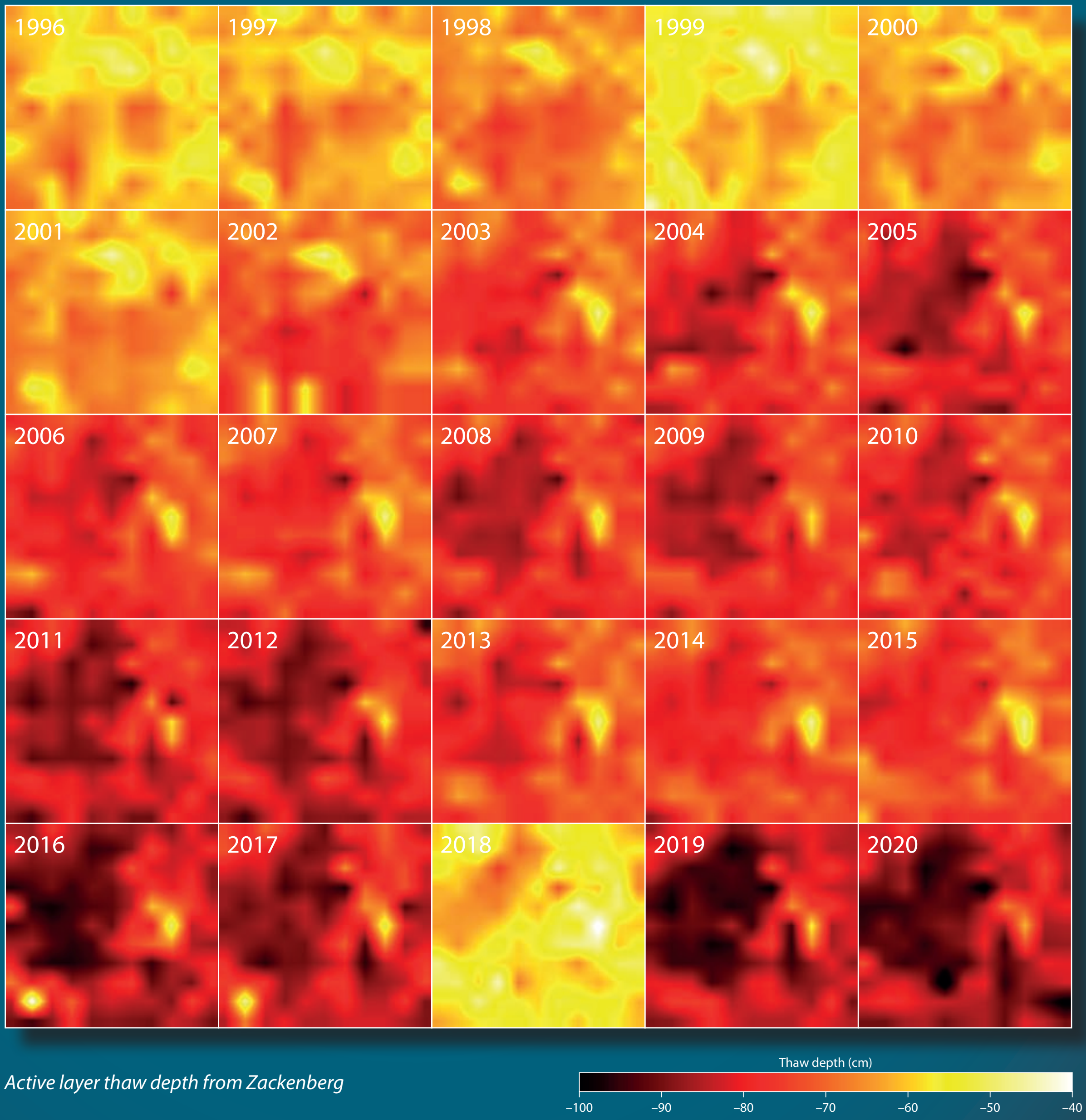
25
years
anniversary

Greenland Ecosystem Monitoring

ANNUAL REPORT CARDS 2020



Active layer thaw depth from Zackenberg

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Front cover: 25 years of Circumpolar Active Layer Monitoring (CALM) showing interannual variations and increased thaw depth over time.
Credit: GeoBasis Zackenberg

Back cover photos: Top to bottom: Jakob Abermann, Laura H. Rasmussen, Bula Larsen, Thomas Juul-Pedersen and Michele Citterio

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GREENLAND ECOSYSTEM MONITORING

ANNUAL REPORT CARDS 2020

PROGRAMME DESCRIPTIONS

GEM

Greenland Ecosystem Monitoring

GEM
INTRODUCTION

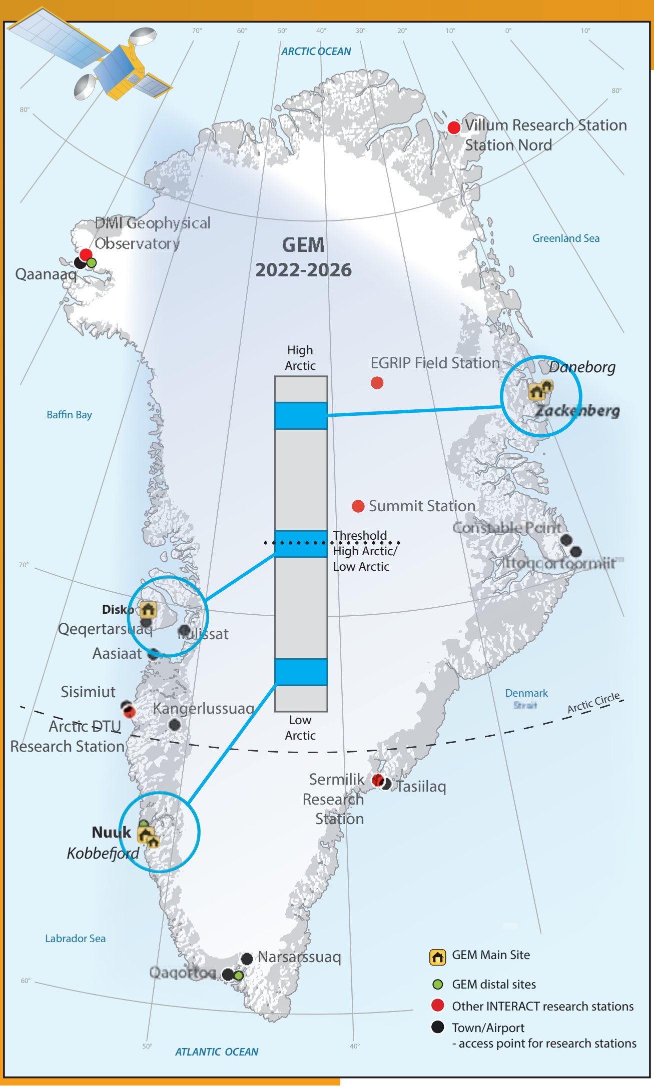

Figure 1. The GEM programme combines intensively studied ecosystems at three main sites (Disko, Nuuk and Zackenberg) with remote sensing and long-term single disciplinary sub-sites and short term research projects located along environmental and climatic gradients.

About GEM

Greenland Ecosystem Monitoring (GEM) is an internationally recognized climate and ecosystem monitoring programme in Greenland, operated by research institutions in Denmark and Greenland. It was established in 1995 and thus celebrates 25 years of monitoring essential climate and ecosystem variables. GEM has been an important Danish/Greenlandic contributer to working groups of the Arctic Council and the long-term data has improved the scientific understanding of climate and ecosystem change in the Arctic.

The programme has developed from a comprehensive climate change and ecosystem monitoring programme at a single site in the National Park of North-East Greenland, to also include two almost equally comprehensive programmes in West Greenland, supplemented with initiatives at other locations (Fig 1).

The three main sites are located at Zackenberg in the high Arctic North-east Greenland, on Disko at the boundary between the high Arctic and low Arctic in West Greenland and at Nuuk in the low Arctic West Greenland.

The GEM organisation consists of a Steering Group, a Secretariat, a Coordination Group and sub-programme leaders. The long-term monitoring efforts of the programme is funded by the Danish Ministry of Climate, Energy and Utilities (Klimastøtte til Arktis) and the Danish Environmental Protection Agency (Miljøstøtte til Arktis), and by the Government of Greenland. Additional funding for programme development and improved process understanding is provided by the institutions behind the GEM programme and other external funding sources.

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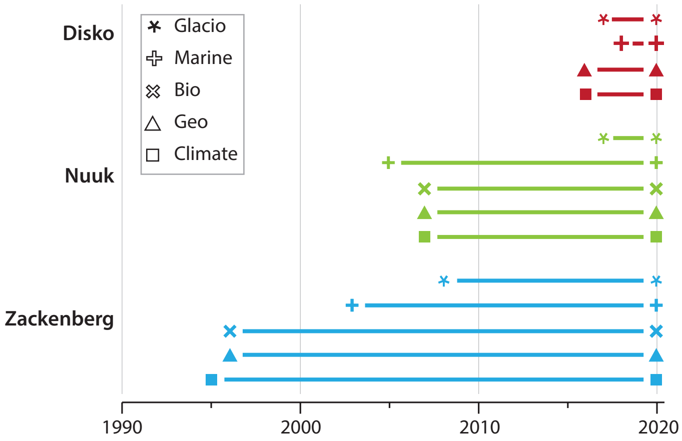

Figure 2. The GEM programme was initiated in 1995 as the Zackenberg Ecological Research Operations (ZERO). In the years 2005-2007 a new main site was established around Nuuk, and in 2016-2018 Disko area was included. All 5 Basisprogrammes are now funded at all three main sites, except for BioBasis at Disko.

GEM
Greenland Ecosystem Monitoring

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The vision of GEM

GEM will contribute substantially to the basic scientific understanding of Arctic ecosystems and their responses to climatic changes and variability as well as their potential local, regional, and global implications.

International cooperation

The GEM programme and scientists work closely with more than 30 international scientific networks to implement standard methodologies and share data for inter-comparisons and assessments. GEM scientists are involved in monitoring programmes of Arctic Council working groups (CAFF and AMAP) contributing with data and taking on leading roles in coordination, development and synthesis efforts. GEM scientists and data also contributes to regional and global intergovernmental assessments by IPCC and IPBES.

Education and Advice

GEM aims to play a central role in educating the next generation of scientists, with several university courses using GEM data, and associated Ph.Ds and Post Docs. GEM scientists reach out to younger students in schools and high schools through course and information materials based on GEM knowledge and data - also in international cooperations reaching a wide Arctic audience. GEM also creates awareness and provide public insight into the changes that occurs in the Arctic climate and ecosystems. GEM aims to provide government advice on climate change and impacts, and where relevant GEM knowledge and data are used to address sustainability and adaptation efforts.

Free and open access to data

GEM provides free and open access to all data collected under the programme since the start in 1995. At all three GEM sites there are data series from before GEM started operating, and being highly relevant for long-term monitoring, these have been integrated in the database. Data collection efforts have grown since the start of the programme and today includes more than 2000 parameters collected at the three main sites Zackenberg, Disko and Nuuk. Additional data are collected through remote sensing and supplementary transects and sites contributing to gradient studies and scaling efforts. All data are made available, quality assured and with DOI assigned to allow citation.

Explore GEM data on https://data.g-e-m.dk/

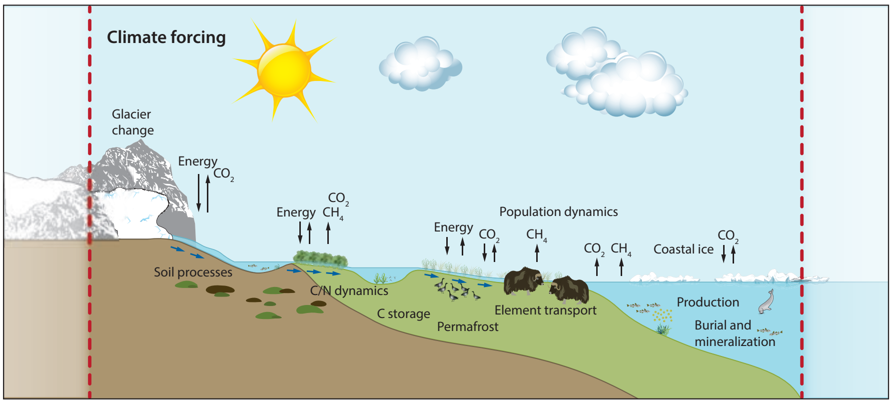

Figure 3. The GEM domain covers the glaciological, terrestrial, limnic and coastal marine compartments of the ecosystem.

Read more about the GEM programme and its achievements on: **www.g-e-m.dk**

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@GEM_Arctic

Greenland Ecosystem Monitoring

Feel free to get in touch with the GEM Secretariat if you have questions or want to explore possibilities for collaboration at g-e-m@au.dk

Arctic Station – Disko.

Zackenberg Research Station.

Kobbefjord Station.

GEM ANNUAL REPORT CARDS
INTRODUCTION


Photo: Laura Lønstrup Frendrup .


Photo: Henning Thing.

The Zackenberg 1995 team, including rightmost the current scientific leader of GEM.

Celebrating 25 years of monitoring in Greenland

The history of GEM started with discussions among Danish scientists active in NE Greenland on the need for a high Arctic monitoring station. This led to a report "Betænkning om Zackenberg Forskningsstation" on the exact location and suggestion for establishing af research station in the Zackenberg Valley. Initial recognessense trips were made in the early 1990s and in 1995 the Zackenberg climate station was established as the first pivotal piece of monitoring infrastructure. This has remained in service ever since continuously collecting weather data. This issue of the Annual Report Cards 2020 is therefore celebrating the first 25 years of GEM data records – all freely accessible on: https://data.g-e-m.dk/

In the summer of 1996, the construction work of the first five main buildings of the station started, leading to the official inauguration of the Zackenberg Research Station on 14 August 1997. The programme gradually developed to become one of the most comprehensive long-term monitoring programmes in the Arctic and now monitor more than 2000 ecosystem variables. A demand for monitoring data covering a wider climate gradient and the inhabited West Greenland led to the expansion of GEM to also include two main sites in Nuuk/Kobbefjord and Disko.

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Photo: Katrine Raundrup.


