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ALFRED-WEGENER-INSTITUT
HELMHOLTZ-ZENTRUM FÜR POLAR-
UND MEERESFORSCHUNG

FACT SHEET

THE ACTUAL KNOWLEDGE OF:

The Greenland Ice

The Greenland Ice Sheet is the largest continuous inland ice mass in the northern hemisphere, with an area of around 1.7 million km² and a thickness of up to 3000 m[1]. Almost all of Greenland is covered by a thick layer of ice, storing around ten per cent of the world's fresh water[2]. If the Greenland ice were to melt completely, this would mean a global sea-level rise of around 7 m[3]. But the ice sheet is not only an enormous freshwater reservoir but also a very detailed climate archive. Ice cores provide important information about the climate of the past[1].

What role does the Greenland ice sheet play in the climate system?

Recently, Greenland's weather made headlines again: on August 14, 2021, rain was reported for the first time over the highest point of the Greenland Ice Sheet. At an altitude of 3,216 m - at 72° 35′ N - the temperature reached just under 0.5 °C that day, about 15 °C above the long-term average for August. Due to the otherwise year-round deep sub-zero temperatures, only precipitation in the form of snow is up to now recorded there[4].

More frequent warm records like this one are driving the melting of the Greenland ice sheet. Lakes of meltwater form on the ice surface, and the ice flows ever faster into the ocean - where it contributes decisively to sea level rise[5]. Meanwhile, the Greenland ice sheet is losing more than 250 billion tons of ice annually[5,6]. The equivalent amount of water could fill Lake Constance more than five times over. Together with the world's glaciers and the Antarctic ice sheet, Greenland's ice melt is causing about half of the current sea-level rise. The other half is due to the physical expansion of water caused by ocean warming[7].

Not only the amount of melting water is an important research aspect, but also its properties. Meltwater is fresh water and thus does not contain any salt components. It is, therefore - at the same temperature - less dense than the salty ocean water. Therefore, the increased input of fresh water changes the conditions in the ocean and could weaken climate-relevant ocean currents such as the Gulf Stream in the future[8]. In addition, the meltwater is enriched with nutrients and nitrogen as it travels to the sea[5]. Glaciers that flow into the sea also ensure good mixing of the water, bringing nutrient-rich water to the surface and positively affecting the fish population there[9].

Overall, Greenland's ice conditions depend on the one hand on the atmosphere, i.e. on weather and climate, and the other hand on conditions in the adjacent ocean. The GROCE research project investigates how these interactions work, what effects they have on the ice sheet, and how they will develop in the future (see infobox).

How fast does the ice move and change?

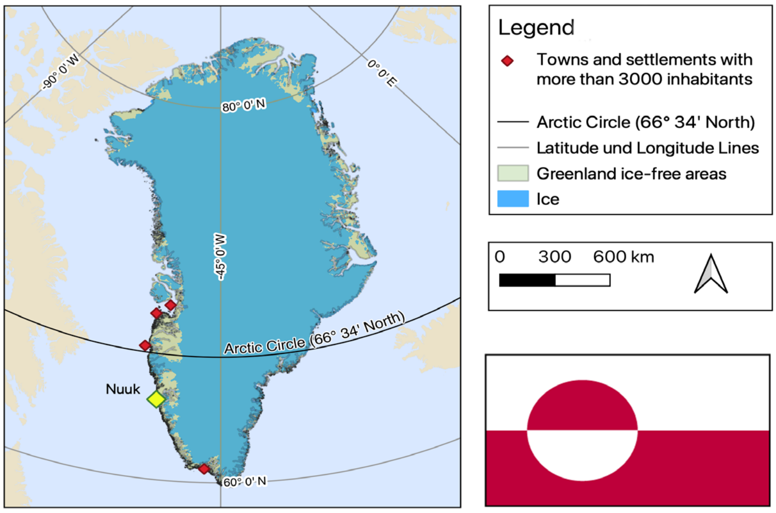
Greenland ice is not a rigid mass of ice but is constantly in motion. From the highest point, the ice slowly flows off to the sides under its own weight[1]. The flow velocities depend, among other things, on the surface slope, the temperature and thickness of the ice, and the nature of the bedrock. In the centre of the ice sheet, where the surface slope is lowest, the flow velocity of the ice sheet is only a few centimetres per year[16]. The ice flows off towards the coast via gigantic ice streams, such as the Northeast Greenland Ice Stream (NEGIS, see figure). At the edge of the ice sheet, the ice streams branch into many smaller outlet glaciers - the thickness of the ice decreases and the flow velocity increases. At the edge of the ice sheet, the glaciers can thus travel up to several kilometres per year[16].

