An iceberg that calved from Jakobshavn Glacier is currently drifting in western Greenland's Ilulissat Icefjord. No other Greenland glacier lost as much ice as it did between 2003 and 2016, chiefly due to the warm fjord water that gnawed away at its ice tongue for nearly two decades.

ON THE SCALE, PLEASE!

TEXT: SINA LÖSCHKE

The Greenland Ice Sheet is more than four times the size of Germany, up to 3,100 metres thick and stores enough water to raise the sea level by seven metres. Accordingly, the more ice that the colossus loses, the more the risk of rising waters in coastal communities increases. But how do you measure the weight of an entire ice sheet? The answer: with a spaceborne scale.

"Three, two, one and ... liftoff!" Clouds of dust were kicked up, and a blaze of fire filled the sky when, on 22 May 2018, a SpaceX Falcon 9 rocket was launched from Vandenberg Air Force Base in California (USA). On board: the second-generation version of the 'Gravity Recovery and Climate Experiment' (GRACE) satellite system. And, since this was the second GRACE mission, the project managers from NASA and Germany's GeoForschungs-Zentrum (GFZ) added the designator 'FO' (for Follow-On) to its name.

Despite this somewhat unwieldy title, hundreds of climate researchers have pinned their hopes on the two GRACE-FO satellites. Why? Because the duo can do something that terrestrial measuring systems can't: measure the gravity field of the entire planet caused by its mass in the course of a month. In other words, the satellites continuously document mass changes on the Earth, and especially the redistribution of water between the oceans, the continents and the ice sheets. Consequently, this 'spaceborne scale' will provide answers to two of the most pressing questions in climate research: how much ice are the Greenland and the Antarctic Ice Sheet losing due to climate change, and in which regions of the world is the sea level rising as a result?

One of the researchers who followed the launch live on site was Dr Ingo Sasgen from the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI). The 43-year-old has been documenting the growth and shrinking of the Greenland Ice Sheet since the first GRACE mission (2002-2017). Yet he still can't find the right words to describe the sheer magnitude of the Ice Sheet; comparisons will have to do.

"The ice sheet and its adjacent glaciers would be large enough to swallow not only Germany, but France, Spain and Italy, all in one go," says Sasgen. On the sheet's central plain, the peak of the Zugspitze, Germany's highest mountain, would still be covered by 300 metres of ice. And if all of Greenland's ice melted at once, the global sea level would rise by more than seven metres, flooding coastal regions around the world and destroying the homes of countless millions of people – including many in Europe.

