How Close is the **Point of No Return?**

Will our climate suddenly tip if we continue with business as usual? If so, how soon could it come? How fast would it happen? And what would the consequences be? Niklas Boers, Professor of Earth System Modeling at TUM, is working with his team to find answers, applying mathematical methods to describe how the Earth's climate works. The researchers use past climate data to test their models and try to produce forecasts. For his part, TUM mathematician Prof. Christian Kuehn makes sure that the entire project is on a sound theoretical footing.

Gesamter Artikel (PDF, DE): www.tum.de/faszination-forschung

Wann gibt es keinen Weg mehr zurück?

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Auf der Suche nach Kipppunkten des Klimas: Im Rahmen des europäischen Programms TiPES beschreiben Niklas Boers, Professor für Erdsystemmodellierung an der TUM, und sein Team mit mathematischen Methoden, wie das Klima unserer Erde funktioniert. Sie testen ihre Modelle an Daten aus der Vergangenheit und versuchen, damit Prognosen zu erstellen. Dabei legen sie besonderes Gewicht auf Kipppunkte, die das Klimasystem abrupt verändern. Der TUM Mathematiker Prof. Christian Kuehn sorgt dafür, dass das Ganze auch theoretisch auf verlässlichen Beinen steht.

Das Klimasystem unserer Erde ist nicht das einzig mögliche stabile, sondern es kann unterschiedliche Varianten geben, zum Beispiel warme und kalte Zustände. Dazwischen gibt es Kipppunkte, an denen das Klima relativ schnell von einem in den anderen Zustand wechseln kann. Paläontologen fanden darauf Hinweise, zeigen doch geologische Befunde, dass sich früher warme Phasen und Eiszeiten mehrfach abwechselten.

Mathematisch gesprochen stellen Kipppunkte (englisch: Tipping Points) kritische Schwellenwerte dar, deren Überschreiten den Zustand oder die Entwicklung eines Systems abrupt und nachhaltig verändert. □

Picture credit: Magdalena Jooss

Link

www.asg.ed.tum.de/esm

www.tipes.dk/

www.math.cit.tum.de/math/personen/professuren/kuehn-christian/

If scientists are sometimes accused of sitting in ivory towers without any real connection to the real world, Niklas Boers is the perfect counterargument. He combines mathematics and theoretical physics with issues that could hardly be more pertinent at present: together with his team, Boers is investigating how the Earth's climate system will develop in the future.
Boers reached a point at which he no longer enjoyed working with pure theory, so looked for a practically relevant field for his doctoral thesis. "That's how I came across climate modeling," he recalls. Today, the 39-year-old mathematician and theoretical physicist is among the leading researchers in his field and has set his sights on an utterly fascinating topic with implications for the future of all humanity: tipping points in the climate system. His achievements to date include setting up the large-scale TiPES project in which 18 universities and research laboratories from ten European countries collaborate. Its successor project, ClimTip – which Boers will coordinate from TUM – started on March 1, 2024.

Graphics: ediundsepp (source: TUM)

The tipping of the rainforest into a savanna-like state is an iterative process associated with positive feedback. Deforestation and forest degradation reduce the moisture content in the system, increasing the probability of fires. Fires in turn thin out the undergrowth vegetation and the soil becomes drier, which favors the formation of new fires, clearing the vegetation further, and so on.