Photo: Kirstine Skov.


Photo: Thomas Juul-Pedersen.

2020

GEM
Greenland Ecosystem Monitoring

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The programme was designed from the onset to monitor ecosystem changes as climate warming would progress. As central results so far GEM has shown:

- **Ecosystems are warming.** Temperatures have been increasing at the GEM sites as in the rest of the Arctic. GEM has documented how this warming extends deep into the soils and causes permafrost warming and deepening of the active layer.
- **Sea-ice cover in the fjords are diminishing.** Increased water temperatures and availability of solar energy in the watercoloumn has lead to altered conditions for primary production and led to changes in species composition with potential implications for coastal and marine foodwebs and local resource use.
- **Change in snow cover.** A general trend of earlier snowmelt and increased variability in snow depth and duration coubled with data on the biotic system enables GEM to assess the effect of interannual variability. GEM has documented implications for e.g. plant/pollinator interactions, musoxen population dynamics, carbon cycling and methane emissions.
- **Extreme events** are pivotal for ecosystem change and can be triggering factors for longer term ecosystem and landscape change. GEM long-term monitoring data enables us to differentiate between trends and variability and to identify extreme events and their impacts, as done for e.g. extreme precipitation events and insect outbreaks.
- **Resilience.** Despite consistent warming not all ecosystem components are showing changes. Bird population dynamics for example show a remarkable degree of stability over 25 years, despite climate induced interannual variability in reproductive success.
- **Glaciers are loosing mass** and adds to run-off with subsequent ecosystem impacts in both land, freshwater and near coastal environments. GEM has documented the importance of sub-glacial meltwater from fjord terminating glaciers for the productivity of Greenlandic fjord systems and at the same time the increased freshwater input to fjords affects planktonic species assemblages, both with potential implications for local foodwebs and resource use.

Looking ahead

The current GEM Strategy terminates in 2021 and new strategic goals and a revised organizational structure has been laid out in the new GEM Strategy 2022-2026. The new strategy provides the framework for ensuring the interdisciplinary nature of GEM and provides clear links to the efforts and priorities of intergovernmental organisations like Arctic Council working groups and IPCC. Central to the new strategy is also the continuation of long-term monitoring efforts coupled with increased focus on international agreed essential variables, technological development and a new Remote Sensing and Modelling component, that will secure GEMs position as a leading Arctic ecosystem monitoring programme as it approaches three decades of operation.

Operating long-term monitoring infrastructures in a pristine Arctic environment necessitates focus on its environmental impacts. The programme therefore work towards increased sustainability of the operations to obtain a level of green transiton that meets agreed emission reduction goals, which for Denmark is 70% by 2030. This requirement also applies to GEM researchers in the field collecting new knowledge on nature feedbacks in the Arctic in response to the human-induced climate change. GEM researchers should be accountable for meeting international and governmental decisions on emission cuts and new efforts by GEM looking forward to the next 25 years will contribute to research-based solutions that can assist in providing the most efficient emission reduction transformation.

GEM will continue to emphasize the efforts to improve the free and open access to data using the FAIR principles and make data available for research and e.g. courses at high schools and universities.

GEM in 2020

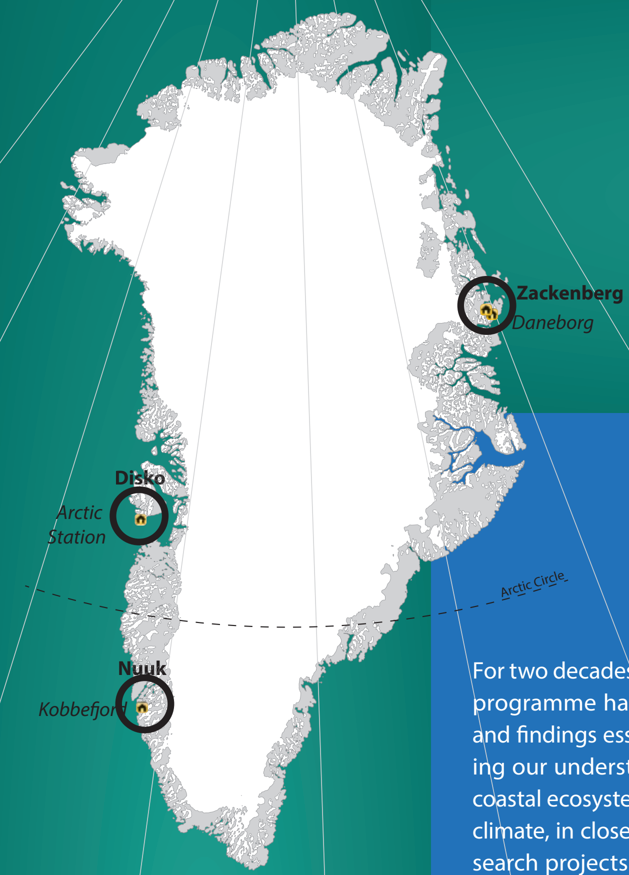
Whilst Mother Nature was having its normal operation in 2020, human societies were seeing something different. The Covid-19 pandemic obviously also affected the field operations of the GEM programme. Some parts were hit harder than others but overall GEM was fortunate in being able to conduct fieldwork at all main sites – something that was prohibited for many of our collaborators elsewhere in the Arctic. A general lesson for the future is to make observations more resilient to disruption of the fieldwork when adverse ground conditions prevent reaching and safely working at the monitoring locations. A number of components in the technological development laid out in the new GEM Strategy 2022-2026 will naturally build on the experiences gained navigating GEM through the pandemic.

GEM at a glance 2020

- Active Basis Programmes in 2020: 14
- Scientists in the field: 65
- Scientific publications: 58
- Conference with GEM representations: 4
- Conference presentations (posters): 8 (5)
- Courses using GEM data: 18

Photo: Charlotte Sigsgaard.

Photo: Asiaq.



FJORDS

Marine Monitoring – The foundation for understanding climate change effects in coastal ecosystems.

For two decades, the MarineBasis programme has produced data and findings essential to improving our understanding of Arctic coastal ecosystems in a changing climate, in close synergy with research projects. The monitoring sites' geographical location provides time series across various climate zones, from sub Arctic to high Arctic, with different physical environments and degrees of sea ice cover. The scientific topics on which MarineBasis has contributed, significantly advancing our knowledge and understanding of these ecosystems, include the following:

Oceanography. The systematic collection of key oceanographic variables, such as temperature and salinity profiles, has contributed to the description of fjord circulation patterns and the effects of seasonal freshwater discharge and coastal inflows (Fig. 1). The marine efforts have contributed significantly to differentiating the ecosystem effects of freshwater introduced into the fjord as surface runoff (land-terminating glaciers) and ice melt from deep subglacial discharge of freshwater (marine-terminating glaciers).

CO$_2$ dynamics. Time series on surface water chemistry have contributed to the quantification and process description of CO$_2$ uptake in fjord waters, characterising these fjords as year-round CO$_2$ sinks driven by biological production (photosynthesis), subsaturated freshwater and sea ice-led convection. It has been shown that these processes result in increasing air-water CO$_2$ uptake toward and along the fjord systems.

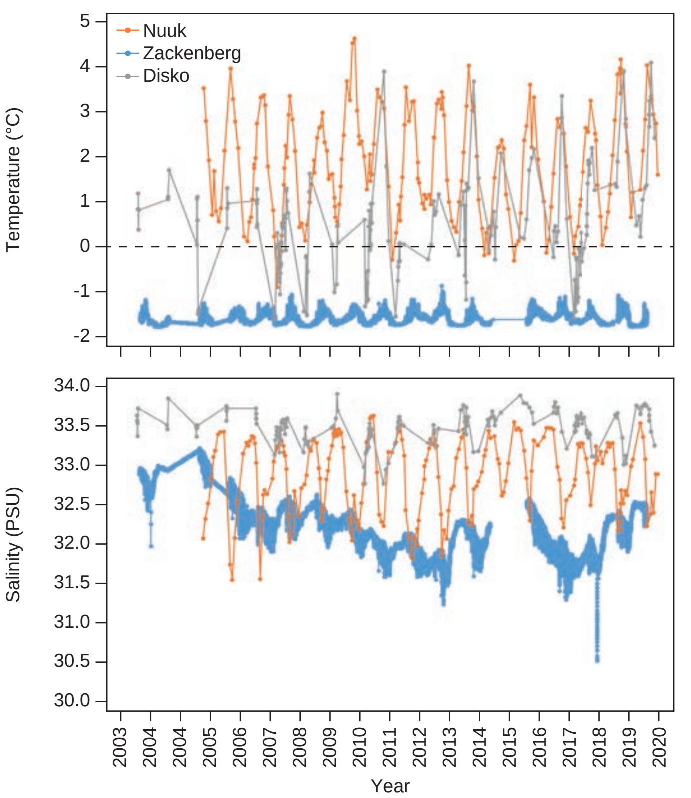


Figure 1. Water temperature and salinity at the permanent monitoring stations in Nuuk, Disko and Zackenberg. The time series from Nuuk and Disko represent one depth (63 m) selected from a monthly profile covering the entire water column. The time series from Zackenberg represents an autonomous mooring deployed at an average depth of 63 m.

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Data source:

MarineBasis-Nuuk
MarineBasis-Zackenberg
MarineBasis-Disko
Data can be accessed on:
https://data.g-e-m.dk/

AND CLIMATE CHANGE

Primary production. MarineBasis has contributed time series data describing the seasonality, interannual variability and magnitude of primary production. Primary producers, particularly phytoplankton, represent the first step in the marine food web, sustaining the energy requirements of all higher trophic levels. The time series have improved our understanding of the positive effects subglacial discharge has on summer phytoplankton production in fjords with marine terminating glaciers due to the upwelling of nutrient-rich bottom water during periods when nutrients are typically depleted.

Plankton dynamics. Time series on both phyto- and zooplankton have provided insight into their seasonality in terms of species composition, abundance, phenology and lifecycles. The seasonal patterns in terms of species composition and abundance have highlighted interannual patterns and anomaly events. The monitoring data have shown that freshwater runoff from the ice sheet can be an important driver influencing both phyto- and zooplankton community structure and that a reduction in sea ice and water mass changes may induce a rapid shift in species composition, which will likely have a vital impact for predators, e.g., fish, sea birds, and marine mammals.

Macroalgae. MarineBasis has systematically collected data on the biomass and growth of selected macroalgal species. Macroalgae are indicators of climate change, and they contribute to shaping the near-shore ecosystems by creating oases of high pH during the Arctic summer, forming new habitats through geographical expansion and their contribution to carbon sequestration. MarineBasis has contributed important knowledge about environmental effects, such as temperature, salinity and ice cover, on macroalgal growth and biomass (Fig. 2).

The MarineBasis programme continuously evolves while maintaining the systematic collection of key variables. New areas of interest include:

- The incorporation of autonomous sampling techniques with higher sampling frequencies and year-round data collection, in which sampling has only been possible during discrete periods.
- Incorporating remote sensing data, with the potential to widen the spatial understanding and usage of *in situ* data and findings.
- Utilising genetic techniques, such as environmental DNA, to significantly improve and expand the data on and knowledge of species composition and biodiversity.

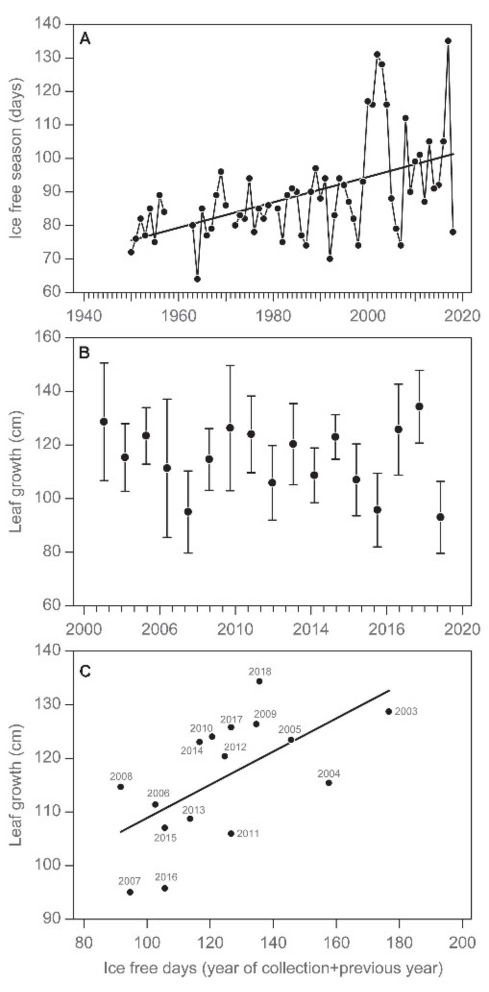
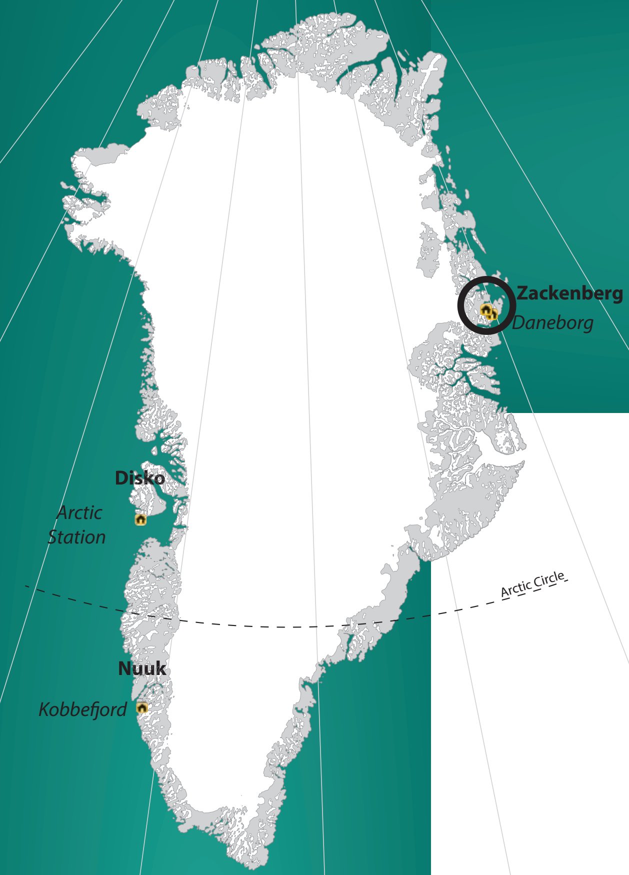


Figure 2. Time series of kelp growth in relation to climate change in Young Sound. (A) Changes in the ice-free season's duration in outer Young Sound over the 1950–2019 period. (B) Average leaf length growth (±95% CI) of Saccharina latissima at 10 m depth in Young Sound over the period from 2003 to 2019. (C) Relationship between leaf growth and ice-free season for the year of growth and the previous year. Reproduced from Krause et al., 2020



HIGH ARCTIC

Living conditions in the Arctic are known to be highly variable not only in the form of extreme seasonal differences but also regarding interannual variability and more long-term trends. Logistic and financial constraints have prevented us from studying this variability in large parts of the Arctic, especially in the high Arctic, until research stations were established relatively recently. This also applies to the Arctic bird fauna, where the birds wintering at lower latitudes so to say disappeared into the Arctic during the critical breeding season.

