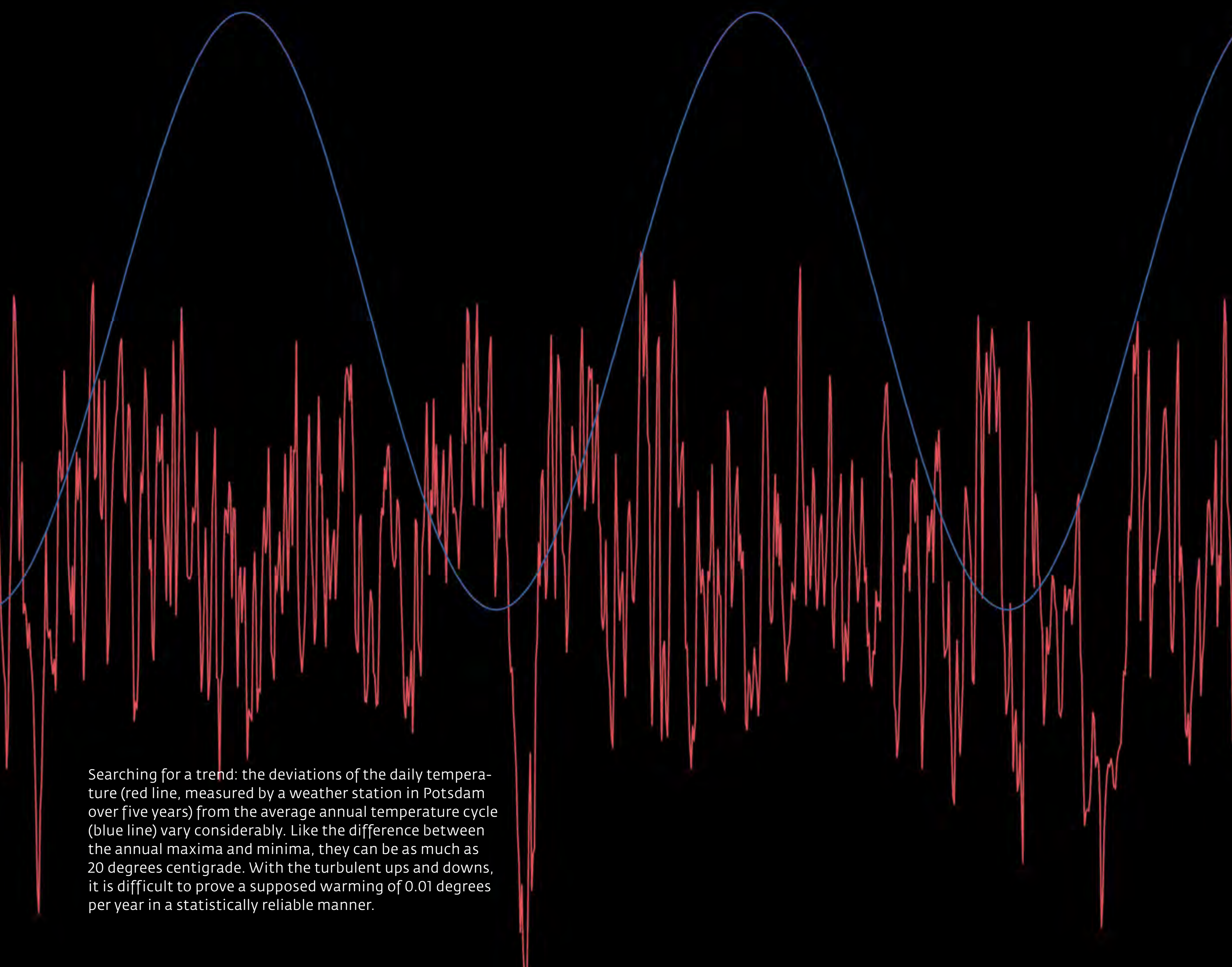
Quirks
in the computer

Storms, droughts and extreme rainfall could become more frequent due to global warming. At any rate, climate researchers are discussing this eventuality and are analyzing measured data to determine whether such a trend can already be observed. **Holger Kantz** and his colleagues at Dresden's **Max Planck Institute for the Physics of Complex Systems** are developing the necessary statistical tools.