Marine glaciers that flow into the sea are particularly fast. The Jakobshavn Isbræ in western Greenland reached peak speeds of up to 17 km per year after a melting period in the summer of 2012[17,18]. This corresponds to almost 2 m per hour. As the flow velocity of a marine glacier increases, so does the mass of ice that is lost to the ice sheet along the way, thus contributing to sea-level rise.

In addition to outlet glaciers fed by the ice sheet, there are also so-called peripheral glaciers that are not in contact with the ice sheet. Although they make up only a small part of Greenland's ice cover, they are currently contributing comparatively strongly to Greenland's mass change[19]. Ice loss from Greenland's peripheral glaciers is accelerating: between 2015 and 2019 alone, they lost more than 7% more mass to ice flow into the sea compared to the period from 1995 to 2015[20,21].

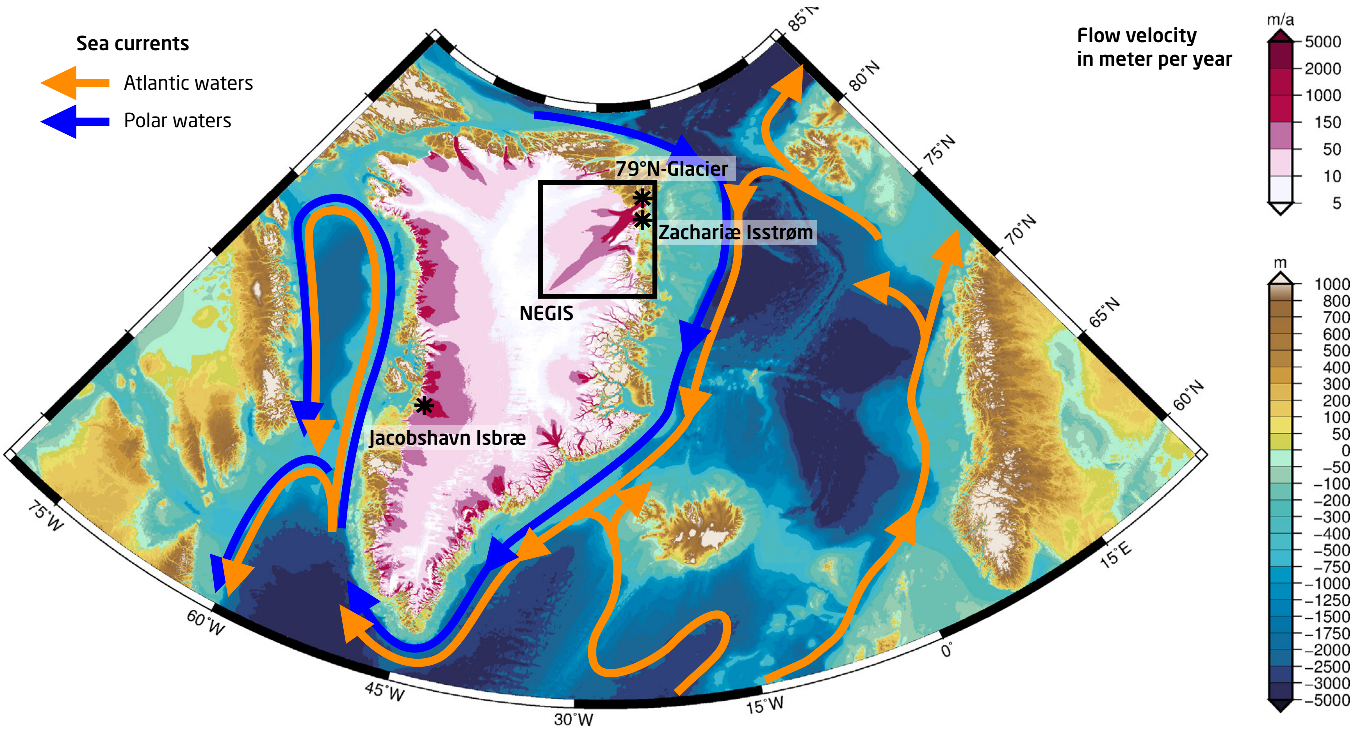
Greenland

Greenland, the largest island in the world, is home to only about 56,000 inhabitants, the majority of whom - about 50,000 people - belong to the indigenous population, the Inuit[10]. The Inuit call their land Kalaallit Nunaat, which translates as „Land of the Greenlanders"[11]. The language of the indigenous Greenlandic population is Kalaallisut. Greenland has been self-governing since 2009 but officially belongs to Denmark, so Danish is the second language[2]. According to legend, the name Greenland was coined by Erik the Red over 1000 years ago. The criminal was exiled and settled on Greenland. To attract as many settlers as possible, he named the island „Greenland"[12] – however, Greenland had already been covered by a thick layer of ice for millions of years at that time.