Fourteen bird species breed regularly at Zackenberg. Most populations remained relatively stable, and the same did timing of their breeding during the study period.

Artwork by: Jon Fjeldså.

Birds are the best studied group of organisms in the world. This is because they are very appealing and relatively easy to watch; they are beautiful, they are very (day) active, and they are highly vocal. About 200 species of birds inhabit the true Arctic, of which the vast majority spend most of the year in temperate and tropical areas and only come to the Arctic in summer to reproduce.

Despite this, we still do not know much about the reasons for the population declines observed in many Arctic bird populations, particularly in Asia and North America. We do not even know whether the most important problems are affecting them on the breeding grounds or at staging and wintering sites. To gain insight into the factors affecting bird populations in high Arctic Greenland, monitoring of the bird populations and their breeding performance has been part of the BioBasis programme from the establishment of Zackenberg Research Station in 1995. At the same time, the monitoring of potential geophysical, as well as biological, impact factors became an integrated part of the monitoring at the station.

Now, after 25 years of fieldwork and analysis, we have one of the longest data series from the Arctic and, probably, the longest from the high Arctic. To the surprise of many, we found that, in contrast to the major ecological changes taking place in several other parts of the Arctic zone, few statistically significant changes were observed in the bird populations and the climatic and biological factors potentially influencing bird populations during all these years. Out of 14 species of regularly breeding birds, eight or nine populations fluctuated, with no significant trend, four increased and only one or two decreased. However, among the same 14 species, six showed increasing year-to-year variability during the study years. Among 36 climatic and biotic factors, only two showed

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Data source:
GEM BioBasis.
Data can be accessed on:
https://data.g-e-m.dk/

TUNDRA BIRDS

increasing trends (July mean temperature and fox encounters). The rest remained relatively stable, with no trend. Like for some of the bird populations, the timing of snowmelt and mean May temperature exhibited increasing variability over the study years. Likewise, we found only few significant correlations between bird population numbers and inter-annual variation in the climatic and biological factors studied, with extent of spring snow cover showing the most pronounced correlation.

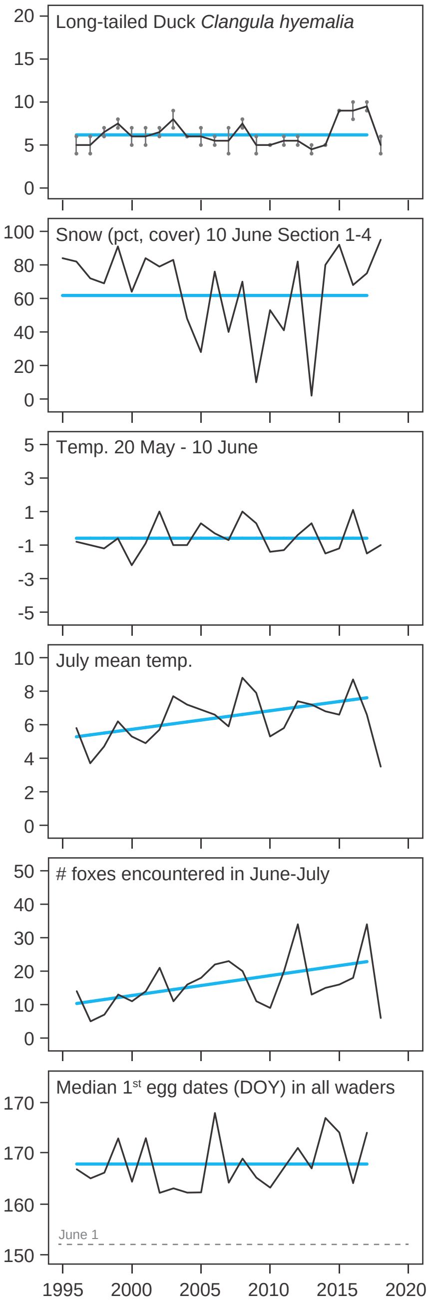
In addition, we found no significant changes in timing of egg laying or clutch size in the most common waders (shorebirds) over more than two decades. With some variation among species, we found earlier egg laying in seasons with earlier snowmelt, more invertebrates during the pre-laying period, earlier appearance of invertebrates and higher June temperatures. In addition, we found larger clutch sizes with earlier snowmelt, lower clutch sizes with later nest initiation dates and increasing variability in clutch size during the study years. Nest success increased with season progress primarily in the form of reduced predation, while nest success was much lower during the last part of the study period as compared to the first part. The reason for this is unknown but could be due to either increased Arctic fox activity on the tundra or increased researcher activity at nests, which leaves olfactory clues for the foxes. The numbers of juvenile Dunlins produced showed a negative correlation with our index of fox activity on the tundra during nesting and fledging, whereas we found no correlations between fox activity and lemming abundance.

Taken together, the analyses show that the bird populations and their environment at Zackenberg changed little during the many study years. Increased variability was the most marked change, and as expected, spring snow cover was the most important driver of year-to-year variability in several bird performance characteristics and living conditions. As part of this, we found that the effects of severe events as seen in several of our study years, including a next-to-non-breeding year in 2018, may be just as important to the wellbeing of bird populations as average conditions.

The relatively unchanged conditions at Zackenberg may be due to the generally benign climate of high Arctic Northeast Greenland as compared to high Arctic Siberia and Alaska, where inclement weather may last for many days on end. Furthermore, the mountainous character of high Arctic Greenland, with a pronounced gradient from maritime conditions at the outer coasts to the arid inland close to the Greenland Ice Sheet, seems to result in favourable breeding conditions, at least in one area or another, in most years so that breeding failure in the birds is rarely widespread.

Our study adds to our understanding that the Arctic is not a homogeneous biome but may show quite different regional patterns of climate change effects. Furthermore, contrary to several other major flyways in Asia and the Americas, our data support that most tundra bird populations on the East Atlantic Flyway, where 'our' birds go, are doing well. This may change in the future, as indicated by the increasing variability in both biotic and abiotic characteristics at Zackenberg. In fact, increasing instability, including more frequent severe events, was one of the hypotheses that we aired already at the beginning of the Greenland Ecosystem Monitoring programme.

Fourteen bird species breed regularly at Zackenberg. Most populations remained relatively stable, as did the timing of their breeding.



Graphs with a selection of data series among the 14 bird species and 35 factors potentially impacting the tundra bird populations and monitored at Zackenberg. DOY is Day of Year.

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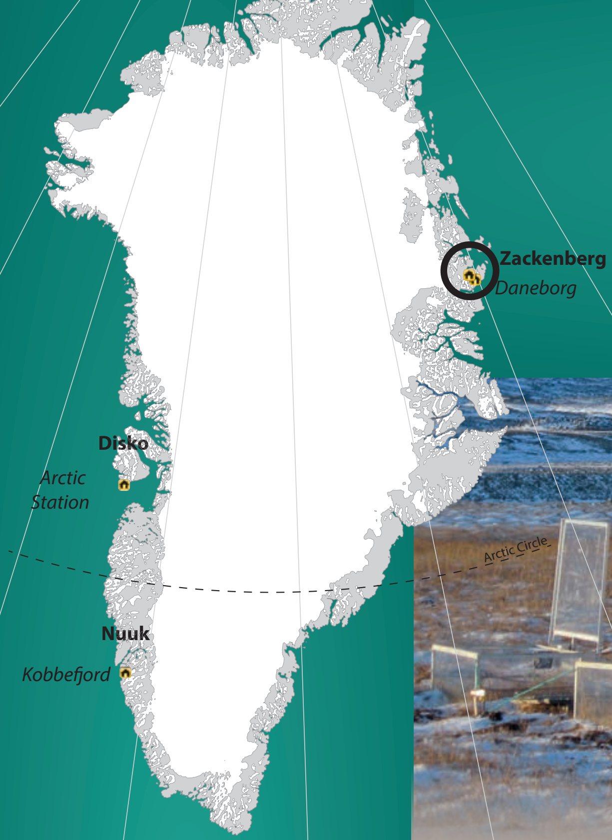


15 YEARS OF MONITORING – WHAT WE DIDN'T KNOW

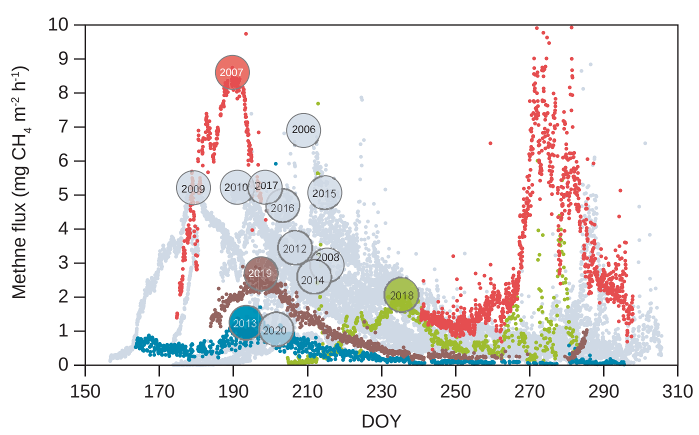
The automatic chamber monitoring of methane fluxes in Zackenberg became a part of the GeoBasis field programme in 2006. Then, the main processes and factors controlling such fluxes were already known, and the monitoring was initiated to document the flux variability and parametrise these factors. Surprisingly, several years of measurements revealed much more than that.

Methane (CH_4) production in Arctic terrestrial ecosystems and natural emissions of this powerful greenhouse gas into the atmosphere attract strong scientific interest in the context of progressing climate change in the Arctic. It was presumed that the majority of both the production and emission of CH_4 happened during the short Arctic summer, the so-called growing season. Fluxes depend on several parameters, e.g., vegetation composition, soil temperature and moisture, all of which can be measured and used for modelling.

The multiyear monitoring of methane fluxes in Zackenberg revealed a highly variable, complex picture of growing season emissions. The seasonal peak of CH_4 emissions can be high or low and occur earlier or later (Fig.1). Both the timing and magnitude of this peak are not directly related to the present climatic parameters. Short-term measurement campaigns cannot reveal this complexity and may be misleading. For example, mid-August fluxes in 2018 were four times higher than in 2019 (Fig.1), simply because of the difference in peak timing.

The timing of these peaks was found to be closely related to the date of snowmelt (Mastepanov et al., 2013), which can vary a great deal between years (Fig.2). Most often, the flux reaches its maximum about 30 days after snowmelt (Pirk et al., 2017), regardless of many other differences in climatic parameters.

Figure 1. June-October CH_4 fluxes, 2006–2020 obtained from the same chamber (same 0.36 m^2 plot) in Zackenberg. Four selected years are shown with different colors, others are in grey for readability. Summer peak fluxes are marked for each year. The variability in autumn peaks (DOY 270–310) is even higher.



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Data source:
GEM GeoBasis – Flux monitoring (AC)
https://doi.org/10.17897/430p-ds31
Data can be accessed on:
https://data.g-e-m.dk/

METHANE FLUXES AT ZACKENBERG
WHEN WE STARTED

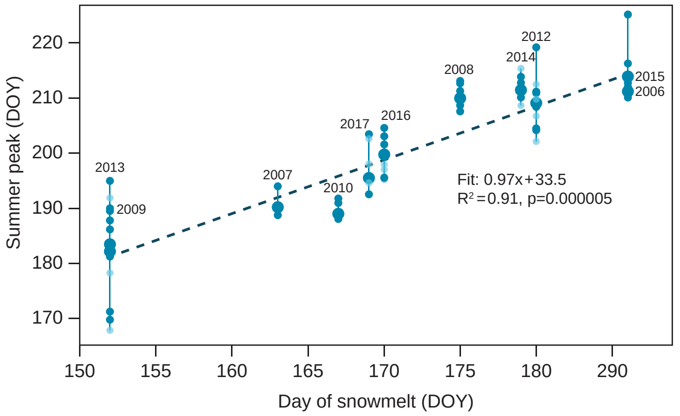


Figure 2. Timing of summer CH_4 emission peak versus day of snowmelt for different years. Modified from Pirk et al. (2017).

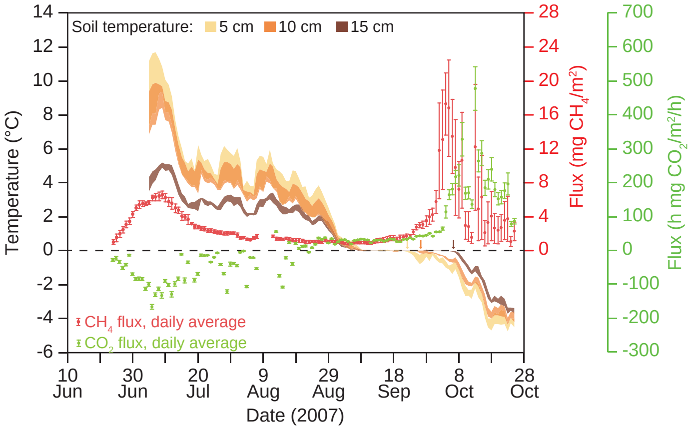


Figure 3. Example of autumn CH_4 and CO_2 peaks in comparison with their growing season fluxes. Soil temperatures recorded at three depths reveal soil freezing propagation (shown by arrows). Modified from Mastepanov et al. (2008).