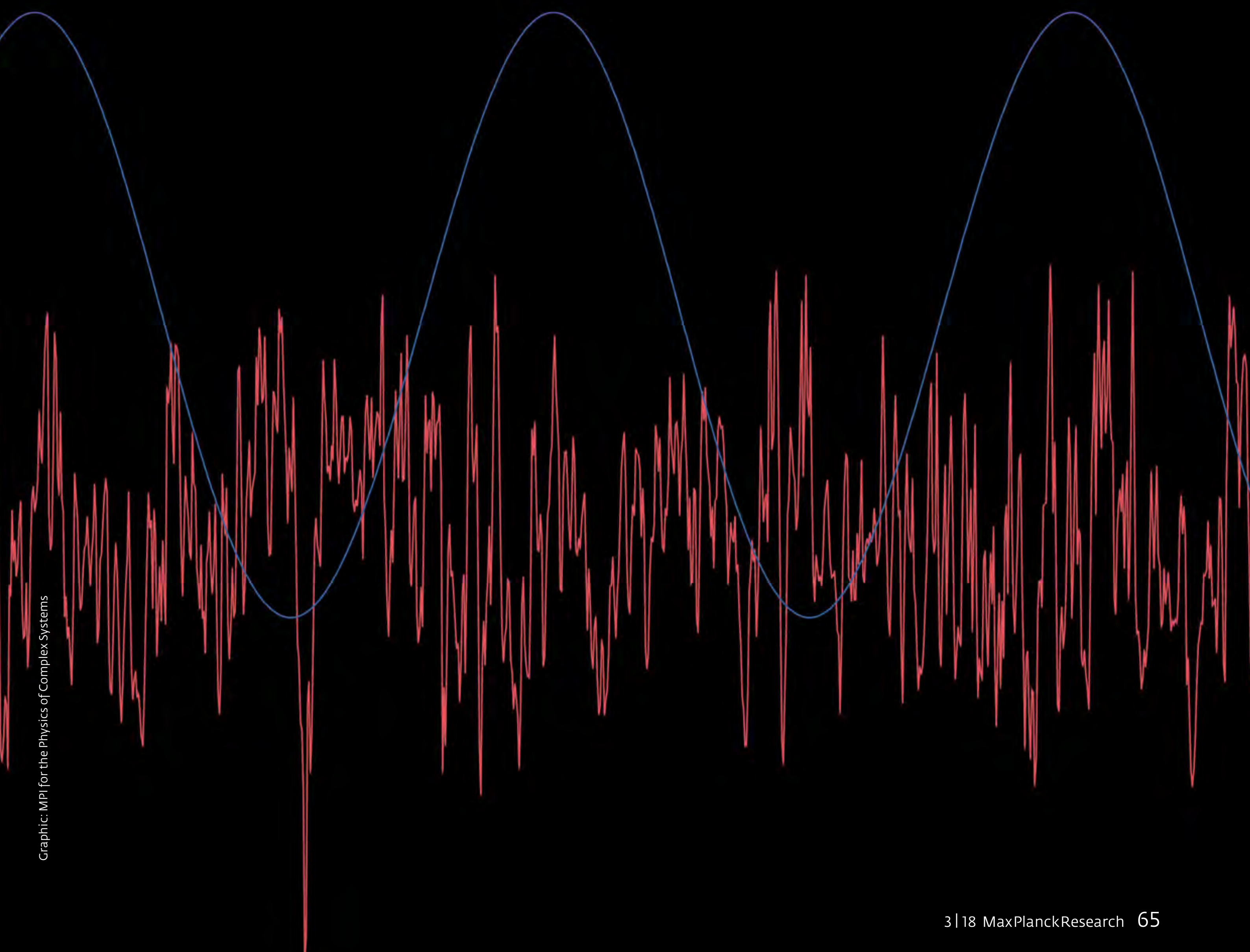
Searching for a trend: the deviations of the daily temperature (red line, measured by a weather station in Potsdam over five years) from the average annual temperature cycle (blue line) vary considerably. Like the difference between the annual maxima and minima, they can be as much as 20 degrees centigrade. With the turbulent ups and downs, it is difficult to prove a supposed warming of 0.01 degrees per year in a statistically reliable manner.

