The Glaciers in Ice Frontiers

The glaciers selected for *Ice Frontiers* are some of the most dynamic marine-terminating outlet glaciers emanating from the Ice Sheet, so they have a huge impact on the overall mass balance. Their scattered geographical location provides a spatial understanding of the various environments that exist along the Ice Sheet. This sheds light on the complexity of the Ice Sheet, given that the factors governing the glaciers are vastly different.

The Petermann Glacier and the Storstrømmen Glacier are the northernmost glaciers in *Ice Frontiers* and are protected by sea ice for most of the year. The Kangerlussuaq Glacier and the Helheim Glacier are located in the eastern and southeastern part of Greenland, which is influenced by the Irminger Current: a warm ocean current fed by the North Atlantic Drift, the northern extension of the Gulf Stream. The final two glaciers, Sermeq Kujalleq and the Upernavik Ice Stream, are located on the west coast up towards the northwestern part of Greenland. What all six glaciers have in common is the fact that their outlet areas are located beneath sea level (Morlighem, Rignot, Mouginot, Seroussi, & Larour, 2014).

Around the turn of the Millennium, in many spots mass loss and acceleration were observed in the Ice Sheet's outlet glaciers. The same was true of many of the glaciers featured in *Ice Frontiers*. Sermeq Kujalleq, the Helheim Glacier and the Kangerlussuaq Glacier, some of the Ice Sheet's largest marine-terminating outlet glaciers, all accelerated at just about the same time, losing mass, both from melting on the surface and from calving at their fronts (Luckman, Murray, de Lange, & Hanna, 2006). The Upernavik Ice Stream was actually the first of the six glaciers to undergo loss of mass, when the front of the glacier retreated. This occurred between 1985 and 1993, and then at a later point again between 2005 and 2010, when the ice stream revealed significant signs of mass loss (Khan et al., 2013; Kjær et al., 2012).

From 2000 to 2012 glacier calving from the Kangerlussuaq Glacier, the Helheim Glacier, the Petermann Glacier and Sermeq Kujalleq accounted for 42% of the total calving loss from the Ice Sheet. This is substantial, when viewed in terms of the hundreds of glaciers that originate from the

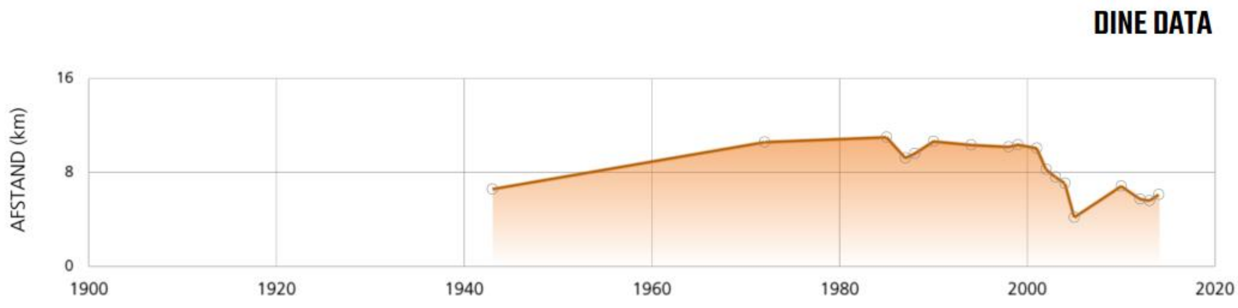
Ice Sheet. If you also look at the areas that experience the most glacier calving, together the northwestern and southeastern parts account for 80% of all calving. (Enderlin et al., 2014).

The Helheim Glacier

The Helheim Glacier is located in South East Greenland and is the southernmost of the glaciers featured in *Ice Frontiers*. Its outlet is in Sermilik Fjord, which is 90 km long. Its width varies from 5 to 12 km, and it is 920 metres deep. The Helheim Glacier is one of the Ice Sheet's largest marine-terminating outlet glaciers. It shares its hinterland with the Kangerlussuaq Glacier (also featured in *Ice Frontiers*) and is located 400 km further north. Their joint loss of mass accounts for more than 50% of the total loss of mass in South East Greenland (Khan et al., 2007).