The rainforest is under threat

"The idea for TiPES came about in 2015 during my time as a postdoc with Michael Ghil at the École Normale Supérieure in Paris," says Boers. Ghil, an Israeli-American mathematician and physicist, is considered one of the founding fathers of theoretical climate dynamics. Even as early as the late 1970s, he understood how to develop mathematical models for air and water flows to describe key climate phenomena. He continued to refine these models over the years, applying state-of-the-art mathematical instruments. In his calculations, Ghil recognized that our Earth's climate system is not the only possible stable state: instead, there are different variants, such as warm and cold states. Between these states, there are tipping points at which the climate can shift relatively swiftly from one state to another. Paleontologists have long suspected as much, and geological findings indicate that the Earth has alternated between warm phases and ice ages many times. In mathematical terms, tipping points are critical thresholds; exceeding these thresholds triggers abrupt, lasting transformations in the state or development of a system.
One obvious example that is particularly relevant at present is the deforestation of the Amazon rainforest. Vast amounts of water circulate in this ecosystem and are exchanged between the atmosphere and rainforest, which leads to extensive rainfall. However, as people continue to clear the forest, the amount of water transported in the air decreases. Eventually, the situation will reach a tipping point at which the ecosystem as a whole dries out and irreversibly collapses – with grave consequences not only for its flora and fauna but also for the regional and global climate. This tipping process could happen within a few decades.
Researching these tipping points and, if possible, producing forecasts is the stated aim of two EU Horizon projects, TiPES and ClimTip. In an arduous process, Boers secured the cooperation of Europe's leading researchers in the field. "It's like a huge mosaic. Everyone knows what they can do best, so we exchange ideas intensively and bring everything together at the end," says Boers, who is Associate Coordinator of TiPES. The project received €8.5 million of funding and concluded on February 29, 2024, after a four-and-a-half year term. ClimTip is set to be even more extensive, with Niklas Boers coordinating the project. ▷

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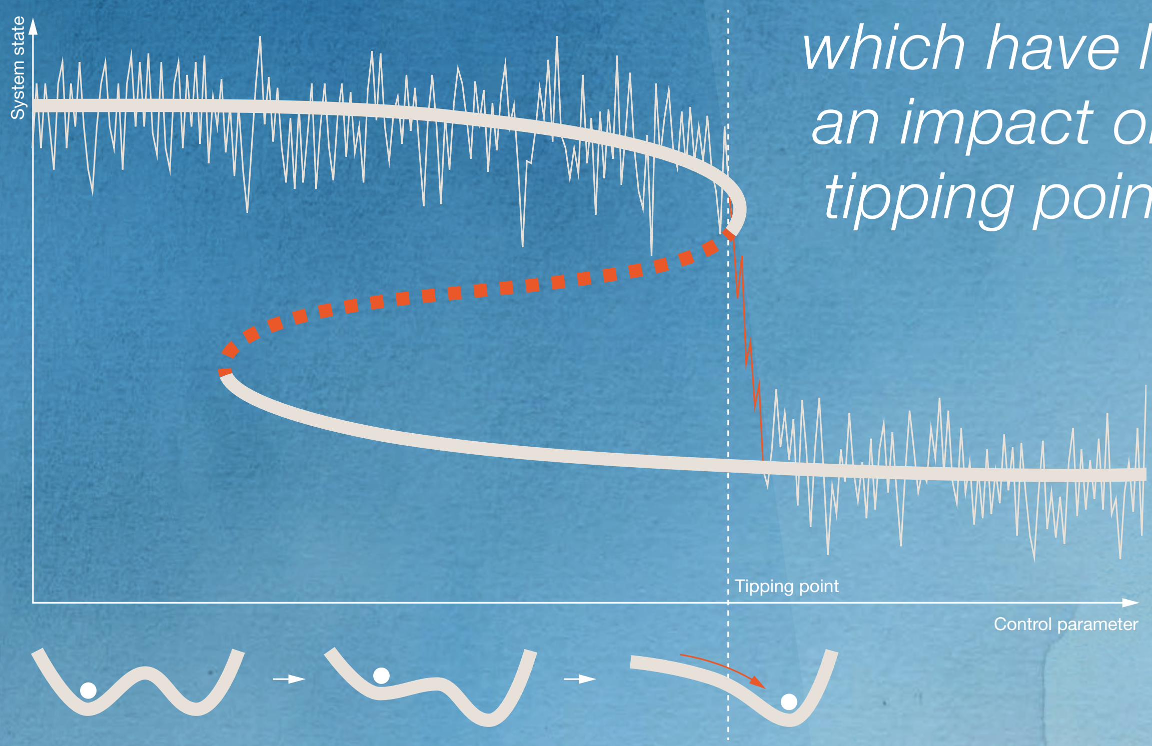
Christian Kuehn



A very simple example of a tipping point is how a ball behaves in a potential well. So long as the walls of this well remain relatively steep, after being deflected the ball will always roll back to its starting point. If a system parameter changes in such a way that these walls flatten, the probability increases that the ball will roll out of this potential well and fall into a neighboring well, from which it cannot return. Thus, it would have passed a tipping point. Even if the original well were restored by resetting the system parameter, the ball would remain in its new state. Mathematically, such behavior is called bifurcation, and the value of the control parameter at which the system jumps to another state, known as the bifurcation or tipping point. If the control parameter resumes its original values, the system remains in its new state. Climate modelers are now trying to find out whether such flattenings can already be observed in the climate measurements before a possible tipping point .