Greenland's ice is melting on the surface

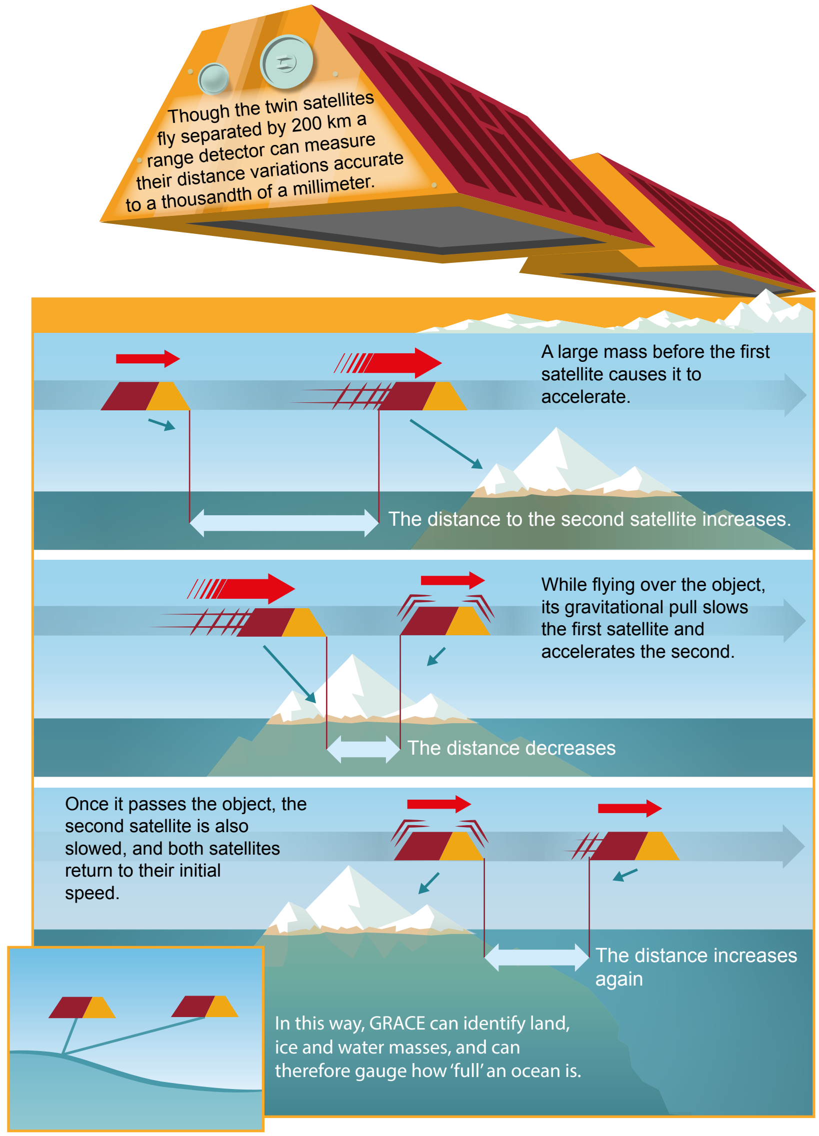
A glance at the GRACE statistics shows how urgent the problem of melting ice on Greenland already is: since the start of the first mission in 2002, the ice sheet and its glaciers have lost an average of 286 billion tonnes of ice per year. "This loss of mass is chiefly due to the fact that the air over Greenland is

When an ice flow runs down a steep drop, it often creates cracks – like the one we see here, in the 79 North Glacier, northeast Greenland.

On 22 May 2018, a SpaceX Falcon 9 rocket was launched from Vandenberg Air Force Base in California, USA, successfully placing the GRACE-FO satellite system in orbit 490 kilometres above the Earth's surface.

warming, causing the intensity and duration of the melting season to increase," says Ingo Sasgen. Today, Greenland is losing nearly twice as much ice due to melting processes on the surface than in the period from 1960 to 1990. Back then, the gains in and losses of ice nearly balanced one another out, but the loss of mass due to calving icebergs has now increased by roughly 25%. In fact, Greenland is now the world's largest source of meltwater: the total annual global sea-level rise is ca. 3.3 millimetres, of which the loss of ice on Greenland is currently contributing ca. 0.8 millimetres.