Since 1933, glacier front movements of up to 8 km have been observed. From 1933 to 1972 the glacier front continued to advance, followed by 20 years of up to 4 km of mass fluctuation. The late 1990s witnessed sudden, major calving, which caused the glacier front to retreat substantially. The speed of the glacier also increased and the front of the glacier became considerably thinner and thus more unstable (Andresen et al., 2011). Between 2001 and 2005 calving increased by 65%, culminating in 2006 with a mass loss of 12 Gt/year (Howat et al., 2011). Subsequently, the mass balance and calving rate returned to a state last seen in 2000. The speed of the glacier was still high, and until 2011 the front of the glacier continued to advance, even though calving was still occurring. Collection of data from satellite measurements has shown that, even though there was an increased loss of mass from the front of the glacier between 2000 and 2010, further into the glacier they measured a distinctive addition of mass due to increased precipitation in the form of snow (Khan, Kjeldsen, et al., 2014).

Studies of the Helheim Glacier in recent decades have shown that calving follows almost synchronously changes in the local summer temperatures and the sea temperatures of the Atlantic Ocean. The calving rate increases when sea temperatures rise, and when the export of polar water is low (Andresen et al., 2011). Elevated summer temperatures can also trigger major calving, while cold periods cause the glacier front to move forward. This shows that the Helheim Glacier is extremely sensitive to fluctuations of temperature, given that the same occurred in the warm period of the 1930s.

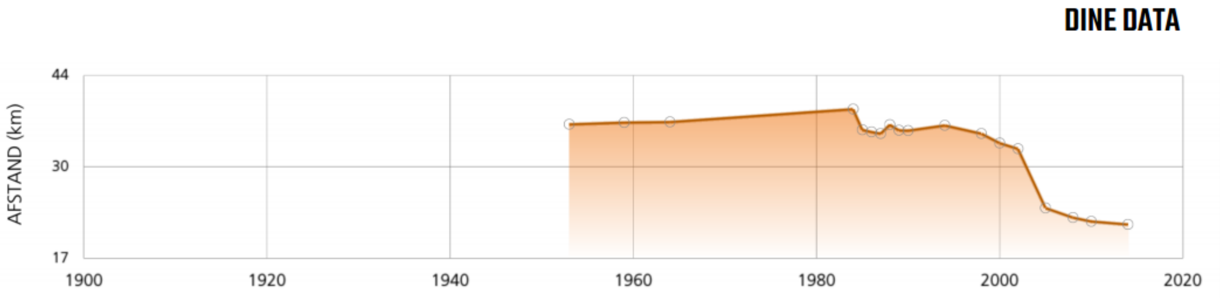


An example of data from a pupil's measurement of the Helheim Glacier in Ice Frontiers.

Sermeq Kujalleq

Sermeq Kujalleq (also known as the Jakobshavn Glacier) is located on the west coast of Greenland. It has its outlet in Disko Bay. It is the fastest glacier in the world with speeds of up to 50 metres a day, and its hinterland accounts for about 7% of the Ice Sheet: approximately 110,000 km^2. The actual glacier and the surrounding area are spectacular, which earned them UNESCO World Heritage site status in June 2004. Every year it discharges between 35 and 50 km^3 of ice: more than 10% of the total production of icebergs from the Ice Sheet. Since 1850 the front of the glacier has moved back about 35 km, but it was not until 1998 that the significant mass loss in the front started (Weidick & Bennike, 2007). Between 2000 and 2010 the glacier lost 321±12 Gt, 2/3 of which occurred before 2005 (Howat et al., 2011). The speed of Sermeq Kujalleq progressed from 5.7 km/year in 1992 to 12.6 km/year in 2003 (Joughin, Abdalati, & Fahnestock, 2004). By 2012 the speed had almost tripled, making it the fastest-flowing glacier in Greenland and Antarctica (Joughin, Smith, Shean, & Floricioiu, 2014).

It is thought that the reasons for this rapid retreat are partly the deep, warm sea currents and partly a weakening of the ice mix. The ice mix is the matrix of the ice, which has broken off and lies like a solid barrier in front of the glacier, and which may have a protective effect for the front of the glacier. Sermeq Kujalleq has reached an approximately 1300-metre trough in the fjord, where the front of the glacier is no longer connected to the mainland, thereby allowing deep, warm sea currents (<4°C) to penetrate deep beneath the ice. This leads to melting of the glacier from underneath, which then thins the front of the glacier and makes it unstable (Joughin et al., 2014). Aerial laser scans have helped scientists to map the bottom of the fjord under the ice. This reveals that the trough is 50-km long, so it will take quite some time before the front of the glacier is once again connected to the mainland and thereby stabilised (Morlighem et al., 2014).