TEXT **KLAUS JACOB**

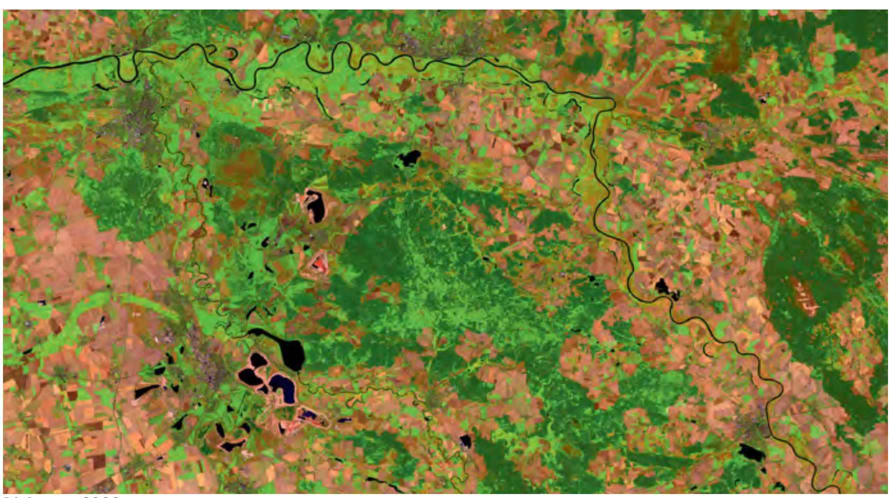
As if on cue, the weather sets the scene perfectly for our appointment in Dresden: frost and snow in late March is unusual, or you could even say: extreme. Holger Kantz, whose office is on the second floor of Dresden's Max Planck Institute for the Physics of Complex Systems, has spent the last decade studying extreme events with readings that deviate from the norm – a heartbeat that suddenly becomes erratic, a share price that plummets from one day to the next, or ocean waves that build up to form dreaded freak waves. In the last three years, the physicist and his team of six doctoral students and two postdocs have also turned their attention to studying weather and climate. The key question here is whether the number and intensity of extreme weather events are increasing. Are the rising temperatures brought on by climate change also leading to a greater risk of storms, floods, heatwaves and other quirks of the weather?

It's been a long time since climate researchers, who use models to look far into the future, first raised the alarm – and the regular reports of the Intergovernmental Panel on Climate Change (IPCC) have taken on an increasingly ominous tone. The arguments are clear: a warmer atmosphere can hold considerably more moisture, which leads to increased rainfall and therefore to flooding. Storms also risk becoming more severe, according to the reports, not to mention the heatwaves.

However, "the relationship between climate change and extreme weather is not quite that clear," says Kantz. Indeed, there are also arguments that point in a different direction: if it gets