Map: QGreenland v1.0.1, data source: NSIDC 2021

The total area of Greenland is 2,166,086 km², of which less than 20% is ice-free today. Therefore, Greenland also has the world's lowest population density. Only about 18,000 people live in the capital, Nuuk. Due to the ice cover, there are no roads between the towns; long-distance traffic is by ship and plane instead[2]. Economically, in addition to fishing, raw material mining is also playing an important role as the glaciers continue to melt. Especially the mining of uranium is controversial and widely discussed by the Greenlandic population. On the one hand, there is the prospect of potential jobs and financial benefits; on the other hand, there are environmental and health risks[10].



Greenland ice flow velocities and ocean currents[15]. Marked are the Northeast Greenland Ice Stream with outlet glaciers 79°N-glacier and Zachariæ Isstrøm, and Jakobshavn Isbræ in western Greenland.

With the Greenland ice continuing to melt and flow away, the enormous mass weighing on the subsurface also decreases. This leads to the effect of glacial isostatic compensation, in which the land slowly rises under the decreasing load[22]. Especially along the coasts of Greenland, a strong mass decrease takes place. This mass change of the ice sheet over time can be determined from satellite gravity field mission data. While the entire Greenland ice sheet loses about 250 billion tons of ice per year, the northeast of Greenland, with a mass loss of about four billion tons of ice, so far contributes little to this loss. In comparison, northwest Greenland loses nearly 55 billion tons of ice per year[23].

How does the atmosphere change the ice?

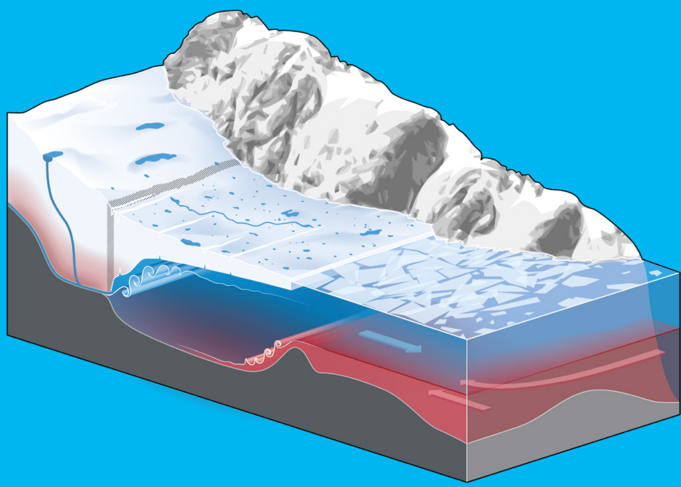
Both precipitation and air temperature significantly determine the surface melting of the ice. The mass of the ice sheet is basically dependent on two mechanisms: accumulation and ablation. Accumulation includes all processes that accumulate mass, which essentially occurs through snowfall. Ablation, on the other hand, includes all processes that remove mass. These include the runoff of meltwater, evaporation and calving, i.e. the breaking off of entire blocks of ice along the glacier front that form icebergs in the sea[24]. Due to weather influences such as precipitation or changes in temperature, the mass and the surface structure of the ice changes, which in turn has an important significance for its thermal balance: the light-coloured snow and ice surfaces reflect a high proportion of the incoming solar radiation. This results in a cooling effect since less radiation is absorbed and thus less thermal energy is absorbed[24]. While fresh snow's reflection (albedo) is still up to 95%, this value decreases after the transformation of snow into glacier ice. This reflects only up to 45% of the incoming radiation[24]. When the ice surface melts, the meltwater collects in so-called supraglacial lakes. Their comparatively dark surfaces, in turn, reduce the albedo of the ice. As a result, more energy is absorbed by the surface, and the melt is driven further[25]. The deeper and thus darker the lakes become as a result of the melt, the more energy they absorb and the faster the melt progresses[24, 26].