What data matters – and what doesn't?

Climate models are extremely complex constructs that push the limits of available computer power. Consequently, researchers rely on the most powerful supercomputers on the planet for their model calculations, some of which require months of computation time. The results can show how climatic changes, which often accumulate over many years, can suddenly escalate and reach a tipping point – from which there may be no return. In this context, physicists and mathematicians talk about feedback and non-linear dynamics, while the resulting "bifurcations" are a mathematical concept to describe abrupt transitions in the Earth system.

Probability calculus meets non-linear dynamics

Christian Kuehn uses theoretical methods to examine the reliability of climate models. "In principle, there are two different ways to look at the world in mathematical terms."

On the one hand, scientists can trace physical processes based on their deterministic laws. However, the resulting values can entail certain uncertainties due to perturbations caused by external influences (noise). These perturbations can amplify each other or cancel each other out. It is therefore important to consider the potential uncertainties involved in every result.

The alternative is to consider all processes as probabilities, like a die that randomly shows numbers. The interaction of these probabilities can be used to derive certain laws, and any result must be accompanied by the probability of its occurrence. So, while certain tipping points might be highly improbable, if they were to occur, the consequences would be catastrophic (high impact, low probability).

"The reality lies somewhere between the two," says Prof. Kuehn, who is therefore developing a combination of non-linear dynamics and probability theory to make his models more robust.

Graphics: ediundsepp (source: TUM)

Being able to simulate such complex issues on computers at all requires many simplifications. At this point, a number of fundamental questions arise: "Can we even do that? Does that work? What impact will it have?" So, in order to ensure that such computer models are reliable from a mathematical perspective, and describe reality as accurately as possible rather than producing artificial effects, Niklas Boers collaborates with Christian Kuehn. The 41-year-old mathematician worked at various prestigious mathematical research institutes, including the University of Cambridge and Cornell University, before coming to TUM in 2016. Here, he holds the Professorship for Multiscale and Stochastic Dynamics. Kuehn applies his insights in numerous practical areas, such as neuroscience, epidemiology, opinion formation, fluid mechanics and medicine. In 2011 he first engaged with the topic of climate modeling and found the topic so fascinating that he examined it further.

Boers and Kuehn met at a conference in 2016 and have worked together closely since 2017. Kuehn and his team work on a purely theoretical level to develop rules and testing mechanisms that ensure such models do not deliver unreasonable results. "We are researching which parameters should be given particular attention in simulations and which have less of an impact on such tipping points," says Kuehn. "In sum, we are trying to create a sort of toolbox for climate modelers, so that they can choose the right techniques depending on their requirements and objectives." Ultimately, there is a whole array of different approaches – some of which are more suitable for tackling certain issues, while others are less so. ▷