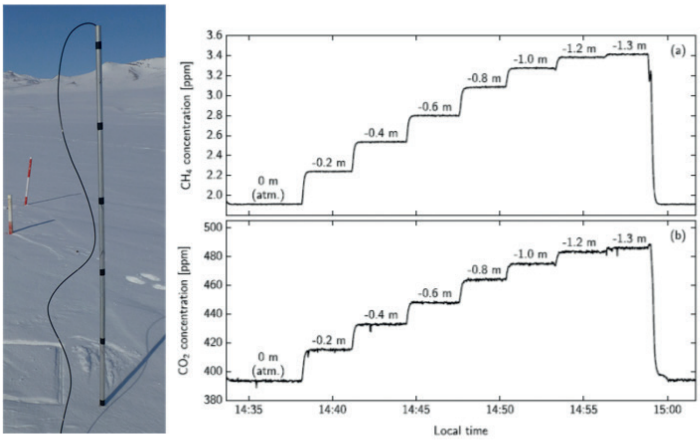
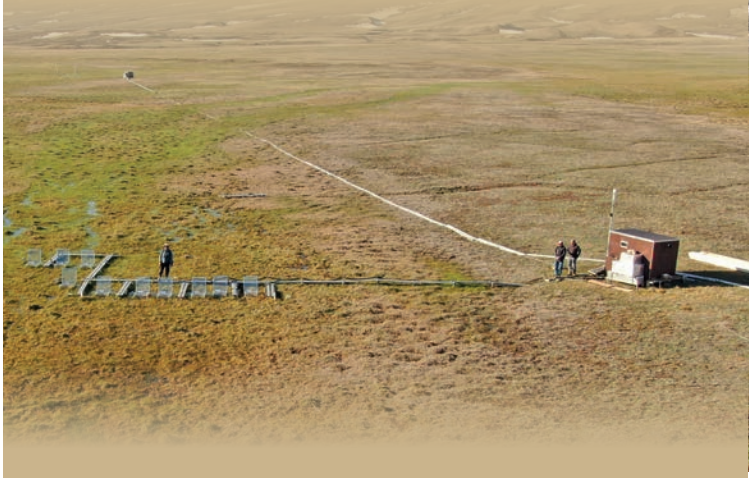


Figure 4. Snow concentration probe and example of CH_4 and CO_2 concentrations in different depths of snow. Modified from Pirk et al. (2016).

Another novel finding from Zackenberg was the second peak of methane emission during autumn (Mastepanov et al., 2008). It happens in October—November, when the soil is freezing, and some years, this peak can even bring more methane into the atmosphere than the summer peak (Fig.1, 3). These autumn emissions are not directly connected to ongoing methane production; they are a result of the squeezing out of the gas accumulated in the soil during summer (Mastepanov et al., 2013; Pirk et al., 2015). To a certain extent, the fluxes during the summer will therefore depend on the efficiency of this soil reservoir depletion in the previous autumn (Mastepanov et al., 2013). Such autumn bursts seem to occur only in the regions where permafrost is present, which makes the inter-annual variability of fluxes in these areas more complex than at lower latitudes.

Even when the soil is completely frozen in winter, the methane story is not over. Wintertime fluxes can amount to 15% of the annual budget (Pirk et al., 2016), but the variability of this number is still very uncertain. During winter, methane is slowly diffusing through the snow (Fig. 4); how much of that is actually produced in winter remains unclear. Probably, winter fluxes are closely interrelated to summer and autumn fluxes, but only long-term systematic monitoring can reveal these relationships.



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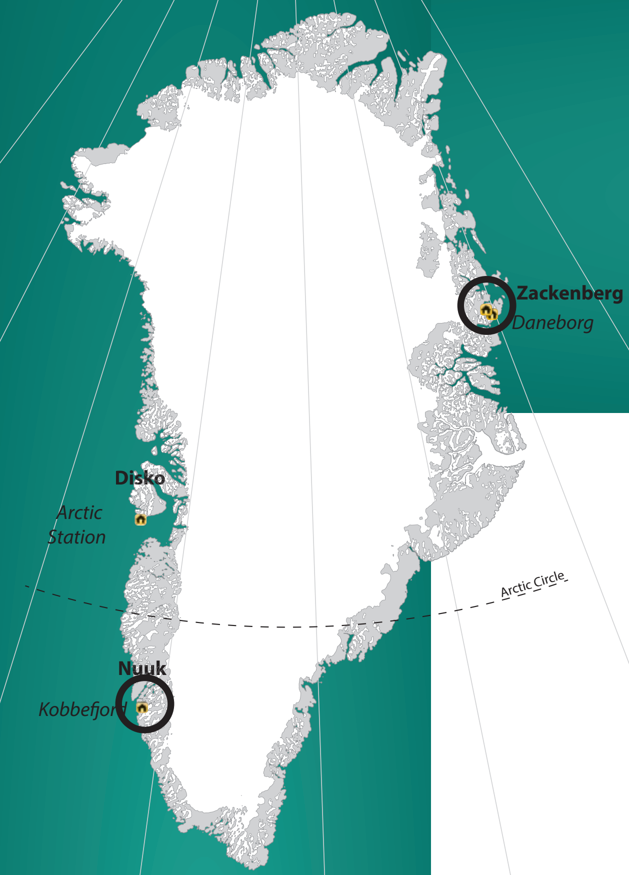

Annual Report Card 2020

BREAK-UP OF LAKE – STRONG LINKAGE TO

Arctic lakes are typically ice-covered for a majority of the year (7-10 month) and the further north the longer the ice cover lasts. The formation and especially the thickness of the ice cover is determined by actual weather conditions including the autumn/winter temperatures, the amount of snow accumulating on top of the ice, the compactness of the snow and the wind conditions. Thus, it is expected that the duration of the ice-cover will vary with the prevailing climatic conditions, which also implies, that the breakup date will vary from year to year. Obviously, the longer the ice-free season lasts the longer time for warming up the water.

Will the overall increase in air temperatures in the Arctic have implications for lake ecology because of increasing average water temperatures? Will it lead to more productivity in the form of more primary production, which is the base for the lake food web? The long-term monitoring efforts at Kobbefjord (since 2008) and Zackenberg (1997) may provide answers to these questions. The lakes at the two locations vary considerably in depth and length of the ice-free season (Table 1).

Arctic shallow lakes may reach temperatures between 15°C and 20°C during summer. In contrast, deeper lakes (> 20 m) often have a temperature gradient from the top towards the bottom (thermal stratification).

During winter the lake water is inversely stratified as the top layers are constantly cooled by the ice (i.e., very close to 0°C) and bottom waters stays a few degrees higher (usually 1-4°C). As soon as the ice-breakup starts, the water column will be mixed which implies that e.g., heat, gasses and nutrients will be transferred from the bottom towards the top. The mixing process along with the heating of the water from the incoming solar energy provides good growth conditions for the lake food web (Fig. 1).

If these thermal conditions change it may have far-reaching implications for the phenology of organisms, species composition and for the function of the entire lake food web.

The long-term monitoring effort illustrate, that there is a clear relationship between lake water temperature and day of ice breakup in all four lakes (Fig. 2 A and B). Thus, an early ice breakup results in warmer lake water in the peak-season (July-August). Intuitively this makes sense as more time allows for more impact of the solar energy.

A longer and warmer season affects the biota at least in Zackenberg (Fig. 2D) as we detected more chlorophyll i.e., more primary producer biomass with the warmer and longer seasons. However, the relationships are not strong which may be attributed to the fact that other especially biotic components are in play (such as grazing from zooplankton, temperature gradients and thereby

Table 1. Basis data of the monitored lakes. The open water period is defined as the time from 50% ice cover and until the formation of new ice in the autumn. For Zackenberg the ice formation date is set to mid-September (values +/- one week).

Location	Lake	Max depth (m)	Size (ha)	Open water (days; year(s) of observation)		
				Min	Average	Max
Kobbefjord 64°N	Badesø	38	74	115 (2015)	145 (2008-2020)	202 (2010)
	Qassi-sø	28	51	99 (2015)	128 (2008-2020)	159 (2010)
Zackenberg 74°N	Langemandssø	7	1.1	62 (2018)	103 (1997-2019)	122 (2013)
	Sommerfuglesø	2.5	1.7	69 (2018)	107 (1997-2019)	123 (2010/2019)

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Data source:

GEM BioBasis
https://data.g-e-m.dk/

ICE IN THE ARCTIC

MEAN SUMMER TEMPERATURE

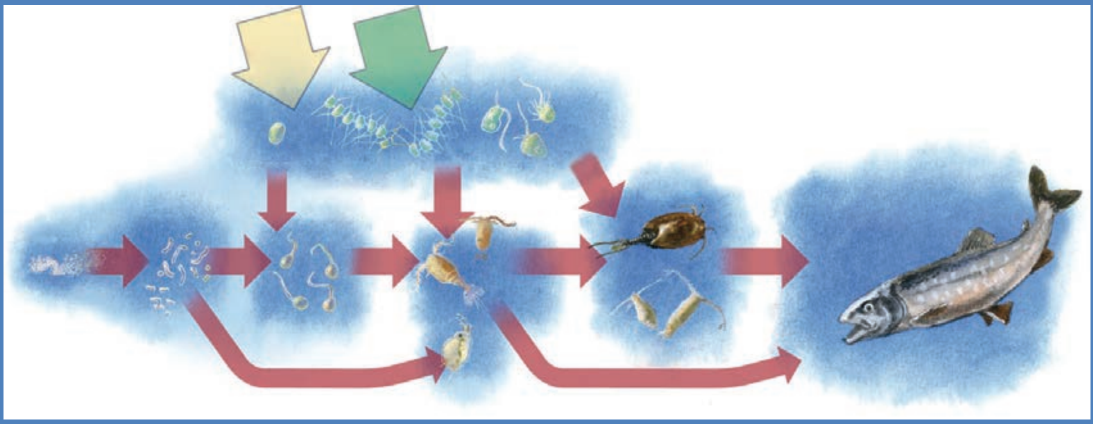

Figure 1. A simplified food web structure in Arctic lakes. Light (yellow arrow) and inorganic nutrients (green arrow) fuel the pelagic and benthic algae that is the building blocks for all the other components. These include the microbial community (left side), the zooplankton (middle part) as well as the predatory invertebrates and fish (right side). Red arrows illustrate connections. Source: Christoffersen (2006). Drawing layout by Claus R. Schierbeck.

exchange of nutrients between the top and the bottom waters). For Kobbefjord we find the same weak relationship for Badesø but not for Qassi-sø (Fig. 2C). The latter is a typical colder glacier lake with a high silt content probably affecting the primary production and thus the chlorophyll content.

Thus, the answers to the initial questions are that there is a clear connection between the duration of the ice cover and the average water temperature in summer (July-August) which in turn coincide with more primary producer biomass that potentially can support more consumers in the food web.

Furthermore, long-term monitoring is essential in assessing the status of Arctic lakes as interannual variation is tremendous and may thus blur the short-term effects of climate change.

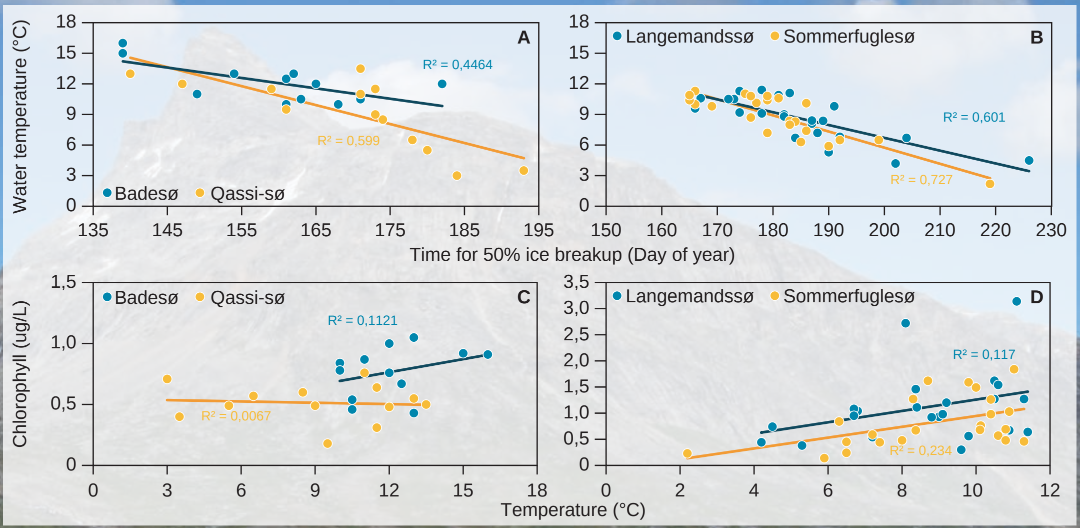

Figure 2. A+B: The relationships between average water temperature in July-August and time for ice breakup in Kobbefjord (A) and Zackenberg (B). C+D: The relationships between phytoplankton biomass (expressed as chlorophyll) and average water temperature in July-August for Kobbefjord lakes (C) and Zackenberg lakes (D). Temperature measurements at 0.5 m in lakes in Kobbefjord; temperature of depth-integrated water sample in lakes in Zackenberg. Chlorophyll measurements are from depth-integrated samples in all lakes.