GRACE detected extremely high melting rates in the summer of 2012, when un-

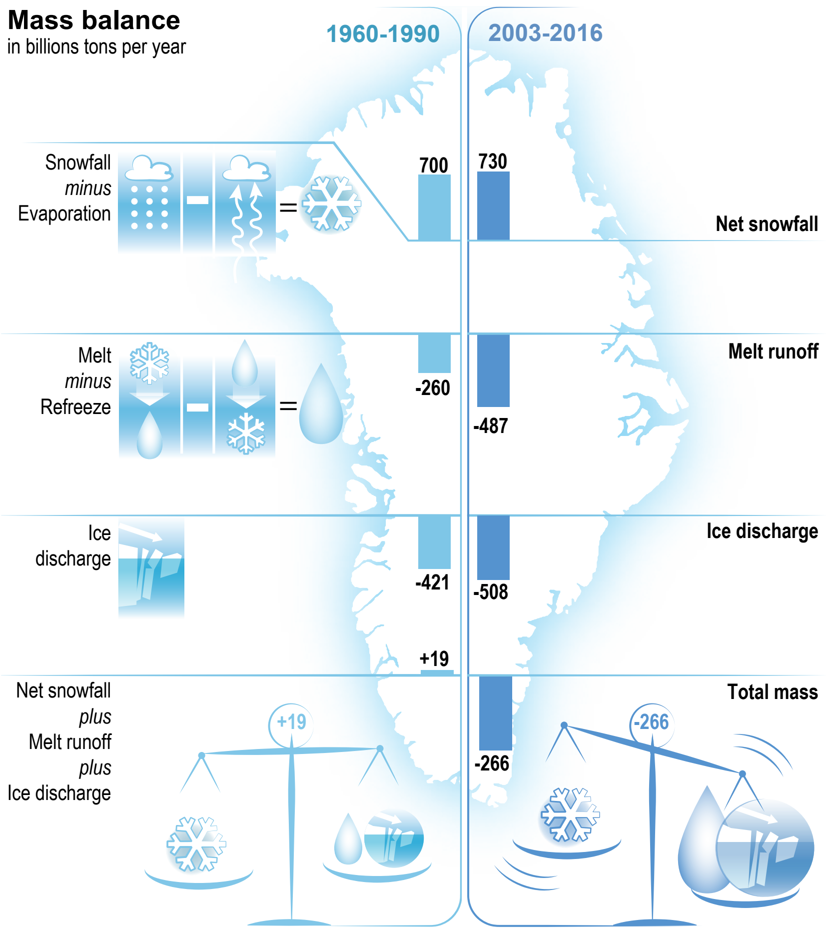


usually warm air and a sustained period characterised by cloudless skies produced melting on no less than 97 percent of the Greenland Ice Sheet's surface area. In the month of July 2012 alone, the ice sheet lost between 400 and 500 billion tonnes of ice, which led to a global sea-level rise of more than one millimetre. "We would never have been able to quantify these changes without GRACE: the 18 snow and ice monitoring stations on Greenland simply can't cover the entire ice sheet. GRACE is the only instrument that allows us to make such accurate long-term observations and monthly comparisons for the ice sheet as a whole," says Ingo Sasgen.

Much to the researchers' surprise, the summer of 2012 was followed by a cold year in which the total amount of new snow nearly compensated for the loss of ice from melting and calving. "The trend since 1990 is clear – Greenland is warming, and losing more and more ice. Yet the GRACE data also shows that the ice sheet's mass balance can vary considerably. From extreme melting to years with plenty of snowfall and little melting; anything's possible," the researcher explains.

The best of both worlds

In order to determine in which regions the Greenland Ice Sheet is shrinking most rapidly, Ingo Sasgen will combine the GRACE gravity-field data with radar data from the ESA satellite CryoSat-2. It measures changes in the surface elevation of the Greenland Ice Sheet at a resolution of typically five kilometres and can, unlike GRACE (which has a resolution of only 400 kilometres), portray individual glacier systems. "We basically take the best aspects of both datasets and 'marry' them, so that we can identify regional differences," says Sasgen. The goal of this REKLIM project is to create a map of the Greenland Ice Sheet that shows in high resolution how the ice masses are changing, and how the ice-loss zones have expanded over time. This optimised dataset will also help to refine climate and ice sheet models. Before



Whether an ice sheet grows or shrinks depends on how much snow falls in winter, how much of that snow melts in the summer, and how much ice is lost due to calving events. The mass balance of the Greenland Ice Sheet for the past 16 years is extremely negative – especially because the melting on its surface has intensified.

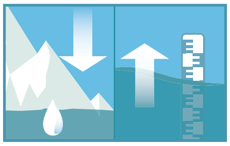
GRACE, researchers had to rely on the handful of scattered readings provided by Greenland's snow and ice measuring stations to calibrate their climate models. Yet there was no guarantee that the models also correctly calculated the mass balance. Today they can easily compare their models' findings with the GRACE data to check their quality. As Sasgen underscores, "It's extremely important that we know exactly how much ice Greenland is losing. We won't be able to precisely forecast the future of the ice sheet and the sea level until we can accurately depict these loss rates in our models."