Climate systems at risk of tipping

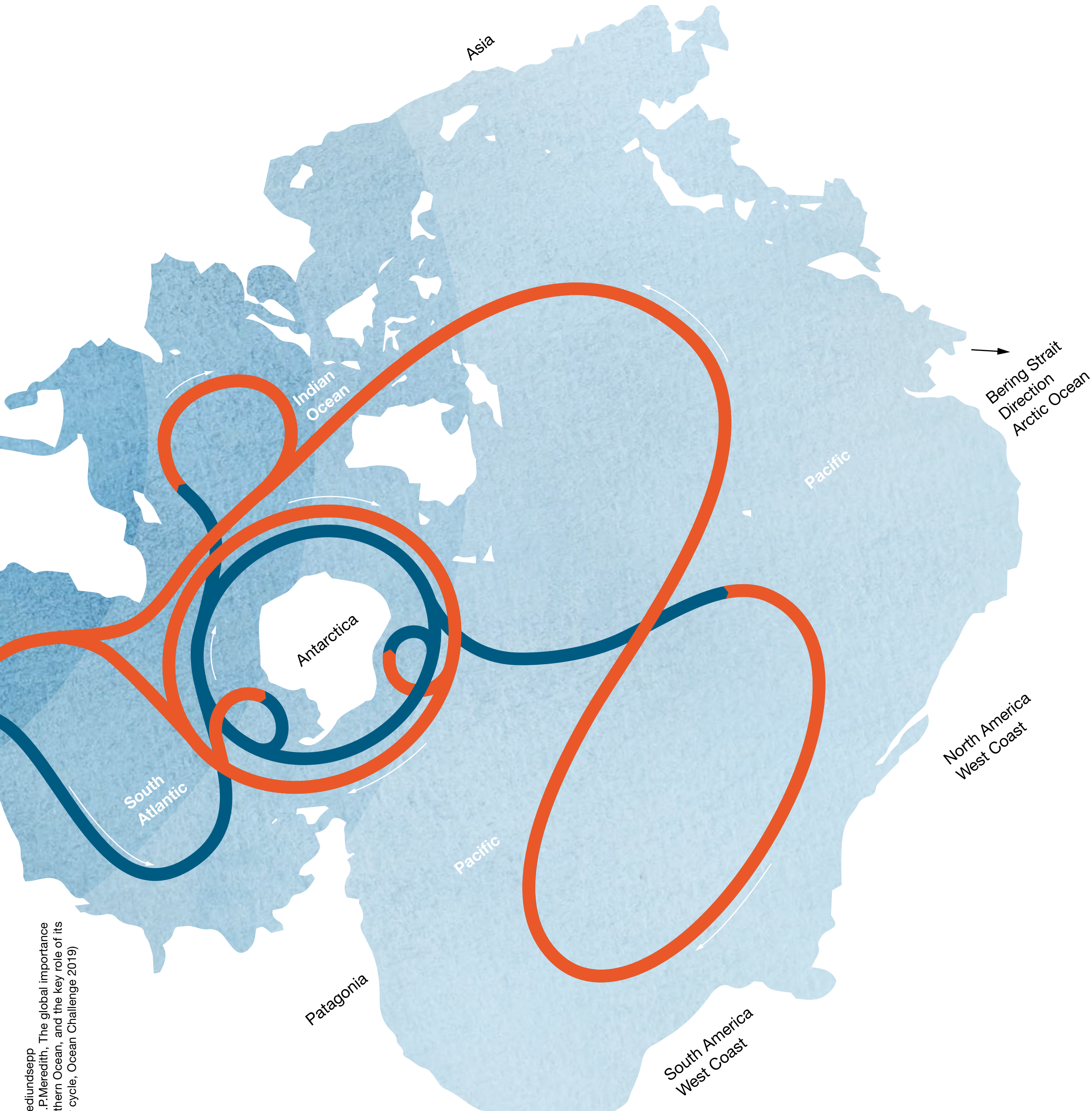
TiPES and ClimTip are researching a whole host of tipping points in the Earth's climate system. These tipping points are influenced by human actions and impacts, including global warming. Here are four examples:

1 If the uppermost, white layers of the **Greenland ice sheet** melt, darker ice will rise to the surface. This darker ice will absorb more and more solar heat; at the same time, the ice sheet will continue to shrink, with warmer temperatures at lower altitudes. Both factors will amplify the melting process; the effects will continue to accumulate until they can no longer be reversed. "In one study, I was able to show that part of the Greenland ice sheet has already become less stable over the last century," says Niklas Boers.