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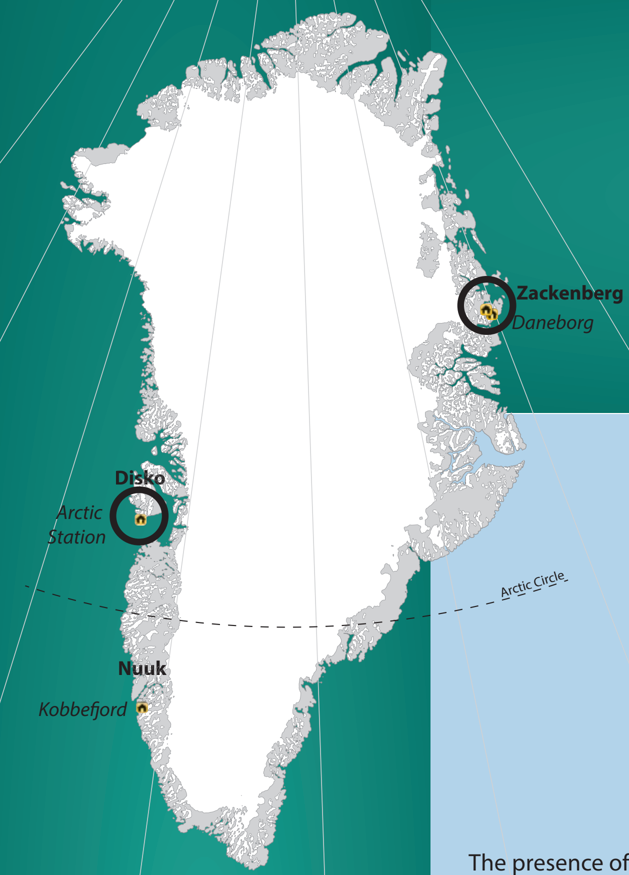

CLOUDS IN A

Clouds can cool or warm the earth's surface, depending on their type and where and when they occur. Due to a paucity of observations – especially in remote areas such as the Arctic – and an incomplete understanding of the microphysical processes occurring inside clouds, their net effect is little known quantitatively on both the global and regional scales. This lack of knowledge represents one of the largest sources of uncertainty in the projection of future climate change, globally and in the Arctic. Our instrumentation collects data that are vital to improving our understanding of Arctic clouds.

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Data source:

GEM ClimateBasis

Data can be accessed on: https://data.g-e-m.dk/

The presence of clouds in the atmosphere alters the amount of radiative energy the earth's surface receives: they reflect solar shortwave radiation back into space, but they also absorb and re-emit longwave radiation from and to the ground. The first effect reduces the energy received at the earth's surface, whereas the second increases it; the sum of both (termed cloud radiative forcing) may be either positive or negative. Climate model results disagree regarding whether a warming climate will entail a higher or lower level of cloudiness overall, although they mostly show an increase in the Arctic (Vihma et al., 2016). Most models, however, show positive feedback with atmospheric warming as a result of cloud cover changes (Ceppi et al., 2017). The climate sensitivity calculated from model simulations – the amount the earth's surface air temperature increases for a given amount of CO_2 added to the atmosphere – appears to be much less than that reconstructed from the geological record, and a severe underestimation of cloud feedback has been suggested as a major cause of such (Zhu et al., 2019, Tan et al., 2016).

The sign and magnitude of the cloud radiative forcing depends on local conditions but is generally positive for the Arctic as a whole (Nygård et al., 2019), particularly during the polar night. Winter temperatures in Greenland are more variable than summer temperatures, and this is, to a large extent, related to moisture influx from outside the Arctic and associated increases in cloudiness (Messori et al., 2018, Cao et al., 2017). From a GEM perspective, ecosystems experience variability in cloudiness through its effect on photosynthetically available radiation, summertime temperatures and the extent and duration of the seasonal snow cover, which, in turn, affect the length of the growing season.

Observations of clouds and associated atmospheric properties are sparse in the Arctic but essential to improving our understanding of their effect on the Arctic climate and ecosystems. For this reason, ClimateBasis has installed several instruments at GEM sites that collect data on clouds and related atmospheric processes: at several GEM sites, hemispherical sky cameras collect optical imagery, which is processed into timeseries of fractional cloud cover (Wacker et al., 2015), and at Arctic Station in Qeqertarsuaq, a microwave radiometer retrieves vertical profiles of atmospheric temperature and humidity, which allow for a deeper understanding of the relationship between clouds and the dynamics of the atmospheric boundary layer (Fig. 1).

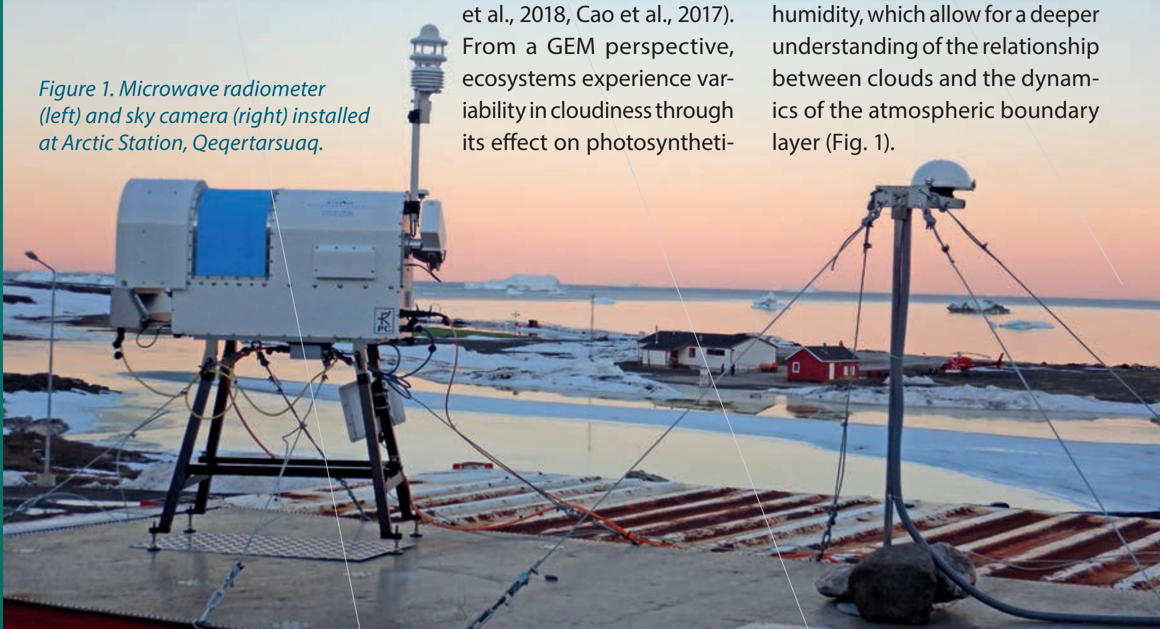

Figure 1. Microwave radiometer (left) and sky camera (right) installed at Arctic Station, Qeqertarsuaq.

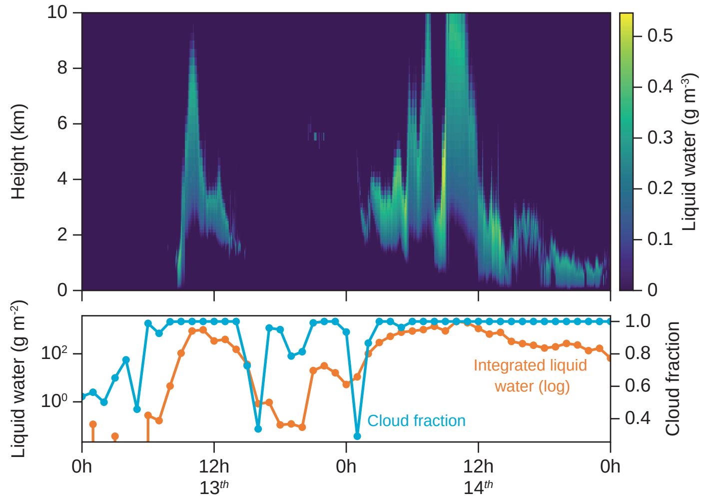

Figure 2. Atmospheric liquid water during two days in June 2019, as detected by the microwave radiometer at Disko, compared to the cloud fraction calculated from cloud camera images. The top plot shows the atmospheric profiles of volumetric liquid water content, while the bottom plot compares the integrated liquid water (plotted on a log scale) with the cloud fraction derived from the camera data.

The relationships between the variables measured are not straightforward; a cloud fraction derived from optical camera images does not directly compare to the liquid water profiles retrieved by the microwave radiometer. The camera cannot distinguish between thin or thick clouds, while the profiler looks only at a column of air vertically above the instrument and does not integrate over the entire field of view (Fig. 2). Nonetheless, it is of great interest to extend the temporal coverage of the fractional cloud cover timeseries, which, at present, can only be obtained for daylight hours (i.e., neither at night nor during winter), by exploiting statistical relationships with other measured parameters, such as incoming longwave radiation and atmospheric temperature (Fig. 3). This not only sheds light on the longwave forcing of clouds itself but also allows for the utilization of longer existing timeseries than the cloud observations themselves in order to assess trends in cloudiness.

The effort of understanding the relationships between Arctic cloud cover and other atmospheric parameters is further supported by the development of a cloud cover product within the context of the GEM RemoteBasis initiative. This cloud product is validated against the timeseries derived from the sky camera images and can, in turn, be used to validate statistical analyses of the type presented in Fig. 3.

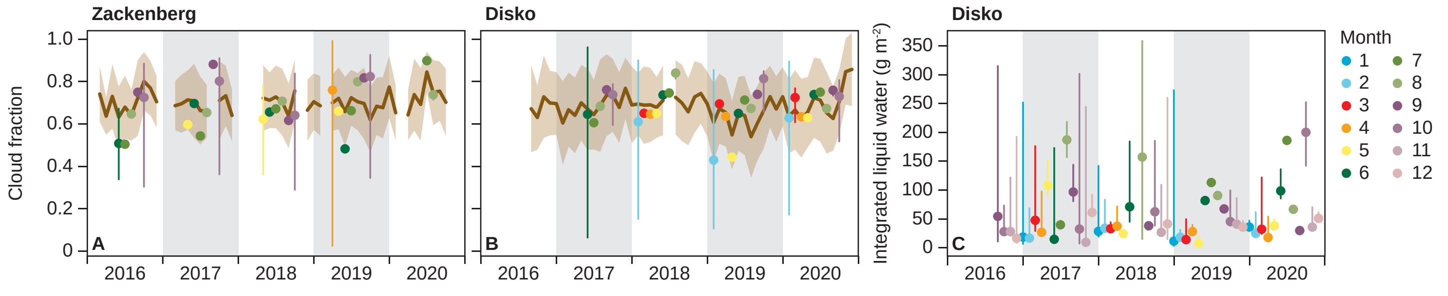

Figure 3. The A and B plots show the monthly mean cloud fraction (dot markers), as observed by the cloud cameras at Zackenberg and Disko. Days with too few observations are discarded, visualized with the vertical error bar, where a longer bar indicates that more data is missing. Months without dots have no data at all (e.g., during winter, when the camera does not deliver data). For comparison, the brown line corresponds to a regression that predicts cloud fraction as a function of longwave radiation, air temperature and relative humidity. More data are available for these variables, but months with missing data still occur. The brown shaded area illustrates the uncertainty of the regression. The C plot shows the total amount of liquid water in the column of atmosphere directly above the microwave radiometer at Disko. As for the A and B plots, dot markers represent mean monthly values, and the error bars give an indication of missing data.

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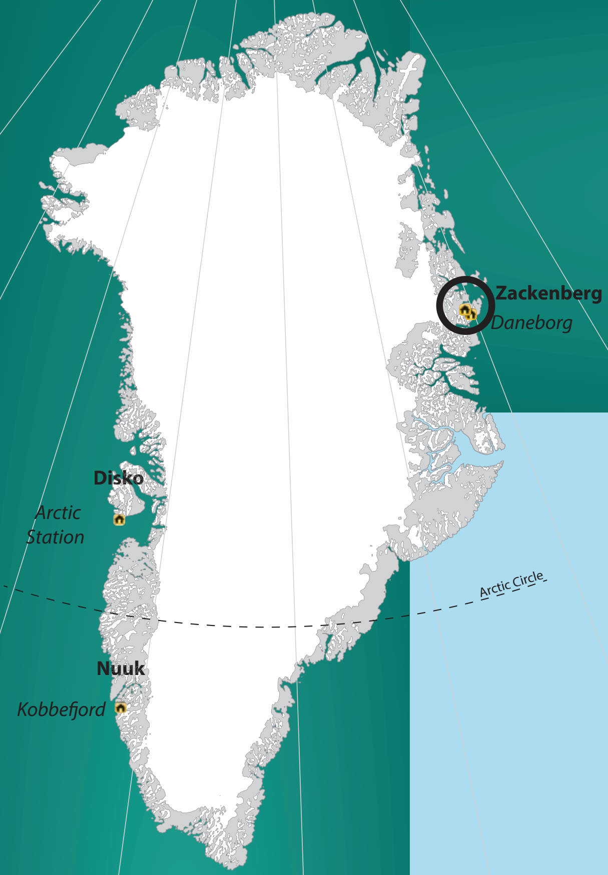

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MIXOTROPHIC ALGAE
AS THE GREENLANDIC

It is often assumed that future annual pelagic net primary production in Young Sound and across the Arctic Ocean will increase as the ice-free season lengthens. Counteracting this longer growing season is, however, the recent increase in freshwater flows from glaciers and the general freshening of the Young Sound fjord and the Arctic Ocean. This freshening may lead to stronger stratification and, therefore, a weaker vertical supply of nutrients. Our findings demonstrate that Young Sound fjord, with less available nutrients and low salinity surface layer, may provide a niche opportunity for potential toxic mixotrophic-dominated algae blooms. Mixotrophs are frequently associated with harmful and toxic algal bloom events, as seen in Norway, with high costs for fish farming; therefore, it is crucial to determine their role and future prevalence.

Since the long-term monitoring programme MarineBasis was implemented as an integrated part of the Zackenberg monitoring program in 2002, the mapping of the high Arctic marine ecosystem in a changing climate has been a major focal point. Therefore, by merging the knowledge acquired through the monitoring programme and research projects, it is possible to obtain a more complete understanding of this high Arctic marine ecosystem.

Traditionally, biological productivity is thought to be driven by photosynthetic phytoplankton that bloom in the brief period in spring when the irradiance increases or during sea ice breakup in summer. However, this view has recently been challenged by observations of extensive diatom- and *Phaeocystis*-dominated under-ice blooms beneath thick melting sea ice. These blooms are triggered by increasing irradiance and fuelled by an excess of nutrients in the under-ice waters. The Young Sound fjord is covered by sea ice for most of the year (8–10 months) and has a pronounced summer stratification that impedes the vertical nutrient supply. The combination of light limitations and low nutrient supply in the surface waters in Young Sound is responsible for the low primary productivity, and recent studies have shown that the fjord is among Greenland´s least productive.