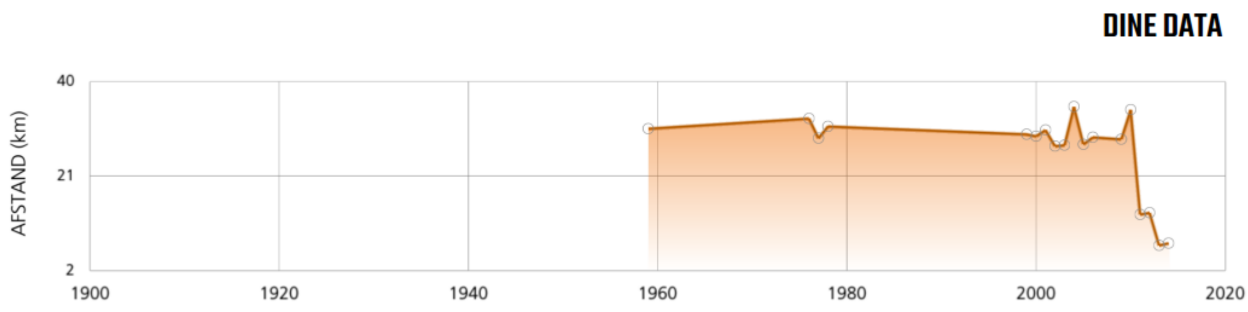
An example of data from a pupil's measurement of Sermeq Kujalleq in Ice Frontiers.

The Petermann Glacier

The Petermann Glacier is one of the most notable glaciers in Northern Greenland with a hinterland that accounts for about 4% of the Ice Sheet. Compared to many of the other glaciers in Greenland, the Petermann Glacier has a positive surface mass balance. In other words, every year the ice accumulates mass in the form of snow, which also leads to a stable calving rate (Khan, Kjær, et al., 2014). The largest mass loss from this glacier is invisible to the naked eye, since it occurs beneath the ice. The Petermann Glacier is located at the end of a valley, which is 750-km long and 800-metres deep and stretches all the way into the innermost Ice Sheet. It is believed that this valley stabilises the Ice Sheet, because it removes water from the bottom, thereby reducing the movements of the ice. The meltwater runs along the underside of the Petermann

Glacier and slowly melts the glacier's tongue from underneath (Griggs, Marshall, & Spada, 2013). In this way, as much as 80% of the mass loss from this glacier is carried away. So, unlike the majority of the other marine-terminating outlet glaciers along the edges of the Ice Sheet, this glacier is not dominated by surface melting and calving. Surface melting on the Petermann Glacier is four times less than on Sermeq Kujalleq (Motyka et al., 2011). The melting of the glacier from below is 20 times greater than its surface and 18 times greater than the loss by calving. That means that the shape of the Petermann Glacier is highly distinctive. But this is not visible on the surface. If you make a cross section, you can see an 80-km-long tongue of ice extending from where the glacier is connected to the mainland. This makes it the longest flowing glacier in the Northern Hemisphere (Rignot & Steffen, 2008).

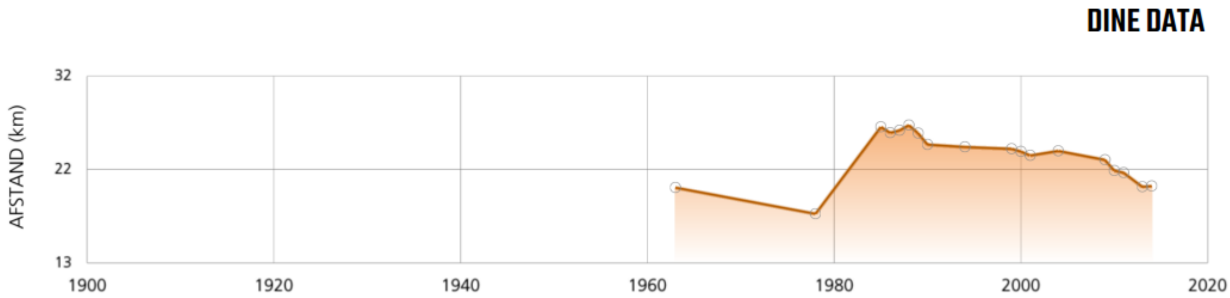
The summer contributes to increased speed: partly due to the lack of sea ice and partly due to meltwater lubricating the sole of the glacier. However, the average speed is about 1 km/year (Nick et al., 2012). At intervals of 5-10 years or more, large ice floes tear themselves away from the front. In 2010 the Petermann Glacier attracted people's attention, when a floe measuring 200 km^2 (the equivalent of 25% of the glacier's tongue) tore itself off and floated down along the east coast of North America (Falkner et al., 2011). In 2012 a new calving occurred, but this time it was a mere 120 km ^{2}. These two calvings reduced the length of the tongue from 81 km to 46 km: the largest withdrawal since 1876 (Münchow, Padman, & Fricker, 2014). So scientists began to observe the Petermann Glacier more carefully, because further retreat would allow sea currents to gain a foothold deep under the ice, given that the sole of the glacier is located far below sea level. But nothing happened: neither an increase in mass loss nor an increase in the glacier's speed. This prompted scientists to conclude that it was part of a natural cycle (Nick et al., 2012).