Graphic: MPI for the Physics of Complex Systems



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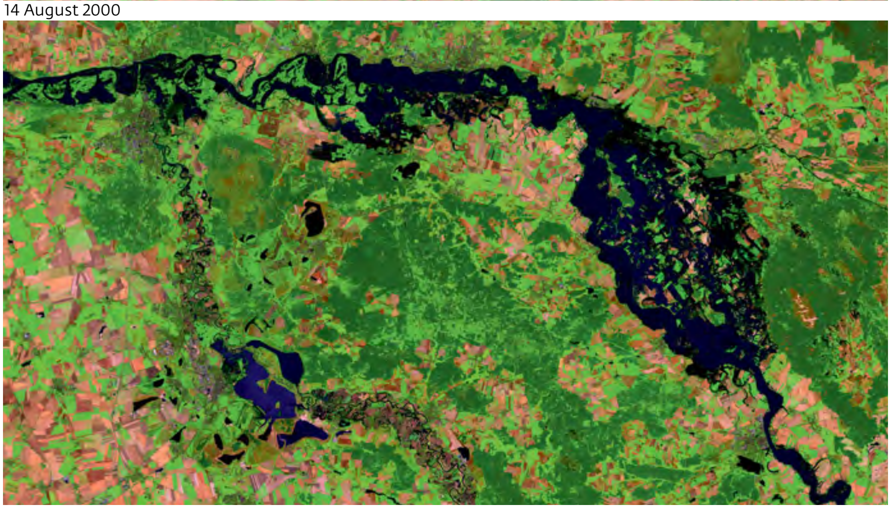


20 August 2002

Two exceptional floods in four years: the Elbe flooded at several points in April 2006, including in the small town of Hitzacker in the district of Luechow-Dannenberg. Just four years earlier, the river had overflowed its banks by some margin, as seen in satellite images of the region south of Wittenberg.

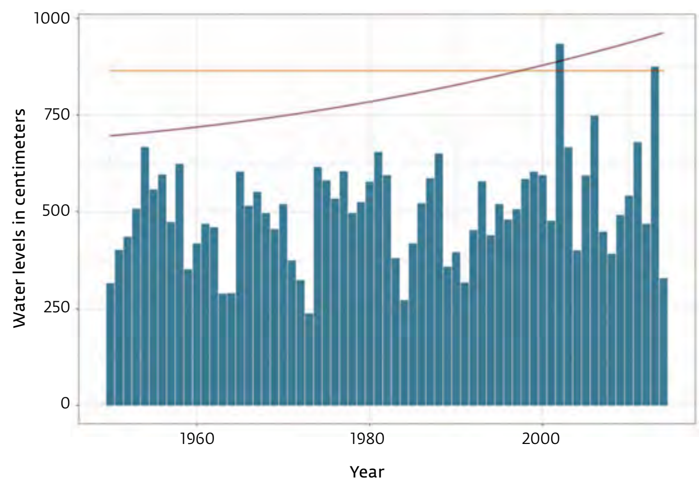
warmer at the poles, the temperature difference between high and low latitudes will decrease, which ought to lead to a calmer atmosphere. Moreover, if climatic zones shift, as will indisputably happen, it need not automatically lead to a rise in extreme weather events. Germany, for example, is predicted to develop a Mediterranean climate, which is no more dangerous than the temperate climate we enjoy today. Last but not least, the trend in local weather conditions can be completely different from that seen on a global scale.

BETTER ANALYSIS METHODS FOR MEASUREMENT SERIES

A look back at the recent past can help to determine how climate change and extreme weather are connected, and what types of storms threaten to strike individual regions. After all, the global average temperature has already risen by about 0.8 degrees since the industrial revolution, and this ought to have made its mark on the weather. The question is therefore whether storms and flooding have already become more frequent and intense.

Non-scientists who are worried about climate change believe they have known the answer for a long time. They have a tendency to blame climate change for every hail shower and every storm. Scientists, on the other hand, are more cautious because they must be able to pick out a clear trend in the

Photos: dpa/Holger Hollemann (top), NASA (bottom)



A trend or just pure chance? The maximum annual water levels of the Elbe have fluctuated considerably in recent decades. Although several exceptional floods have struck since the turn of the millennium, the statistics do not demonstrate a clear, systematic trend. Extreme event statistics were used to calculate the 100-year flood level, resulting in the purple line if the researchers allowed a trend or the yellow line if they assumed that the statistical properties do not change over time. For reasons of consistency, both lines should be exceeded, on average, only once every 100 years.