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Data source:

GEM MarinBasis

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MAY PLAY A CRUCIAL ROLE

FJORDS FRESHENS

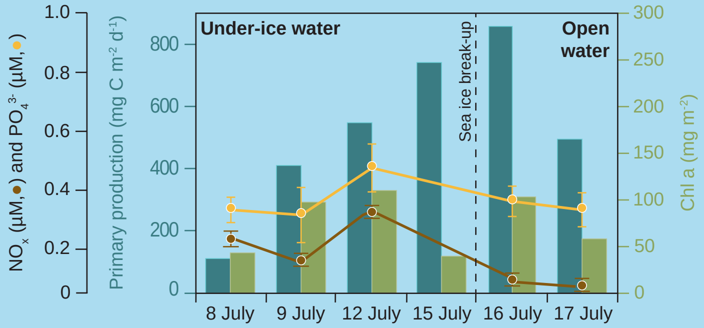


Figure 1. Temporal development of under-ice and open water integrated primary production mg C m^{-2} d^{-1} (dark green bars), integrated Chl a in mg m^{-2} (green bars), NO_x concentration in µM (brown circles) and PO_4^{3-} concentration in µM (yellow circles). The figure is adapted from Søgaard et al. (2021).

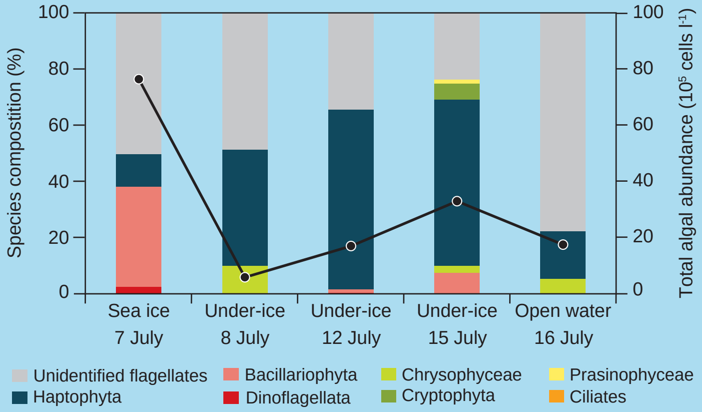


Figure 2. Temporal development of algal species composition (%) in the sea ice column and under-ice water at 1 m (bars) and the total algal abundance (black circles). The figure is adapted from Søgaard et al. (2021).

In July 2017, we travelled to Young Sound to study the potential for an under-ice photosynthetic phytoplankton bloom fuelled by an excess of nutrients and increased under-ice irradiance due to melt pond formations.

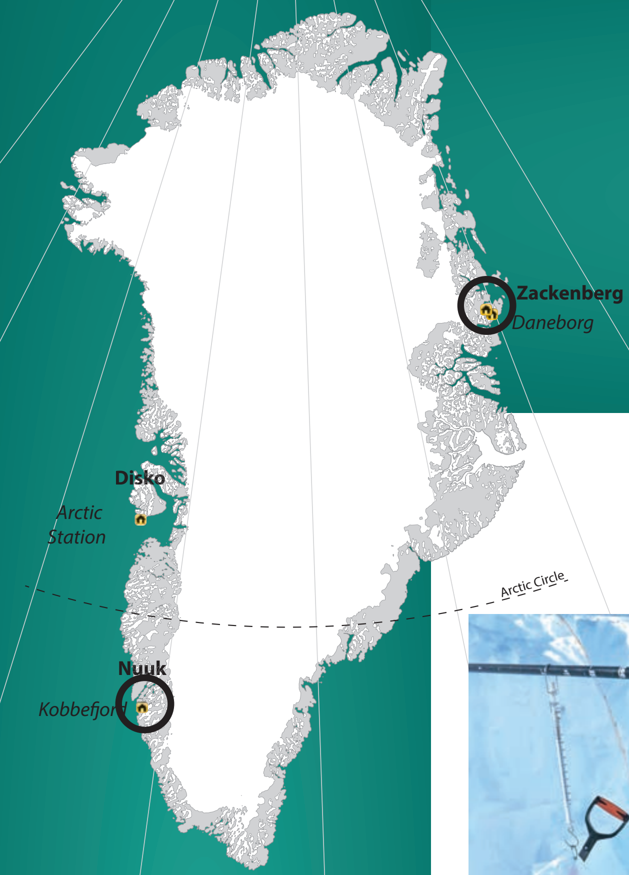
Instead, we observed, for the first time, an acute 9-day under-ice bloom driven by potentially toxic mixotrophic brackish-water haptophytes in nutrient-poor waters (Fig. 1).

Our findings therefore challenge the classical view that low nutrient concentrations control algal productivity because the under-ice bloom produced 5.7 g C m^{-2} of new production under nutrient-limited conditions. This estimate represents about half the annual pelagic production in Young Sound, occurring below sea ice with a large contribution on the part of the mixotrophic algae bloom.

The bloom was primarily dominated by mixotrophic haptophytes (dark blue bars in Fig. 2) with a relative abundance of 64%, as compared to 36% relative abundance of typical strictly autotrophic phytoplankton species (Fig. 2). Thus, our findings strongly imply that the marine food web in Young Sound fjord is much more complex than previously envisaged.

Mixotrophic organisms combine photosynthesis and prey uptake, which is particularly beneficial and provides a competitive advantage in these Arctic brackish waters, where nutrient concentrations are low. Therefore, mixotrophy can radically change traditional Arctic food web interactions by enabling primary producers to acquire nutrients directly from eating prey, such as bacterial and algal competitors and even their predators. This finding implies that the ongoing freshening of Young Sound and the Arctic Ocean, with increased stratification and reduced vertical supply of nutrients, can accordingly promote mixotrophic-dominated algae blooms. Given the rapid changes in Arctic marine systems, it is increasingly important to understand the effects of climate change on phytoplankton structure because minor effects at the base of the Arctic food web could be amplified through trophic chains. The indication of a mixotrophic-based bloom suggests that mixotrophic algae may play an important role in driving the Arctic spring bloom and, thus, the biogeochemical cycling and fish production in this area.

Sea ice covered with melt ponds in Young Sound in July 2017.
Photo: Dorte H. Søgaard.



IMPACT OF WINTER
ON SUMMER ICE MELT

Winter snow cover is important in the Arctic ecosystem. Not only does it release stored water when melt starts, but by covering the surface, it changes the interface between the atmosphere and the ground. For glaciers it has a direct effect as snow has to be melted away before ice can start to melt. Here we investigate observations of winter snow accumulation and ice melt in two different climate zones, one near Nuuk, SW Greenland and the other in Zackenberg, NE Greenland.

Snow pit and buried weather station.
Photo: Michele Citterio.

Annual winter accumulation of snow on the glacier can vary depending on the length of the winter (here defined as the period where precipitation falls as snow rather than rain) and the total amount of precipitation. The timing of ice melt start of the glacier, thus not only depends on the energy available for melt, but also the snowpack thickness. This means that changes in winter climate have a direct impact on summer ice melt. GlacioBasis was established in 2008 and can now in 2021 present more than a decade of glaciological observations from A.P. Olsen Ice cap (APO), close to Zackenberg and six years of observations from Qasigiannguit glacier (Qas) in Kobbefjord close to Nuuk (Fig. 1). The time series from the most recently established GlacioBasis site, Chamberlin Glacier on Disko Island, are still rather short and are not included. GlacioBasis Automatic Weather Stations (AWS) automatically collect a large range of observations directly from the glacier surface including data on snow depth, ice ablation and temperature.

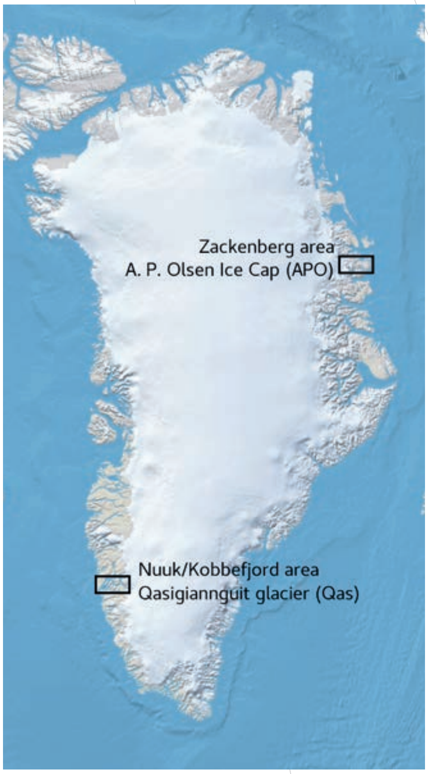


Figure 1. Monitoring of the glaciers A.P. Olsen Ice cap (APO), close to Zackenberg, and Qasigiannguit glacier (Qas) in Kobbefjord close to Nuuk.

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Data source:

GEM GlacioBasis

Data can be accessed on: https://data.g-e-m.dk/

SNOW

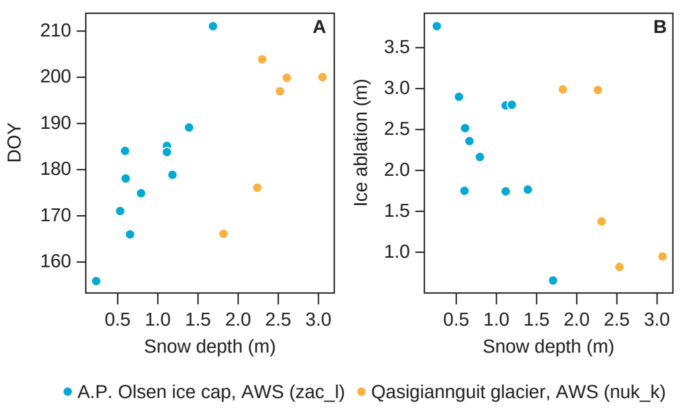

Figure 2. Annual end of winter snow depth compared with day of year when the ice melt starts (left) and annual total ice ablation (right).

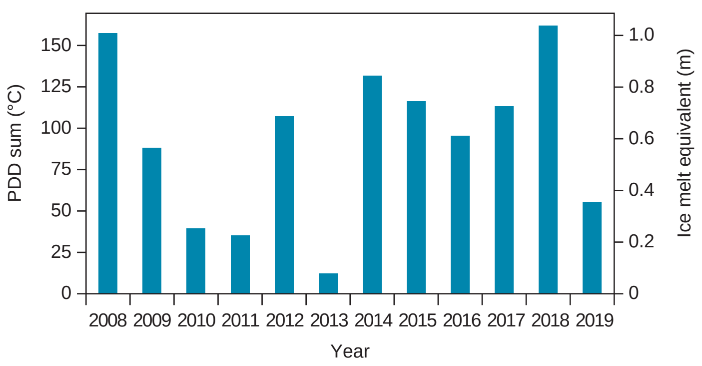

Figure 3. The positive degree days (PDD) sums for the period when snow is melting, shown on the left vertical axis. On the right vertical axis the potential ice melt the PDD sum would induce, assuming that approximately 7 mm of ice melts per PDD.

In Fig. 2 we compare snow depth against the day of year when ice melt started (left panel), and snow depth against total ice surface lowering due to melting and sublimation of ice (known as ice ablation, right panel). At the AWS sites, observed winter snow accumulation ranges between 0.2 and 2 m snow at APO, and at Qas snow depth observations range between 1.8 and 3 m snow. Thus, while there is generally more snow on Qas, the inter-annual variability in snow depth is c. 2 m at both sites. Observed annual ice ablation at the two AWSs ranges between 0.5 m and 3.5 m ice at APO and 3 m at Qas. There is a clear tendency towards years with more snow having a delayed starting date of ice melt (Fig. 2 left panel) and this late start date affects the total ice ablation so that years with high winter snow accumulation show a general trend to lower total annual glacier ice melt.

The energy available for melt during the period of snow melt is approximated by the positive degree day (PDD) sum before ice melt starts (Ohmura, 2001). Assuming that 7 mm of ice will be melted per PDD (the ice melt factor of 7 mm/°C is an average found from observations at APO) we can approximate how much ice could have been melted by the same amount of energy that was used for snow melt (we call this ice melt equivalent). Fig. 3 shows how the ice melt equivalent can vary between 10 cm and 1 m. In the 12 year record there is a tendency towards more years with high ice melt equivalent in the recentmost half than in the first half. This is due to generally more snow in the second half of the observational period.

The results from the GlacioBasis data show that changes in winter climate does directly impact summer ice melt. This means that glacier melt is particularly affected by extreme years in terms of snow accumulation. The effect of the start of the ice melt season has an impact on the total meltwater runoff, which affects both the natural ecosystem, perhaps most strongly via the nutrient and sediment transport to the fjords, and human activities in areas where glacier runoff is an important natural resource as drinking/irrigation water and for hydropower production. On annual to decadal time scales, this effect could dampen the impact on glacier melt, of future warming scenarios, because the warming, in NE Greenland is expected to be followed by an increased precipitation. In regions where increased temperatures are expected to be followed by a shorter period with precipitation falling as snow, the impact on glacier retreat due to less accumulation will be enhanced by the increased ice melt due to an earlier start of the meltseason.