A question of attraction

Using GRACE to determine the increase in water mass in the ocean and the related sea-level rise, is considerably more difficult than measuring the weight of the ice sheet, for two main reasons. First of all, Greenland's meltwater is spread across the entire ocean, which has an area 200 times the size of the ice sheet. Consequently, the mass signal is so small that it's barely detectable for GRACE. Secondly, the extent of water-level rise on a coastline is determined by three factors: 1) the amount of additional water; 2) expansion of the water due to warming, and 3) the degree to which the land rises or sinks. According to Ingo Sasgen, "GRACE measures mass changes in the ocean to tell us where the ice sheet's meltwater is flowing to, and how much water is accumulating on the coasts. If we then combine that data with satellite-based measurements of changes in the height of the ocean, and with the temperature data from autonomous, deep-sea measuring systems, it produces a comprehensive image of global sea-level rise. However, extending these data from the open ocean towards the coast remains a challenging task, we would like to tackle in REKLIM in

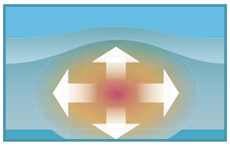
A meltwater stream snakes its way across the Greenland Ice Sheet. To date, there has only been sufficient surface melting for pond and stream formation on the fringes of Greenland; as global warming progresses, it will likely also spread to the centre.

THREE TYPES OF SEA-LEVEL RISE



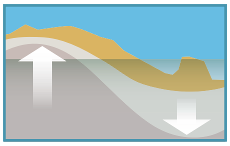
MELTWATER INFLOW

When glaciers and ice sheets melt, the meltwater flows from the land out to sea, adding tremendous quantities of additional water. Ice loss in Greenland and the Antarctic now accounts for one third of global sea-level rise; another third is contributed by dwindling alpine glaciers.



THERMAL EXPANSION

When water grows warmer, it expands, and consequently takes up more room than before. The same holds true for our oceans. At the moment, thermal expansion there is responsible for a third of global sea-level rise – and that trend will continue. Why? Because climate change is especially warming the oceans.



LAND SINKING

Substantial water-level rise is currently being reported in coastal regions throughout North America and Europe that were located at the margins of large ice sheets during the last glacial period. Back then the ice essentially lifted up these regions; they have been gradually sinking ever since, worsening sea-level rise in some cases.

LOOKING AHEAD

> **I hope to use GRACE to investigate when the ice-mass losses on Greenland and in the Antarctic are nearing a 'point of no return' in terms of melting, no matter how the climate changes afterwards. Identifying these tipping points is extremely important, particularly when it comes to sea-level rise.**
>
> **INGO SASGEN**
> Geophysicist, Alfred Wegener Institute,
> Helmholtz Centre for Polar and Marine Research (AWI)

Meltwater flowing from underneath Russell Glacier. The water predominantly comes from ponds that formed on the glacier's surface, and subsequently drained into cracks in the ice.

future." In a nutshell, the current situation is as follows: when the ice on Greenland melts, the overall sea level initially rises, because there is more water in the ocean. But over time, Earth's gravity redistributes these water masses. In other words, regions with a weaker gravitational field and therefore less attractive force end up with less water; those with a stronger field end up with more. "And since both Greenland and the Antarctic are losing mass, and with it, attractive force, the water is especially collecting in the mid-latitudes," Sasgen says. "So the changes in the polar regions have the greatest effects on those of us here in the mid-latitudes." He's now anxiously waiting for the first science data from GRACE-FO, which the satellites have been gathered in the control center in Oberpfaffenhofen since June 2018. Based on the new findings, Sasgen and a fellow researcher at the AWI plan to develop a statistical method for predicting future changes in Greenland's ice mass balance. A similar approach has worked well for Arctic sea ice. GRACE-FO will provide the required data and – if everything goes as planned – keep a close eye on the gravity fields of the ice sheet and oceans for the next ten years.