However, the meltwater not only changes the albedo of the ice but can also flow down to the underside of the glacier via water channels. It thus influences the stability of the glacier and can also reduce the friction between the flowing ice and the underlying rock on its underside, thus increasing the flow velocity of the ice[27]. This results in an increased loss of ice mass and a corresponding input of fresh water into the ocean[25,28].

In order to better study the supraglacial lakes, they are detected fully automatically in northeastern Greenland, for example, with the help of satellite images. In this way, 880 meltwater lakes on the 79°N glacier were recorded over an area of approximately 82,000 km² from 2016 to 2019. In addition, the average size of the lakes was quantified at around 64,000 m² for this period[29]. This corresponds to an area of almost nine soccer fields. The aim of these detections is to be able to observe the expansion of the lakes over several years. In addition, information about the length of the melting periods and the timing of the maximum expansion of the meltwater lakes in the annual cycle is obtained[25].

In addition to detecting the meltwater lakes, the atmospheric conditions on the 79°N glacier that lead to melting and thus the formation of supraglacial lakes are also being studied. In 2016 and 2019, summer air temperatures were higher than average, and a number of precipitation events were recorded, leading to extensive meltwater lakes up to 1600 m

The national collaborative project GROCE (Greenland Ice Sheet Ocean Interaction) has been funded by the German Federal Ministry of Education and Research since 2017. The project's overall goal is to better understand the Greenland ice sheet and its interactions with the ocean and atmosphere to improve predictions of global sea level rise.



GROCE scheme (Martin Künsting, AWI Graphics)

After the glaciers in northeastern Greenland were considered comparatively stable for a long time, significant changes and thickness decreases have been observed in the far north of Greenland for some time. Therefore, the glaciers Niogshalvfjerdsbræ (79°N glacier) and Zachariæ Isstrøm in this region are the focus of GROCE[13]. 79°N glacier is the largest marine outlet glacier of the Northeast Greenland Ice Stream. It is also made particularly interesting by its floating glacier tongue[14] that extends some 80 km into the ocean.

There are currently eight different themed areas in GROCE: Ice sheet-ocean interaction, Basal meltwater fractions, Peripheral glaciers, Glacial isostasy, mass balance and ice dynamics, Supraglacial lakes, Atmospheric processes, Quantification of melt rates and Impact of meltwater on the ocean. The subprojects are located at eight different German research institutes and universities.

For more information, please visit the GROCE homepage at: www.groce.de.

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GROCE Greenland Ice sheet Ocean Interaction

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Supraglacial meltwater (Photo: Ole Zeising)

above sea level. In contrast, 2018 was quite cold, resulting in no lakes above 800 m elevation this year. Overall, the area of lakes has been increasing since the beginning of the millennium, and they are occurring more inland and at higher elevations[30].

How do the ocean and ice influence each other?

More than 200 glaciers form a direct connection between ice and the ocean on the coasts of Greenland. There, meltwater from the ice sheet enters the ocean on one side, and on the other, the ocean influences the adjacent ice, which often reaches hundreds of metres deep into the water. Rising water temperatures here lead to increased melting of the ice[31]. While the melting of ice on contact with ocean water is a natural phenomenon, observations show that the acceleration of melting is accompanied by a warming of the adjacent water[31]. This process is clearly related to anthropogenic climate change. About 93% of the additional heat in the atmosphere due to man-made climate change is stored in the world's oceans[6]. With the ocean currents, this heat also reaches the coast of Greenland.

Glacial tongues that float on the water offer a particularly large surface for the melting of glacier ice by the ocean. The 79°N glacier has the longest glacier tongue on the coast of Greenland, at 80 km. As this has thinned over the last 20 years, basal melt rates, i.e. melting on the underside of the glacier tongue, are coming into focus as a cause.