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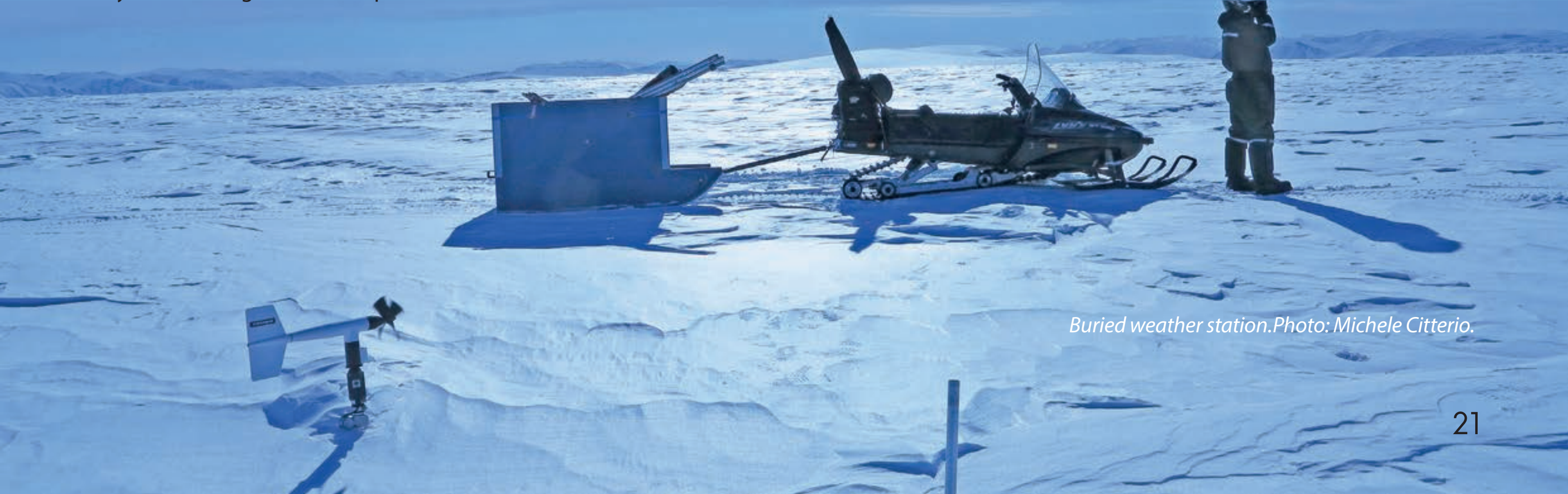
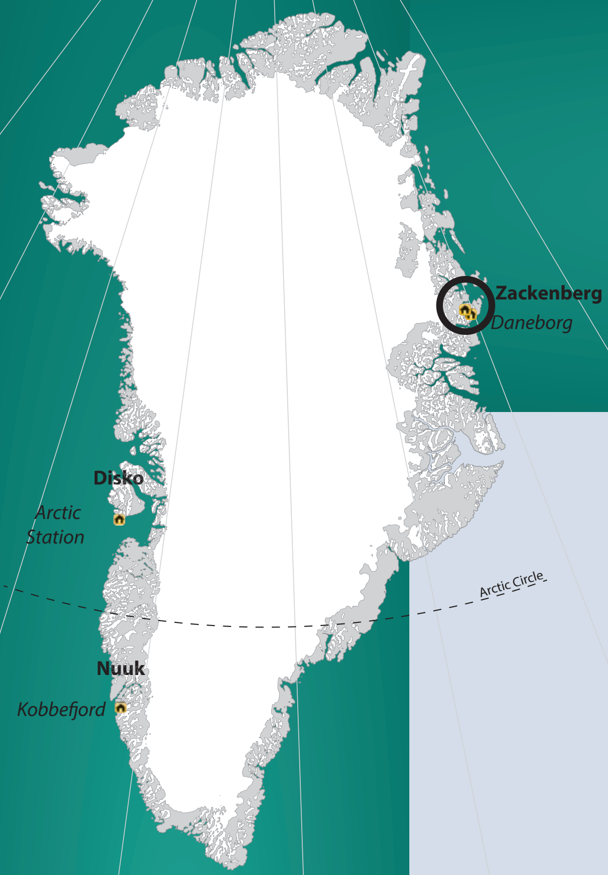


Buried weather station.Photo: Michele Citterio.



Annual Report Card 2020

A MECHANISTIC OF MUSKOX POPULATION

Understanding how individual animals respond to environmental change and how these responses translate into population-level dynamics is at the core of animal ecology. By using a combination of long-term monitoring, research and modelling, we have developed a model framework that allows us to gain mechanistic insights into the drivers of muskox population dynamics and which demographic parameters are the most sensitive to environmental change. The model framework constitutes a powerful tool with which to assess future scenarios in terms of environmental and anthropogenic change for animal populations.

Photo: Lars Holst Hansen.

To protect Arctic biodiversity and inform decision-making, we must be able to predict biological responses to environmental change. In nature, however, multiple complex interactions often limit our ability to accurately quantify and predict population dynamics in response to factors such as the changing climate. To meet the demand for credible predictions of population trajectories, process-based models that dynamically describe the underlying mechanism driving animal fitness are increasingly being used. The muskox is a key species in the tundra ecosystem, and in our efforts to understand the drivers of muskox population dynamics in the high Arctic, we have developed a model framework that integrates two types of process-based approaches, namely dynamic energy budget (DEB) modeling and individual-based modeling (IBM) (Desforges et al. 2019). Process-based models integrate theory and the available empirical data to arrive at a model framework that, first, describes the dynamics within a population adequately and, second, makes projections under various scenarios regarding future conditions. Within our DEB-IBM framework (Fig. 1), we use energy as the governing currency and explore how its availability to muskoxen is determined by the environment and how it is allocated to physiological processes within individuals. To arrive at meaningful population-level predictions, the model introduces inter-individual variability in physiological parameters and summarises information from all individuals to generate population data.

Using the above-mentioned DEB-IBM framework, we have integrated various data sources across the continuum from fine-scale experimental research to long-term monitoring to describe the muskox population at Zackenberg (Desforges et al. 2021). While the DEB-IBM framework is founded in DEB theory and parametrized with data from studies conducted across the Arctic, the primary data used for the validation of the population outcomes that emerge from the model have been collected at Zackenberg since the beginning of the Greenland Ecosystem Monitoring programme. These data include the muskox densities, calf recruitment and the sex and age composition of the muskox population (Schmidt et al. 2015). We were interested in understanding how access to forage in winter (determined by snow conditions) and summer (determined by plant growth) affects the seasonal dynamics of muskox energy storage, as

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Data source:

GEM BioBasis

Data can be accessed on: https://data.g-e-m.dk/

UNDERSTANDING
DYNAMICS

well as how this, in turn, influences muskox life history and population dynamics. Through the DEB-IBM model, we found that access to winter forage and, thus, winter snow conditions, was the main driver of muskox population dynamics, primarily through impacts on calf recruitment. Hence, in snow-rich years, muskox energy reserves are depleted, resulting in more miscarriages and lower calf production. We then used the model framework to explore how muskox populations may respond to environmental change in the future. Specifically, we subjected the muskox model population to successive years of heavy or light snow scenarios and found that even moderate scenarios for winter snow conditions resulted in reduced population growth, with decadal-long recovery times, for the muskox population.

Notably, our mechanistic approach allowed us to pin-point the most important metabolically-driven processes within individuals that caused population-level responses, thereby providing insight into snow-induced thresholds in key population demographic parameters. The DEB-IBM framework can be extended to explore various environmental scenarios but also to include more direct anthropogenic stressors, such as hunting, and thus also serve to inform muskox management and conservation initiatives.

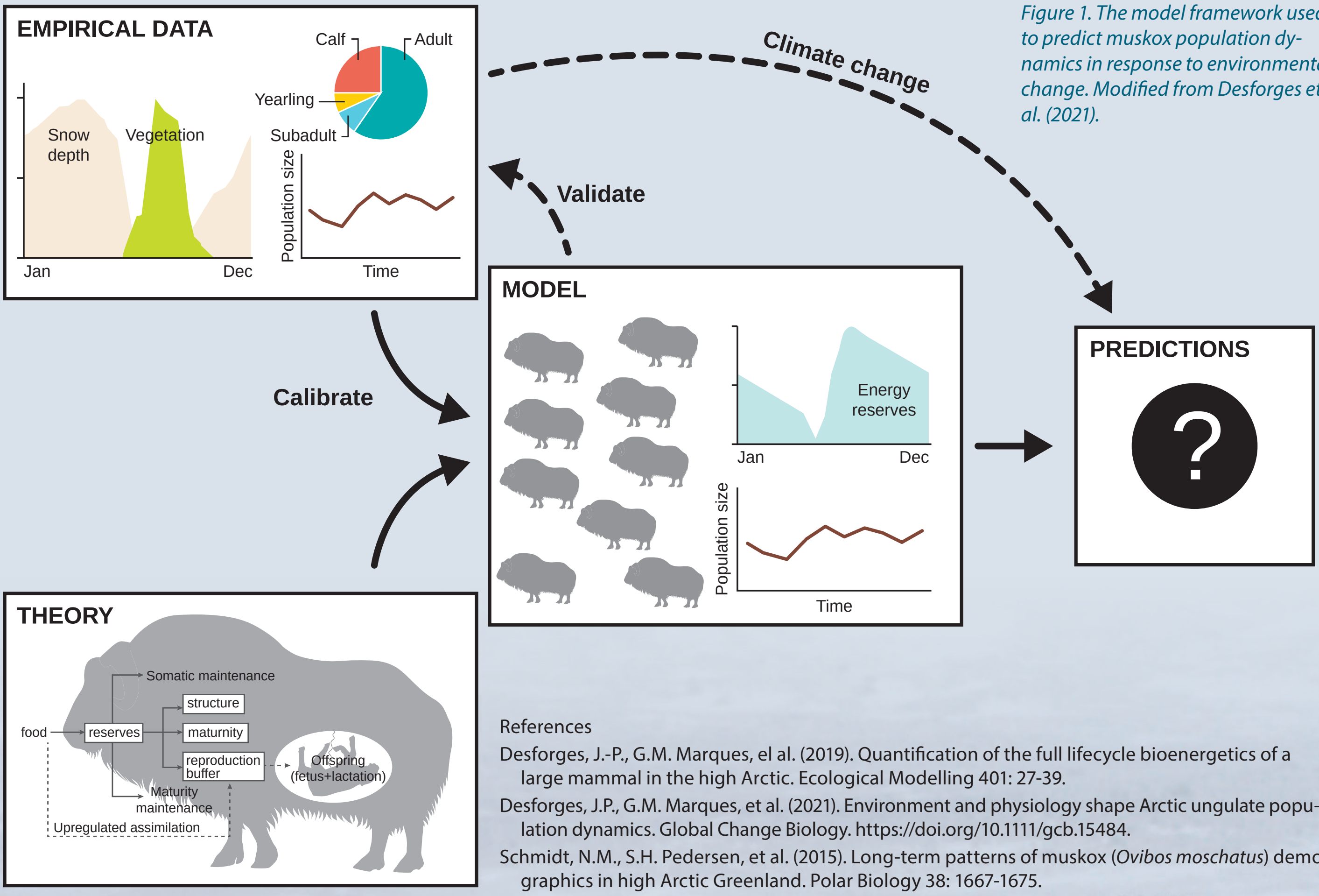

Figure 1. The model framework used to predict muskox population dynamics in response to environmental change. Modified from Desforges et al. (2021).

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Photo: Lars Holst Hansen.

EXTREME DISCHARGE
IN THE ZACKENBERG RIVER

Arctic rivers in Greenland transport freshwater, sediments and dissolved material from glaciers and terrestrial landscapes towards coastal and marine environments. Monitoring data from the Zackenberg river reveals that extreme discharge events play a dominant role in the total annual sediment budgets. The extreme events also show some general patterns depending on the main driver initiating them and on the seasonal timing.

Thermo erosional undercutting along the river bank after an extreme flood event in the Zackenberg river. Photo: Charlotte Sigsgaard

Extreme discharge events initiate many changes in the terrestrial and coastal environments in the Arctic. Sediment transport capacity in rivers increases, the cross-sections of the river alter and valley slopes erode (Tomczyk et al., 2020). They also change the channel configuration on the delta plain and cause increased sedimentation in the fjords where suspended sediment plumes include more sediments and extend over larger areas.

The discharge of glacier-fed rivers strongly fluctuates on a daily and seasonal basis. Most rivers in the Arctic are mainly active during a number of months between river break-up in spring and freezing in fall. Daily variations in solar radiation and air temperature cause daily variations in snow and glacier melt and result in daily discharge variations in the rivers. Cloud cover dampens this temporal variation of the hydrologic regime. Extreme discharge events, defined as periods where the observed discharge is over a threshold discharge, often overrule the regular cycles. Days of intense snowmelt, heavy rainfall, or the sudden drainage of lakes near or on the glaciers, the so-called Glacial Lake Outburst Floods (GLOF; Carrivick and Tweed, 2019; How et al., 2021) can drive these extreme discharge events.

Here we use the collected hydrological GEM monitoring data from 1996 to 2019 for the Zackenberg River. The drainage basin of the Zackenberg River is 514 km^2 of which about 20% is glaciated. The annual precipitation is 230 mm (1996-2019) and the catchment has continuous permafrost. We focus on the characteristics of the extreme discharge events, here defined as periods with discharges over 70 m^3 s^{-1} (Fig.1).

Extreme events at the Zackenberg River show a clear pattern over the season (Fig. 2). The snowmelt events occur in the early runoff season and they often have the lowest discharge peaks and relatively low suspended sediment concentrations in the river. The heavy rainfall events tend to occur later in the season, they have often higher discharge peaks and

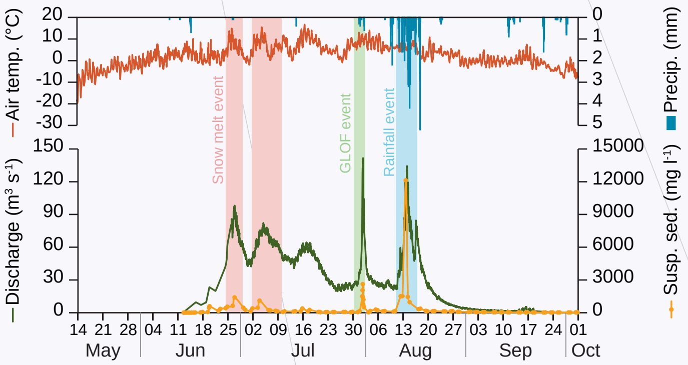

Figure 1. Example of discharge and suspended sediment concentration during extreme discharge events primarily triggered by either rain (blue), snowmelt (red) or lake drainage (GLOF) (green) in 2015 (Zackenberg river). Air temperature and daily precipitation from a local meteorological station.

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Data source:

GEM ClimateBasis

GEM GeoBasis

Data can be accessed on: https://data.g-e-m.dk/

they transport significantly more sediments towards the deltas. The heavy rainfall not only affect the discharge through the main river, but it also increase the input from many smaller streams, and trigger thermo-erosional niching and many mass movements on the slopes like block-falls, slides, slumps and mudflows (Cable et al., 2018). GLOFs have very high peak discharges and occur especially in the mid and later parts of the season. They only affect the main river and flush all sediments through the riverbed towards the delta, and erode the riverbanks, but they do not trigger many other mass movements in the drainage basin. GLOF events have the highest discharge peaks, and shortest duration (Fig. 3) .