Graphic: MPI for the Physics of Complex Systems

data. These experts include Kantz and his working group, who have spent a great deal of time analyzing data series and searching for patterns. However, it is not his job to make concrete statements about climate and weather. Kantz openly admits that "the researchers at the Max Planck Institute for Meteorology in Hamburg are the better people for that."

Ultimately, Holger Kantz has a different set of objectives: he is more concerned with finding better analysis methods than with gaining a deeper understanding of the climate or issuing weather warnings. He is working to develop principles that help other researchers solve specific problems. His field of work revolves around the world of formulas with a view to bringing order to chaotic graphs, since understanding the ups and downs in measurement series allows researchers to look into the future and make useful predictions. Kantz scopes out the limits of different methods (see box on page 69), seeking to identify their respective pitfalls, and tends to publish more of his papers in physics journals than in publications relating to weather or climate.

Nevertheless, meteorology is a field that suits the researcher well because it provides extensive data series relating to floods, temperature or rainfall over long periods of time – precisely what he needs for his work. Unlike many other data sets, most of this data is publicly available.

Of course, from time to time, he inevitably comes across a result that can be put to practical use. Rather than being his actual objective, however, this is something of a collateral benefit. For example, he has found a way to use measured wind data to predict strong gusts. Although the prediction only stretches one or two seconds into the future, that is sufficient to protect gigantic wind turbines. In this time, it is possible to adjust the rotor blades' angle of attack relative to the direction of wind flow so that there is no risk of damage. The Max Planck Society has even applied for a patent to protect this forecasting technique.

Of course, some paths also lead to a dead end in basic research. For example, Holger Kantz has examined whether there is a universal mechanism that causes extreme events – a mechanism that is applicable to any variable that fluctuates erratically, such as wave height, wind strength or heart rate.

"As a physicist, you tend to think about feedback loops," says Kantz, explaining his approach, which is guided by dynamical systems theory. His idea was that, in any given system, an initial deviation will build up into an extreme value, before the system returns to normal because a resource that triggered the process has been used up.

Kantz searched a wide range of data series for a typical cycle of this kind. A universal formula would be invaluable because it would allow researchers to make reliable predictions. However, Kantz has now reined in his expectations: "After ten years of research, we can safely say: there is no universality to extreme events." Apparently, the causes are too multifaceted to be described by a single dynamic mechanism.

TWO 100-YEAR FLOODS IN QUICK SUCCESSION

A simpler but by no means trivial task is to study the records of one type of extreme event, such as the flooding of the River Elbe. In August 2002, the river burst its banks following a period of heavy rainfall. The water level in Dresden reached 9.40 meters, more than seven meters higher than the normal value. This was the first time since records began that the river had risen to such levels, and the media rightly reported that it was a 100-year flood. Large parts of the city were submerged, and the floods caused well over eight billion euros of damage in Saxony. >

» Although climate change already seems to be having a considerable impact at first glance, the statistics of local time series data do not provide a clear conclusion.

A statistical toolmaker: Holger Kantz leads a research group that develops mathematical methods so that, among other things, climate researchers can analyze weather data to identify possible trends.

Just eleven years later, in June 2013, the waters rose again, this time reaching a level of 8.76 meters. Many people assumed that two 100-year floods in such quick succession must be evidence of a trend. Did climate change already have a grip on the Elbe? Or had human interventions along the river's course led to a higher risk of flooding?

Statistics expert Holger Kantz set about answering these questions. However, he had to contend with a problem that is also a continual headache for climate researchers: the data series available to him was relatively short. After the Second World War, the water level gauge in Dresden had been moved, meaning that reliable data was only available for the last 65 years. Nevertheless, Kantz got to work. Plotting the maximum levels for each year on a graph, he obtained a varied picture of movement back and forth, with two particularly high peaks in 2002 and 2013. An extreme value analysis over time pointed to a surge in levels approaching those of 100-year floods. This seemed to be a clear indication that the risk had increased.