An example of data from a pupil's measurement of the Petermann Glacier in Ice Frontiers.

The Storstrømmen Glacier

The Storstrømmen Glacier is a huge marine-terminating outlet glacier that flows into Borgfjorden at Dove Bay in North East Greenland. The glacier is 15-25 km wide and up to 60 km long. The Storstrømmen Glacier is a 'galloping' glacier (surge glacier), and this makes it rather special. Several years can pass, during which the glacier's front barely moves and the glacier simply accumulates mass. Then comes a sudden eruption and off it gallops. Such eruptions occurred in the late 1970s and the early 1980s. The eruptions of galloping glaciers are a cyclical phenomenon. They are not directly triggered by melting, but by the build-up of snow and the destabilising of the glacier's sole. An accumulation of meltwater occurs, formed either by surface melting or by the weight of the glacier reaching pressure/melting point. Prior to an eruption, the front of the glacier gets thinner and the speed comes to s standstill while, further in, the glacier has more mass than usual (Reeh, Bøggild, & Oerter, 1994).



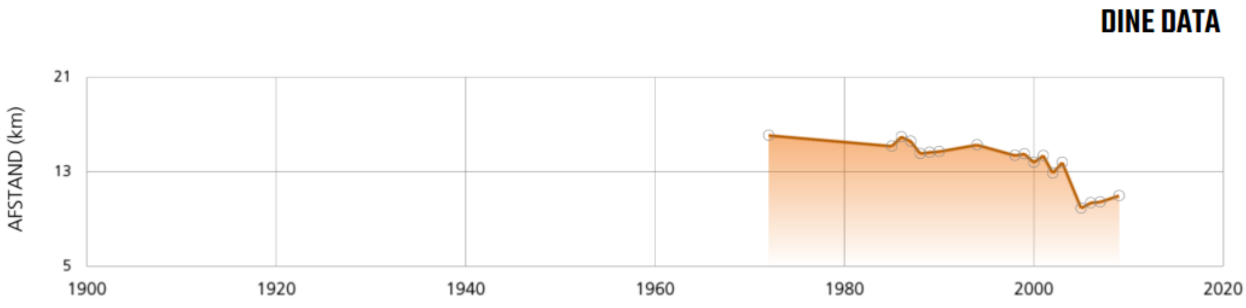
An example of data from a pupil's measurement of the Storstrømmen Glacier in Ice Frontiers.

The Kangerlussuaq Glacier

The Kangerlussuaq Glacier flows out into Kangerlussuaq Fjord, which then flows out into the Denmark Strait on the east coast. The name 'Kangerlussuaq' should not be confused with the better-known town, fjord and airport of the same name in West Greenland. It is the largest glacier in East Greenland, one of the fastest glaciers originating from the Ice Sheet and the second largest in terms of calving incidences (Enderlin et al., 2014). From 2000 to 2005 the Kangerlussuaq Glacier withdrew significantly, while the glacier's speed showed a marked increase up to 2005. In 2010 the glacier started to accelerate once again.

From 2000 to 2011 the Kangerlussuaq Glacier underwent a mass loss of 152±10 Gt. The largest portion was discharged between 2004 and 2008 (Howat et al., 2011). During this period, even though the glacier's front did not move significantly, the glacier still incurred major loss of mass after 2005. However, on that occasion it was due to a n increase in surface melting.