IN BRIEF

- **Thanks to the satellite GRACE and its successor GRACE-FO, the movements of water across the Earth, and therefore the expansion and retreat of ice sheets, can be precisely tracked.**
- **The Greenland Ice Sheet and its glaciers are losing an average of 286 billion tonnes of ice per year, and substantially contributing to sea-level rise.**
- **The GRACE data can also help determine where the sea level is rising the most - which is currently in the mid-latitudes.**

26 CENTIMETRES IN 100 YEARS

The water levels along the coast of Lower Saxony are clearly rising, but not at the same rate everywhere. The coastal protection expert Dr Andreas Wurpts explains why the actual amount of sea-level rise is so hard to determine, and the relevance of research for coastal protection.

➨ ***How much has the sea level along Lower Saxony's coast risen to date?***
Andreas Wurpts: It's extremely difficult to answer that question with just one figure, because the development of measured sea levels along the North Sea coast can vary substantially from one monitoring station to another. Here on the Wadden Island Norderney, where the sea level has been measured for over 120 years, the mean high tide is roughly 26 centimetres higher than it was 100 years ago; in contrast, the low tide has only risen 13 centimetres. By way of comparison: on offshore-island Helgoland the level has risen 21 centimetres per century; in the coastal city Wilhelmshaven, 29 centimetres; and on Wadden Island Wangerooge, 31 centimetres – which of course raises the question: where do these differences come from?

➨ ***Do you have an explanation for them?***
There is an on-going collaborative research project, in which we're seeking to use models and statistics to explain the differences, and to determine how large the actual sea-level rise is. For one thing, water levels on the North Sea coast are influenced by the wind. Depending on the weather conditions, the wind either pushes the water into our coasts or away from them. For another, we know that our coastal regions are sinking – and at a scale that can't be ignored. In addition, the tide dynamics have been changed by the estuaries for shipping, which have been made deeper and straightened over the years. The different rates at which the low-tide and high-tide water levels are rising can be explained in part by the fact that, because of the changed water depths, the tidal wave now spreads out differently.

➨ ***How much advance warning do y ou need regarding sea-level rise in order to stock up the levees in time?***
The technique we use to calculate the required levee height in Lower Saxony is based on actual measured values, which we constantly monitor, and assess every 10 years. Important parameters include e.g. the mean high-tide level for the past five years, and the highest storm surge water level recorded to date. If the sea-level rises, the mean high-tide level does, too; as a result, the water-level rise is automatically reflected in the levee-height calculation. In addition, since we now know that the sea-level rise will accelerate, we can add another 50 centimetres per century – twice the rate we're currently observing – to account for the effects. In this way, we arrive at a minimum levee height that should theoretically provide safety for the next 100 years.

➨ ***Do you nevertheless keep up with the latest research findings published on sea-level rise?***
That's one of our core responsibilities at the NLWKN's Coastal Research Station. We gather the scientific data, constantly work to optimise our analytical methods, and prepare all application-relevant findings so that administrators can use them. In addition, we work intensively with other experts in collaborative research projects and maintain close ties e.g. to the North German Climate Office and the researchers at the Helmholtz Centre for Materials and Coastal Research in Geesthacht. These collaborations are very important to us for a variety of reasons: for example, in order to incorporate the latest research findings into administrative actions in a timely and focused manner. And my hope is that, through these joint efforts, researchers also gain a better understanding of administrators' concrete needs. ■

DR ANDREAS WURPTS
heads the Coastal Research Station, part of the Lower Saxony Water Management, Coastal Defence and Nature Conservation Agency (NLWKN), which has facilities in Norden and on Norderney.