STATISTICS MAKE RELATIONSHIPS PLAUSIBLE

A word of warning, however: it is important to bear in mind that relatively short time series such as these don't come close to covering all of the possible scenarios. Next summer, perhaps, the river could rise to even higher levels than in all previous years, even without the effects of climate change. Indeed, after just 65 years, no one can say what the maximum water level really is. Perhaps the 100-year flood of 2002 is therefore not an indication of the impact of the greenhouse effect and instead simply serves to improve future statistical calculations. In that case, the hydrologists would only need to adjust the 100-year flood that is used as a basis for assessing protective measures.

As is befitting for a basic researcher, Kantz describes the difference in general terms: "Am I looking at an additional reality or a different reality?" In this context, an additional reality simply means a new maximum, whereas the different reality is actually driven by climate change, which establishes completely new boundary conditions.

At first glance, it seems almost impossible to achieve clarity regarding the relationships. Even statistics, with its tried-and-tested formulas, fails to provide any certainty. "We can never prove anything," says Kantz. "Rather, we can only make relationships plausible." To do this, he and his colleagues often take the following approach: first, the researchers assume that climate change has no influence on the flooding characteristics of the Elbe, for example, and use a computer to generate numerous possible data series that are consistent with this assumption. The scientists obtain these graphs in various ways, including by recompiling the actual measured values to obtain time series in which the data is combined randomly. They then compare these with the real measurements series of water level.

If climate change is actually at play, the measured data series should deviate considerably from the norm. In the case of the Elbe, however, it does not. So, although climate change already seems to be having a considerable impact at first glance, the statistics do not provide a clear conclusion. The result, as the experts would say, is not statistically significant. "However, that is no cause for celebration," Kantz points out. "It merely shows that our measure-

Photo: Juergen Loesel for TU Dresden

The power of mathematics: Holger Kantz's team has found a way to use measurements of wind strength to predict particularly strong gusts at short notice. Wind turbines can then be protected by altering their rotor blades' angle of attack.

ment series is not complete enough to produce a clear statement."

An example involving a dice demonstrates that appearance and gut feeling are poor guides when it comes to statistical tasks. After numerous throws fail to produce a six, people tend to expect this number when they next roll the dice. It has to come sometime, they think. However, this is actually a misconception: the probability is a sixth again every time, because the dice does not have a memory. Many a roulette player has lost money by listening to their gut feelings and trying to outsmart the statisticians.

UNEXPECTED RESULTS IN TEMPERATURE DATA

It is not only with the Elbe floods that Kantz has come across unexpected results, but also when he was analyzing data relating to temperatures in Germany. Before he could start, however, he first had to consider the locations of the individual meteorological stations. Quite a few weather stations stood in green fields when they were installed but are now surrounded by buildings. The problem is that cities develop a climate of their own; they get hotter as the multitude of brick buildings store up the sun's heat. This *urban warming* effect distorts the calculations and hints at the presence of climate change that may not exist at all. Kantz therefore excluded these stations from his considerations altogether.