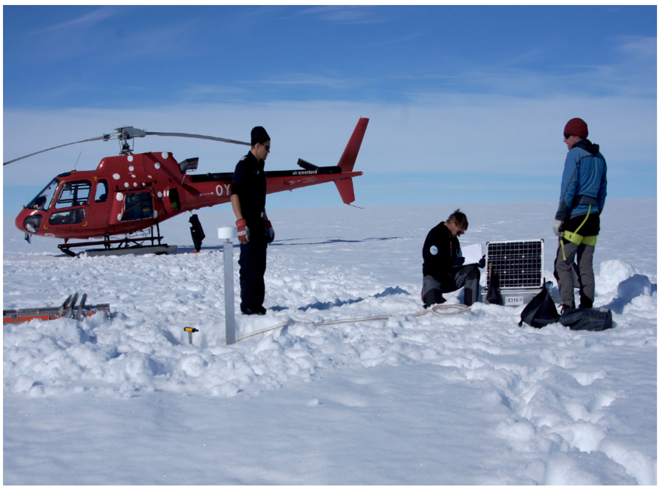
At 79°N Glacier, extremely high basal melt rates of up to 145 metres per year have been measured at points at the beginning of the floating part of the glacier tongue, which also varies seasonally[13]. Over the entire glacier tongue, basal melt rates are estimated to average about 10.4 metres per year[32]. Currently, the floating glacier tongue supports the 79°N glacier. If it were to retreat or break off, this would probably mean a strong increase in velocity of the following ice masses, similar to the Jakobshavn Isbræ in western Greenland mentioned above.

The basal melt rates are controlled by warm ocean water transported by ocean currents under the glacier tongue. Changes in ocean currents hundreds of kilometres away from the glacier can already have an influence on its melt rates[33]. To accurately describe how ocean water controls basal melt rates at 79°N Glacier, both year-round autonomous measurement systems in the ocean and on the glacier tongue are used, as well as high-resolution model simulations[34].

Where does the meltwater flow to?

To determine the role of basal meltwater in relation to ocean circulation, one must first detect the meltwater components in the ocean. Since meltwater can no longer be distinguished from the rest of the water at some distance from its source based on salinity alone, it is identified by measuring chemical signatures (helium and neon isotopes) in water samples. In this way, it can be quantified, and its path followed[35,36].

However, these measurement data come exclusively from the summer months (when a research vessel can be on site) and are not sufficient for a complete picture. Therefore, they are supplemented with satellite observations and ocean models to calculate how Greenland freshwater is distributed in the ocean for different scenarios. This shows that the effects of basal meltwater are detectable near the coast at depths of up to 100 metres. These effects are particularly evident in the ocean west of Greenland, where meltwater leads to warmer, lower salinity water.



Measurements on the ice (Photo: Carl Daniel Niv)

In contrast, the effect of freshwater input is different in the south of Greenland, where it leads to a cooling of the water[37].

The amount of meltwater contributing to sea-level rise and its dispersion and effect in the ocean is important to understand because the large-scale ocean currents in the Atlantic Ocean are very dependent on the density stratification of the water. This means that density differences occur due to changes in temperature and salinity in the water, which drive the circulation of the water[24]. If the density differences along the coast of Greenland increase due to the increased input of meltwater, the climate-relevant Gulf Stream could be weakened as a consequence.

What might the future of Greenland's ice look like?

Recent research reports suggest that the central-western part of the Greenland Ice Sheet may soon reach a tipping point[38]. This would mean that further melting of the ice sheet would set off a negative spiral that would accelerate the melting of the ice. Currently, due to the ice sheet's thickness, most of Greenland's ice surface is at an altitude where it is cold all year round, just like in the mountains. However, the further the ice melts, the further the surface sinks. If the air layers at the ice surface become warmer with lower altitude, this, in turn, leads to an acceleration of the melting[6,38]. In addition to this process, ice-ocean interaction and the feedback effect of decreasing albedo also play a role in the future of Greenland ice[39].

The increasing loss of ice from the Greenland (and Antarctic) ice sheets is a major contributor to the accelerated rise in mean global sea level[40]. In a moderate scenario, which projects a 1.6°C temperature rise by the end of the century relative to 1850-1900, sea level would rise by more than 40 cm by 2100 relative to 1986-2005. In an extreme scenario, projecting a relative temperature rise of 4.3°C by 2100, sea level would even rise by more than 80 cm by the end of the century. While sea level in the first scenario remains below one metre rise until 2300, it would rise by almost four metres in the second scenario compared to 1986-2005[40].

The rate at which the Greenland ice will melt depends heavily on how many degrees Celsius the Earth warms[41,42]. Regardless of how greenhouse gas emissions develop in the future, the Greenland ice sheet will most likely continue to lose mass this century[42]. Therefore, it is important to obtain as comprehensive and detailed a picture as possible of the causes, processes, and effects of ice loss with research projects such as GROCE. Only in this way can forecasts be made for the future and important measures taken to limit the effects of climate change, as stated in the recent IPCC Report:

„Many changes due to past and future greenhouse gas emissions are irreversible over centuries to millennia, particularly changes in the ocean, ice sheets, and global sea level." [43]

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