Both the Kangerlussuaq Glacier and the Helheim Glacier show clear signs of being sensitive to the climate changes that have been observed in their region. We believe that the significant acceleration, which both glaciers experienced in the early 21st century, was triggered by warmer temperatures both in the atmosphere and the sea (Khan, Kjeldsen, et al., 2014). The sudden increase in calving may be triggered by the significant mass loss from the surface, which directs meltwater to the sole of the glacier, causing the ice to flow more quickly over the substratum. It is very likely that the same applies to Sermeq Kujalleq (Luckman et al., 2006).



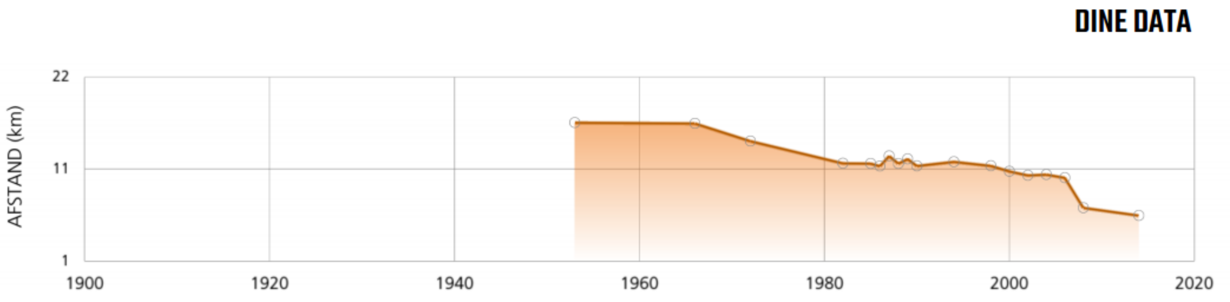
An example of data from a pupil's measurement of the Kangerlussuaq Glacier in Ice Frontiers.

The Upernavik Ice Steam

The Upernavik Ice Steam is located in the northwestern part of Greenland, about 300 km north of Disko Bay. In this region the Ice Sheet is almost in direct contact with the sea, because there is not much ice-free land.

The 40-km-wide ice stream, which is made up of four marine-terminating outlet glaciers, flows into Upernavik Fjord, which is about 80 km long and more than 900 metres deep. Previously the glaciers shared the same ice front, but over time the retreat of the ice stream and the underlying topography separated them from each other. Each time the glaciers moved back it resulted in increased speed, and the fronts of the glaciers became thinner. Using aerial photographs we have also found evidence that since the 1930s there have been three major events, in which the glacier fronts retreated: the first between 1931 and 1946; the second between 1985 and 1993; and the third between 2005 and 2010 (Kjær et al., 2012). It is estimated that a mass loss of about 92 Gt occurred between 1985 and 2010, about 79% of which was due to loss of ice mass caused by calving (Khan et al., 2013).
The glaciers ought to have the same basis for movement, given that they are influenced by the same climatic factors. But this is not the case. The secret is hidden deep down in the fjord, a fact of which scientists became aware in 2014. The bottom of the fjord is pretty uneven. This means that the fronts of the glaciers rest on various depths, ranging from 600 to 800 metres. This may be a partial explanation for their movement pattern, since it has various hydrographic impacts at the threshold of the glacier's sole. While conducting their survey, scientists found out that the water of the fjord was divided into layers, which made up three levels. The first 50 metres of the surface water consisted of dilute salt water at 2°C. Beneath this layer, down to 150 metres, there was slightly cooler polar water: at 0.5 - 1.5°C. At the lowest point the water was warmer and more saline because of deep-sea currents with temperatures ranging from 1 to 3°C. So the topography beneath the glaciers plays a vital role. If the water is very deep at the front of the glacier, this can result in major, rapid withdrawal, whereas the glacier is more likely to be stabilised in shallower water. The three northernmost glaciers in the Upernavik Ice Stream are up to 400-700 metres deep, whereas

the southernmost glacier only reaches a depth of 100 metres. In other words, currently only glaciers 1 to 3 are in contact with the warm deep-sea currents. This may be one of the reasons that the Upernavik Ice Stream reacts asynchronously to climate changes (Andresen, Kjeldsen, Harden, Nørgaard-Pedersen, & Kjær, 2014).



An example of data from a pupil's measurement of the Upernavik Ice Stream in Ice Frontiers.

The Glaciers in Ice Frontiers is written by Lisbeth Rykov, MSc in Geography and Geoinformatics (University of Copenhagen). It is based on her thesis: 'Ice Frontiers - A Didactical Method to Convey Scientific Research of the Greenland Ice Sheet to Earth Science in Danish High Schools (2015).

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