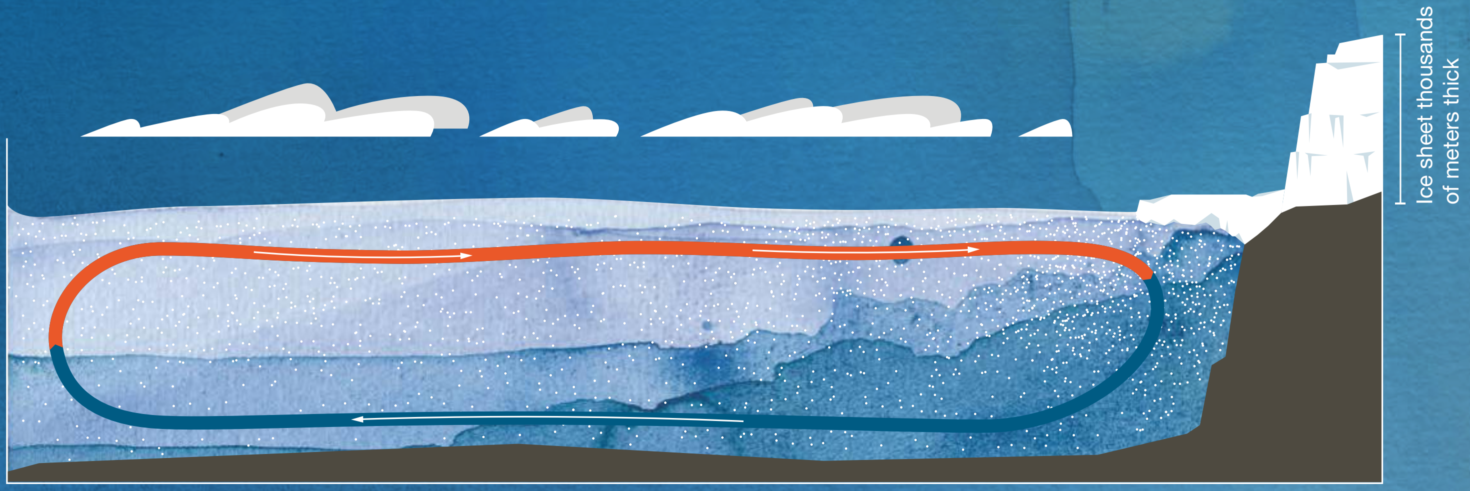
2 The **Atlantic Meridional Overturning Circulation** (AMOC), a large system of ocean currents in the Atlantic Ocean, circulates surface water from south to north, driven by differences in density. A proportion of the water is constantly evaporating as it circulates, so the water's salt content increases as it moves northwards. The warm, salty water eventually reaches the North Atlantic, where it cools down. This very cold, salty water is so heavy that it sinks deeper into the ocean. This process is the motor that drives oceanic circulation. The more salt it transports northwards, the stronger the motor becomes. Unfortunately, it is also the case that the more freshwater enters the North Atlantic – such as due to ice melting in Greenland – the weaker this circulation becomes. If the AMOC were to reach a tipping point, it would have far-reaching consequences for the global climate. In tangible terms, these consequences would include a significant reduction in average temperatures, especially in northern Europe.

3 Tipping of AMOC would also lead to fundamental changes to **tropical monsoon systems**. These could tip over quite rapidly following the collapse of the AMOC, leaving humanity very little time to adapt.

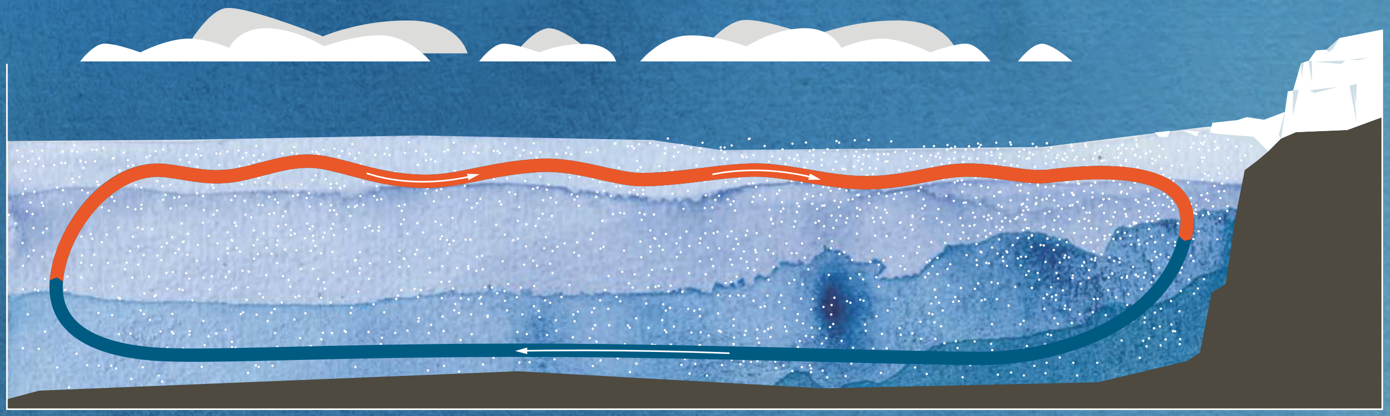
4 **Rainforest** clearing: Water circulates in this ecosystem, including in the form of extensive rainfall. As people continue to clear the rainforest, the water transported in the air decreases. Eventually, the situation will reach a tipping point at which the ecosystem dries out within a few years and therefore collapses completely – with grave consequences not only for its flora and fauna but also for the global climate.