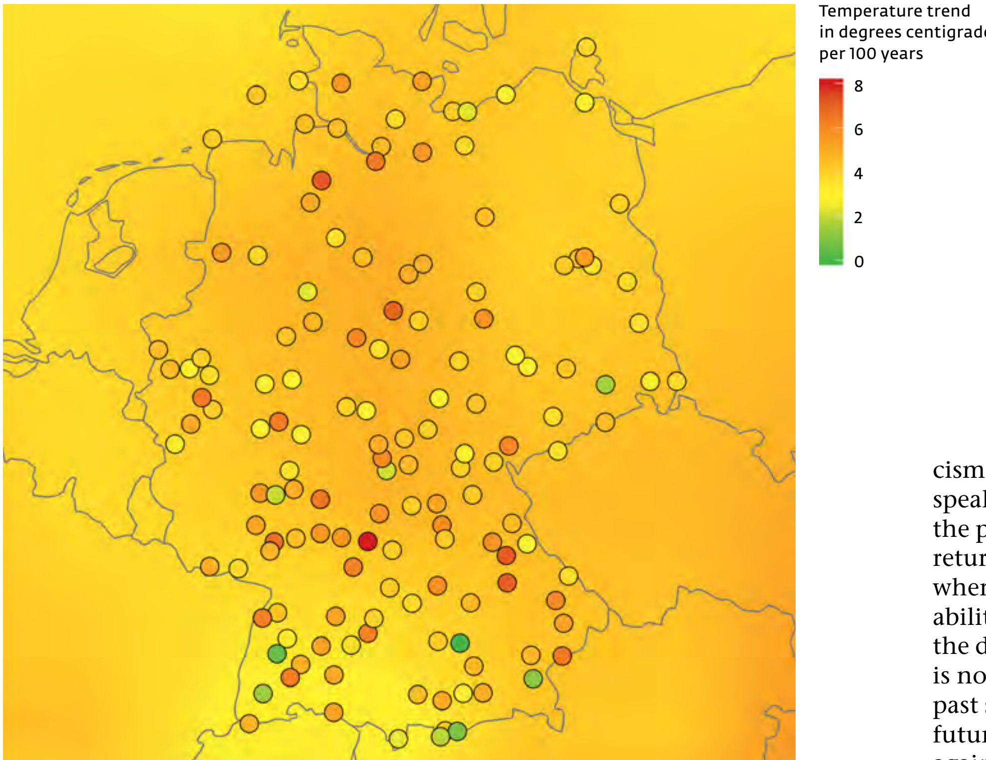
After processing the remaining data series with his statistical instruments, he reached a conclusion similar to that for the Elbe floods: it is not possible to prove that climate change is already influencing the temperatures – the relationship is not statistically significant. This applies to over half of the more than 100 stations.

The result is all the more surprising because meteorologists are constantly talking about new temperature records. It is no secret that the world is getting warmer – everyone can feel it. Here, the limits of the statistical methods become apparent, because when Kantz considers only the last 30 years, he obtains completely different results. In this

A COMPLEX REALITY IN CONCISE FORM

The world is full of complex systems, such as the atmosphere, the circulatory system or a river. Measurement instruments allow us to observe how such systems react, producing long series of data relating to the precipitation, heart rate or river level, for example. Holger Kantz analyzes the dynamic ups and downs and draws conclusions from them, ultimately with a view to making predictions. One important tool in this work is time-series analysis. From the flood of data, Kantz and his team extract important parameters such as the mean, the variance or a trend, the challenge being to find variables that concisely reflect the complex reality. Ultimately, the approach could be described as "data compression", because the researchers in Dresden are essentially slimming down a large number of measurements in order to extract the essential information. However, they must be careful not to lose any important details in the process.

Photo: shutterstock



Model and reality: data from weather stations over the past 30 years was used to determine local temperature trends for a period of 100 years. In some cases, these deviate considerably from the background field, which was obtained by interpolating temperature data using a weather model to create a comprehensive temperature map.

Graphic: Philipp Mueller, Kantz working group (MPIPKS), data from the German National Meteorological Service (DWD), Climate Data Center

case, climate change is clearly visible and even takes on a sinister quality. However, if he uses the last 100 years as a starting point, the picture becomes blurred. The trend has been watered down because the temperatures were fluctuating strongly at the beginning. In other words, the climate change is obscured by the strong fluctuations.

STATISTICAL PROOF OF CLIMATE CHANGE

Even when the results of all stations are considered, the picture is still confusing: all stations show a positive trend. Although the values are not large enough to talk about statistical significance, the degree of concordance is puzzling. All of the values are on the positive side – surely that cannot be by chance. Here, Kantz speaks of an intrinsic contradiction, although this too can be explained without climate change: the weather stations in Germany are not independent of one another, as the locations all experience largely the same weather conditions. Rather than simply stopping when it reaches Hamburg, an area of low pressure also tends to leave its mark in Munich.

