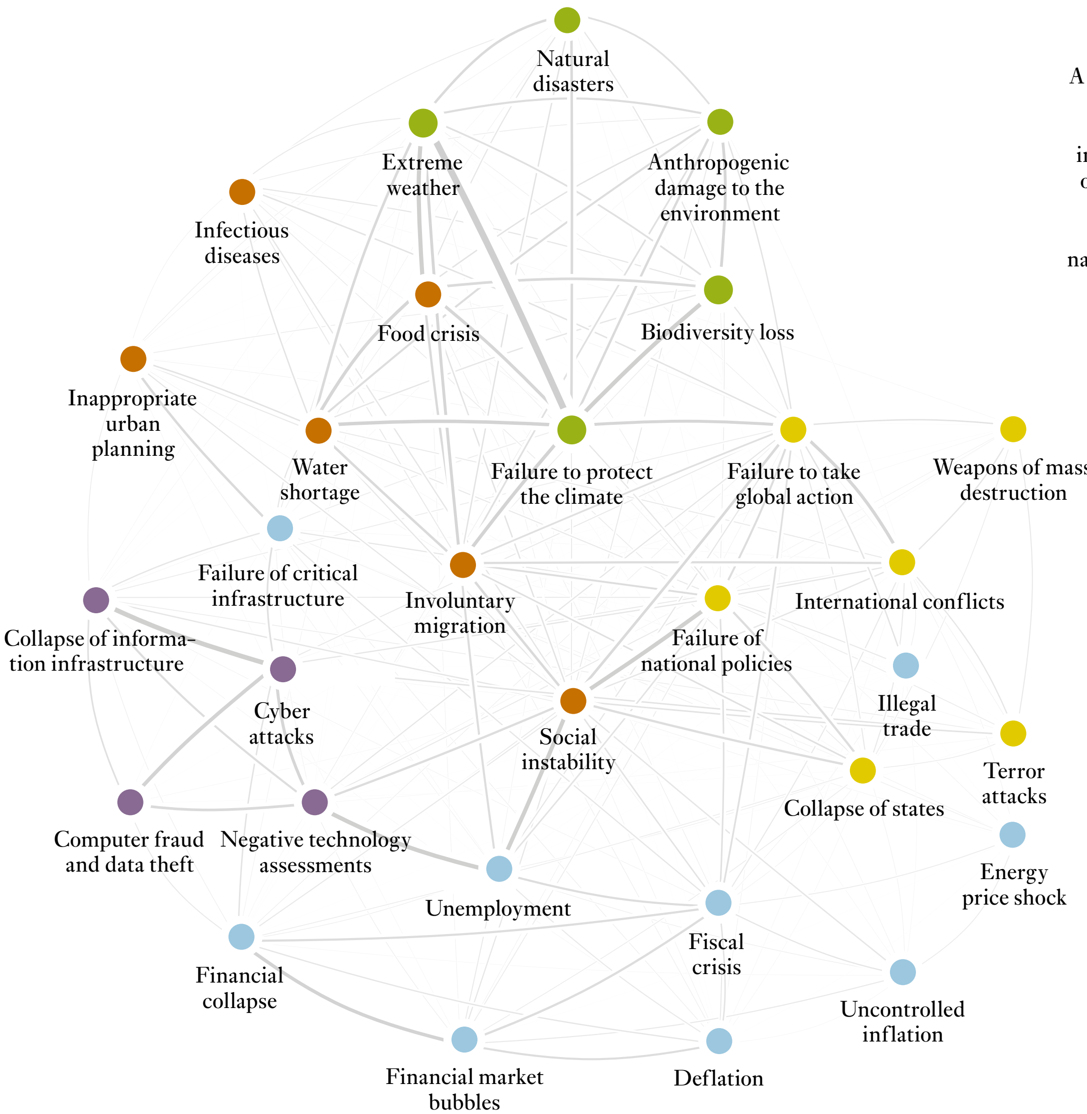
Frank and Reichstein are currently attempting to bolster scientific dialog in relation to extreme events, disaster preparedness, and governance through the Risk KAN initiative, which brings together numerous international colleagues. Together, they want to draw up recommended courses of action for dealing with systemic risks. After all, extreme climate and weather events are increasingly putting states and societies to the test – and whereas wealthy and highly developed countries are often able to avert the most serious consequences of extreme events, the resulting disasters threaten many human lives in developing countries and necessitate the deployment of humanitarian aid. One example of this is the drought that affected East Africa in 2011, along with the resulting famine in countries such as Ethiopia and Somalia. This disaster put more than 10 million people at risk, caused several hundred thousand deaths, and forced almost a million people to flee their homes and homelands. The World Bank estimates that by 2050, up to 143 million people could become climate refugees, many of them due to the effects of extreme climate events. With this in mind, it is vital that we take immediate action, adopt preventive measures, and make the necessary investments. "The aim must be a sustainable society that is as resilient to extreme climate events as possible," says Reichstein. There are a variety of possible measures, which depend heavily on the location in question: near coastlines or rivers, it may be necessary

GLOSSARY

EXTREME CLIMATE EVENT
A prolonged, unusual event such as a drought or heatwave. In contrast, extreme weather is a short, unusually intense event such as a storm or heavy rain.

CARBON SINK
A part of an Earth system that absorbs more carbon – primarily in the form of carbon dioxide – than it emits. Land and ocean together absorb more than 50 percent of anthropogenic carbon dioxide emissions.

MACHINE LEARNING
An artificial intelligence approach in which algorithms spot patterns in large volumes of data – for example, in order to identify the relationship between meteorological data, such as rainfall figures, and reduced plant growth. Researchers can then predict these kinds of consequences in advance.



A network of risks: extreme climate events can have numerous direct and indirect consequences, not only for nature (green) but also for human existence and health (brown), national and global political systems (yellow), the economy (blue), and technical security (violet).

GRAPHIC: GCO ACCORDING TO WORLD ECONOMIC FORUM GLOBAL RISKS PERCEPTION SURVEY 2019–2020

to build higher dams and flood walls, whereas other locations require the introduction of new crops that are more resistant to drought.

Reliable predictions of the effects of extreme climate events, such as those being developed by Reichstein's team, help to make societies more robust. For example, the team is currently collaborating on a large EU-funded research project aimed at establishing this approach in Africa. After all, an early warning system gives people in an affected region time to prepare themselves for extreme events – and the necessary financial resources could be released in advance in order to help local people and prevent a disaster from occurring. Although forecast-based disaster relief is already in use today, it could see significant expansion in the future and would benefit from access to reliable and accurate predictions. Markus Reichstein is convinced of the potential of his data-based research approach and believes it could even be extended to other areas: by using artificial intelligence to analyze climate, ecosystem, and socioeconomic data, researchers could also examine the vulnerability of societies to extreme climate events. However, even if vulnerable societies are identified or the alarm is raised by an early-warning system based on data cubes, it all ultimately depends on how people react to this information. In this regard, the coronavirus pandemic – of all things – has provided Dorothea Frank and Markus Reichstein with some reassurance. "Because this crisis has demonstrated that our society – in Germany and around the world – is absolutely in a position to act quickly and decisively," says Frank. "That same determination is now needed to tackle the climate crisis and avert the huge impact of extreme climate events."

www.mpg.de/podcasts/extreme (in German)