Graphics: ediundsepp
(source: M.P.Meredith, The global importance of the Southern Ocean, and the key role of its freshwater cycle, Ocean Challenge 2019)



Warm, salty water travels north and cools down near the ice shelves. The cold and salty (and thus heavy) water sinks down and travels south.



The melting ice sheet dilutes the salty surface water, it becomes less heavy and the circulation weakens.

Eventually, the thermohaline ocean circulation breaks down. The northern hemisphere cools off and gets drier.

"Studies have shown that current circulation levels are the weakest for at least 1,500 years. So, we wanted to find out whether this is a purely linear weakening or a destabilization towards a critical point."

Niklas Boers

The Greenland ice sheet is melting

Heat flows in the North Atlantic are one issue to which Niklas Boers and Christian Kuehn have devoted particular attention. These flows are the combined result of a number of factors: the winds, which drive vast masses of water; the temperature, because water masses moving north cool down and become heavier, and finally water salinity, because more salt makes the water even heavier. Once they arrive in the North Atlantic, these heavy water masses sink to deeper levels of the ocean. If we consider the interaction of these sometimes contradictory effects, it becomes clear that there is an enormous system of ocean currents in the Atlantic, which is known as the Atlantic Meridional Overturning Circulation (AMOC). It is primarily responsible for the moderate temperatures on the European continent.

If, however, the Greenland ice sheet continues to melt at accelerating rates – including due to global warming – more and more lightweight freshwater will enter the flow at its northern end, which will slow down the system as a whole. Boers and his team set about examining how long this can continue before it reaches a tipping point. "Studies have shown that current circulation levels are the weakest for at least 1,500 years," says Boers. "So, we wanted to find out whether this is a purely linear weakening or a destabilization towards a critical point. At the tipping point, the circulation would abruptly become significantly weaker. We found out that we are actually moving towards a potential tipping point." ▷

Graphics: ediundsepp (source: TUM)

If this tipping point is reached, it could have far-reaching implications for the global climate. In tangible terms, it would lead to a significant cooling and aridification of the northern hemisphere along with changes in the tropical monsoon systems and regional sea level rise. However, when exactly this point will come remains uncertain, with scientific opinion divided on the issue. Some think it could happen in the next few years; Niklas Boers, on the other hand, believes that the AMOC will remain stable for decades to come.

His priority is integrating these and other insights into current discussions surrounding the climate crisis. "I sometimes receive messages from people who are genuinely distressed because they believe we're facing a domino effect of tipping points and are racing inexorably into a climate catastrophe," he says. "I try to calm them down and explain to them that we definitely still have a chance to avoid the most dangerous consequences of anthropogenic climate changes." On a broader scale, he strives to share his insights with people as part of the TUM Sustainable Futures Strategy 2030.

At the same time, he is looking forward to tackling the scientific challenges ahead. "We have to get better, for example, at calculating how resilient a real-life system is, the extent to which it can withstand disruptions. This is another question we're researching and for which we hope to receive new mathematical insights from Christian Kuehn." ■

Brigitte Röthlein

Picture credit: Magdalena Jooss

Prof. Niklas Boers

Born in northern Germany in 1983, Boers moved to Munich to study physics and mathematics – and due to its proximity to the mountains. He earned his doctorate in Berlin and completed research stays at the Potsdam Institute for Climate Impact Research (PIK), the École Normale Supérieure in Paris and Imperial College London. In 2021, Boers was appointed to a professorship at TUM, and was particularly pleased to have the Alps close by again. He is very politically engaged, especially on climate-related issues. He is driven by a desire to leave behind a livable Earth for the next generation.

More about sustainability at TUM:
www.tum.de/en/about-tum/goals-and-values/sustainability