It was only when Kantz plugged foreign stations, which are characterized by different weather conditions, into his calculations that he obtained a different picture. The strong fluctuations in the individual regions canceled each other out – and a significant trend towards higher temperatures appeared. There was statistical proof of climate change after all. These different results can be confusing. However, Kantz stresses that he is in no way seeking to spread doubt about climate change. Rather, his analyses demonstrate how statistics can protect us against false conclusions, especially when it comes to regional events.

Holger Kantz is puzzled by one particularly strange realization: “Our climatic system has a kind of memory,” he says. This sounds more like esotericism than serious science, and yet it speaks to a problem that preoccupies the physicist and his colleagues. Kantz returns to the example with the dice, where there is always a one-sixth probability of rolling a six. In other words, the dice does not have a memory. That is not the case with weather. Here, the past seems to have an influence on the future. If it rains today, it will rain again tomorrow – or, at least, there is a greater likelihood of rain than sunshine. Meteorologists refer to this phenomenon as persistence. Anyone who has absolutely no idea about the weather, they say, should adhere to this rule of thumb.

EXTREME EVENTS ALWAYS OCCUR IN CLUSTERS

But what is the origin of this consistency? It goes without saying that wind and weather react with a certain inertia. A low-pressure area therefore determines the weather conditions for several days, and El Niño dominates half the world’s weather for an entire year. However, Kantz says that the phenomenon persists even if this inertia is excluded from the calculations. He is referring to the concept of long-range correlations.

The capacity for memory becomes apparent not only in short-term trends over the period of a few days, but also in long-term trends over months and years. Moreover, it influences extreme weather events such as storms and floods: these always occur in clusters, separated by long pauses. Kantz suspects that this is due to the enormous complexity of the atmosphere. Here, there is an interplay between phenomena that are – temporally and spatially – several orders of magnitude apart. There are momentary phenomena such as a flash of lightning and long-term events such as the monsoon. The interacting phenomena also differ hugely in size, ranging from a tiny air molecule to a huge thundercloud and the mighty jet stream – and everything is interrelated.

To gain a better understanding of such systems, Kantz works with simplified computer models that have all the relevant properties of this complex reality but that are easier to manipulate. He hopes to clarify why, for example, large structures react sluggishly but small ones react extremely quickly. He also hopes to answer the question of how long a measurement series must be to include all possible states, which would enable him to gain a better understanding of the Elbe's flooding statistics. Perhaps he will also find a cause for the strange concept of "weather memory". He already has his suspicions: the climate may be affected by very long-term phenomena that we aren't even aware of yet. These would give the impression of a memory that does not actually exist. Kantz: "It may be that our measurement series are simply too short." ◂

SUMMARY

- **Extreme weather events – such as storms, droughts and rainfall that leads to flooding – could become not only more frequent but also more intense as a result of climate change.**
- **Holger Kantz and his team develop statistical methods that can be used to analyze time series with a view to determining whether the frequency and intensity of extreme events are changing.**
- **This cannot be proven for the flooding of the River Elbe – despite two 100-year floods occurring in the space of eleven years.**
- **The statistical methods developed by the Max Planck researchers can be used to predict very strong gusts of wind at short notice, so that the rotor blades of wind turbines can be moved to a safe position in good time.**

GLOSSARY

Extreme weather: Weather phenomena that deviate significantly from a region's typical weather situations. These include storms, heavy rain or droughts and can cause considerable damage.

Significance: A term used in statistics to indicate whether extreme values in a measurement series are due to random variation or a specific cause. This can be determined more effectively the larger the quantity of data and the less the measured data is scattered around the mean.

Time series: A series of measured data over a defined period of time, in which the chronological order of the values carries important information.