Analyses of long time-series of water runoff and associated sediment fluxes in the Zackenberg River show that the extreme events deliver a substantial portion of the annual suspended sediment flux. The average annual runoff is presented in Fig. 4. The associated average annual suspended sediment flux in the period 2005-2012 was 43,000 ± 10,000 $t\ y^{-1}$ (rating curve M2 in Ladegaard-Pedersen et al., 2017). The average suspended sediment flux during extreme events was 17,000 ± 5000 $t\ y^{-1}$, which constitutes a year-to-year variation of 20–37% of the total annual flux. An extreme rain event in 2015 even delivered 58% of the total annual sediment flux (Christensen et al., 2021). However, hydrologic models of partly glaciated drainage basins are still not able to quantify these events. The sediment delivery from the terrestrial part of the drainage basin during extreme events is not included in the hydrological models and the GLOF events are difficult to catch. They are episodic and their timing is hard to predict (Behm et al., 2020). Besides, a GLOF is only running through one catchment (Kroon et al., 2017). Changes in atmospheric conditions do not only trigger these events; the reservoir size and glacier dynamics are other important boundary conditions. Regional weather patterns and local variability over the topography affect the magnitude and timing of intense snowmelt events and heavy precipitation events.

The potential societal implications of extreme events include damage of local infrastructure in the catchment like hydropower installations or water supply.

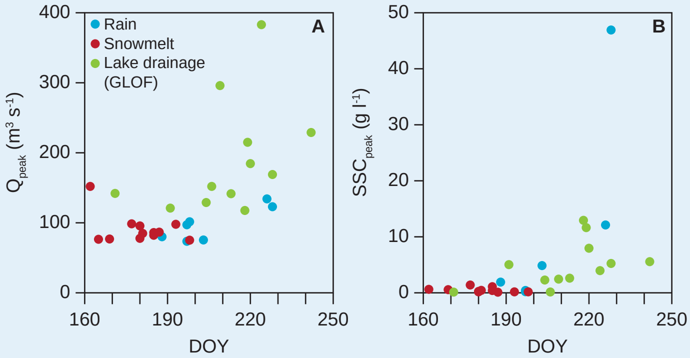

Figure 2. Peak discharge (Q_{peak}) and peak suspended sediment concentrations (SSC_{peak}) of all extreme events primarily triggered by either rain (blue), snowmelt (red) or lake drainage (GLOF) (green) during the runoff seasons in Zackenberg. An event is defined as a period where the discharge is over 70 $m^3\ s^{-1}$. The maximum SSC_{peak} occurred during a rain event in 1998 (46 $g\ l^{-1}$).

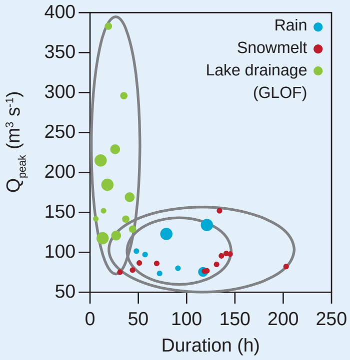

Figure 3. The duration and peak discharge of extreme events during the active river season at Zackenberg; Events primarily triggered by either rain (blue), snowmelt (red) and lake drainage (GLOF) (green). The size of the dots is an indication of the peak suspended sediment concentrations of the extreme events.

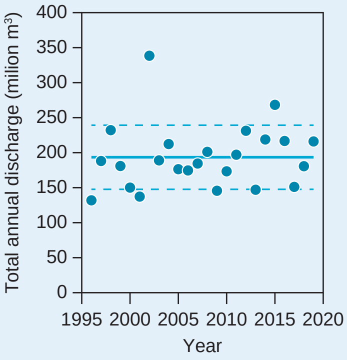

Figure 4. Total annual discharge for the Zackenberg River. The blue line indicates the mean total annual discharge over the period 1996-2019.

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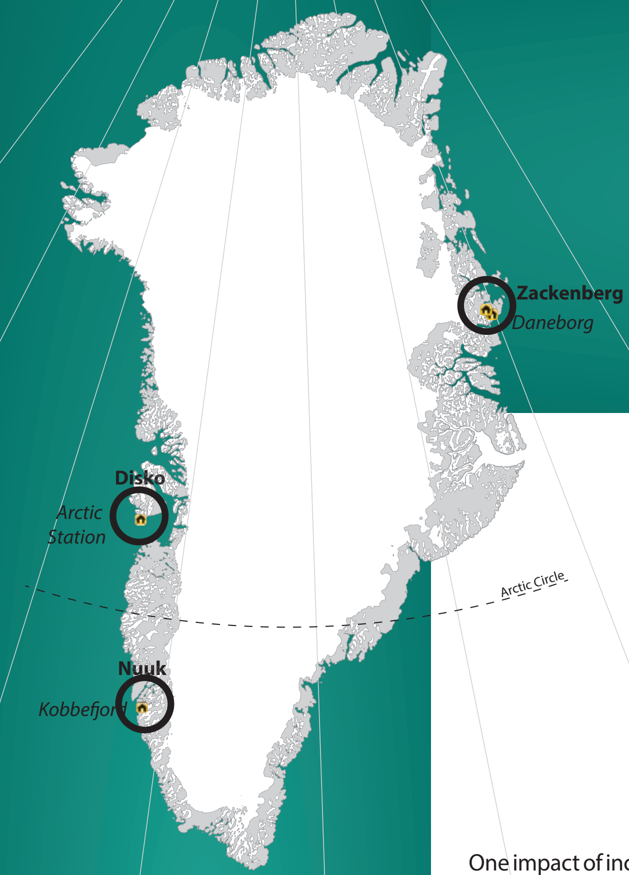
The Zackenberg river during a GLOF in 2016. Photo: Kirstine Skov.



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SOIL TEMPERATURE
CONFIRM PERMAFROST

When Greenland Ecosystem Monitoring started, the projections for future climate suggested a climatic warming in the following decades. Looking back on the data time series, this is now evident; however, we now also have a much improved insight into the magnitude and, vitally, the variability in time and space. This is important because the seasonal nature of temperature changes is key for the derived ecological and societal impacts.

One impact of increasing temperatures can be permafrost thaw. This process is slightly delayed compared to air temperature dynamics, due to a higher thermal inertia in soils. It is also highly dependent on snow, which is an insulating layer between atmosphere and ground, as well as on soil moisture levels. Both of these influencing factors introduce seasonal and annual variability and can act locally [1], with implications for the spatial distribution of permafrost. Data time series long enough to capture this variability are necessary before trends can be assessed.

On a generalized larger scale, however, we can operate with temperature classes to determine the likelihood for permafrost. Assuming a steady-state system, average air temperatures below -5 °C usually indicate the presence of continuous permafrost. Areas with temperatures between -5 to -2 °C indicate discontinuous and -2 to 0 °C sporadic permafrost, respectively [2]. Higher temperatures can usually not sustain permafrost. The GEM core sites cover this gradient, as can be seen from the Geo- and ClimateBasis temperature data. Monthly mean air and ground temperatures (MMAT and MMGT) from Zackenberg are visualized on Fig. 1. Here we observe a statistically significant increase in temperature for both air and ground temperatures (ground temperature is measured at 130 cm depth, close to the permafrost table), yet temperatures are still low enough to sustain continuous permafrost.

In Kobbefjord, near Nuuk, the temperature does not allow for permafrost at low altitudes (Fig. 2). In addition, the relatively high snow depths experienced there insulate the ground from the cold atmosphere during winter, resulting in almost no ground freeze. Therefore GeoBasis focus on soil temperatures at shallower depths in Kobbefjord, with implications for the root zone. The shorter Kobbefjord dataset describes a different, interesting dynamic: while a general warming at or near all three core GEM sites has been observed over the last 25-year period, this is the result of a period with substantial warming in the 1990's, and a period with more stable temperatures in the 2000's and 2010's. The lack of significant temperature change in Kobbefjord since the onset of measurements in 2008 captures the latter part of this period (Fig. 2).

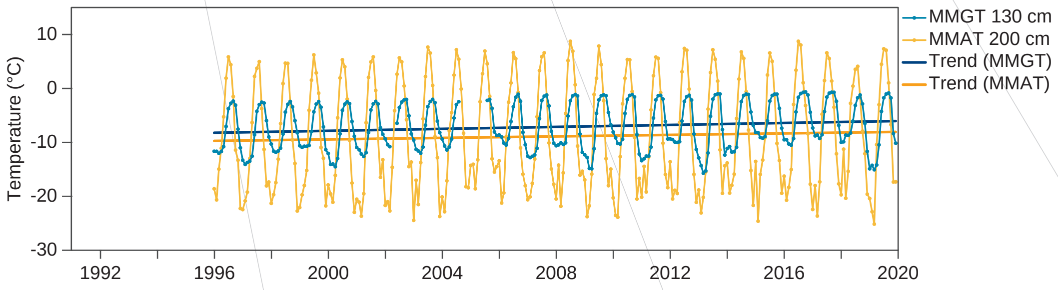

Figure 1. Mean monthly ground (MMGT) and air (MMAT) temperatures from the main Zackenberg climate station. There is a statistically significant increase (Seasonal MannKendall test, p<0.01) through the period, with no statistical difference between air and ground temperature trend. Plotted trend lines are least squares regressions.

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Data source:

GEM GeoBasis

GEM GlacioBasis

Data can be accessed on: https://data.g-e-m.dk/

TRENDS

DEGRADATION

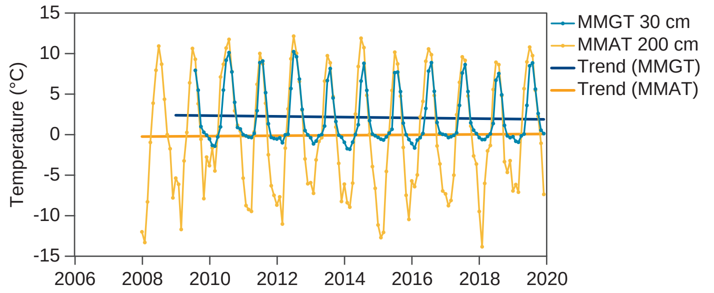

Figure 2. Mean monthly ground and air temperatures from Kobbefjord. There is no statistically significant increase (Seasonal MannKendall test, p>0.05) through the period. Plotted trend lines are least squares regressions.

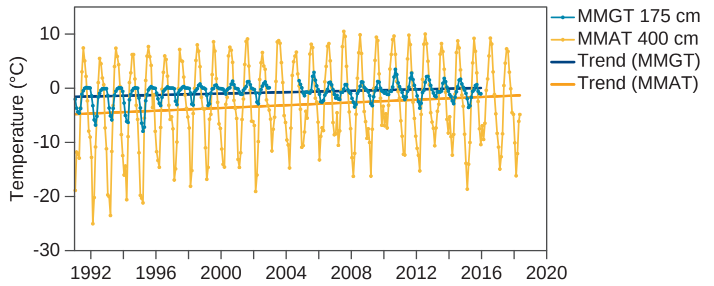

Figure 3. Mean monthly ground and air temperatures from the AWS-1 weather station at Arctic Station, Disko. There is a statistically significant increase (Seasonal MannKendall test, p<0.01) through the period, with no statistical difference between air and ground temperature trend. Plotted trend lines are least squares regressions.

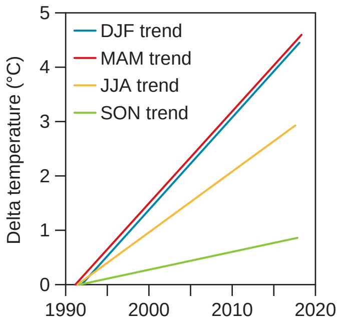

Figure 4. Normalized temperature trends (least squares) per season of air temperatures at AWS-1, Arctic Station. DJF: December-February, MAM: March-May, JJA: June-August, SON: September-November.

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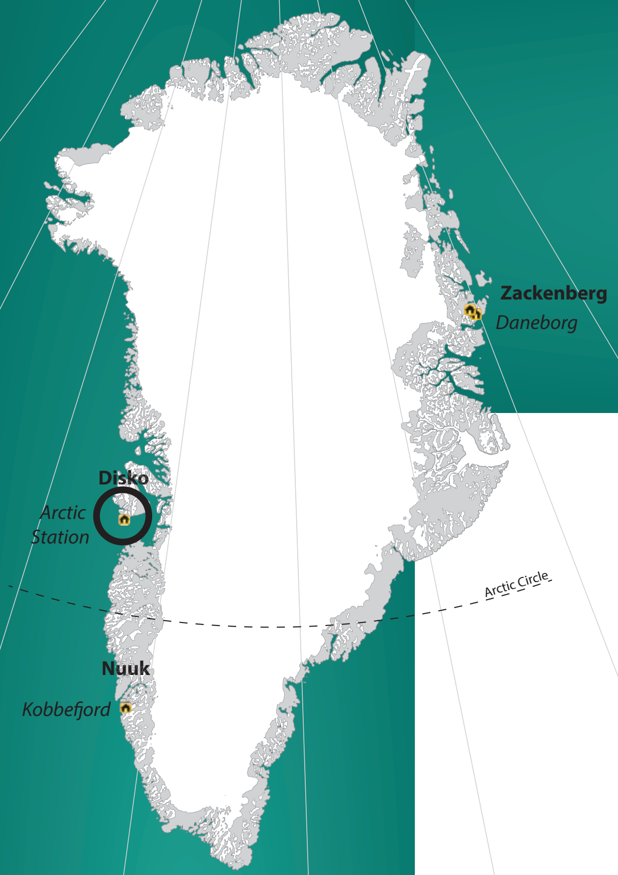
At Arctic Station, Disko, the data captures a shift from a local temperature regime allowing discontinuous permafrost in the early 1990's, to one suggesting no permafrost at the measurement site towards 2020 (fig. 3). At this latitude and temperature regime in Greenland, we therefore expect a current loss of permafrost. While MMGT were below 0 °C in the 1990's, a least squares trend line suggests a critical crossing of this threshold around 2012, although measurements indicate that permafrost was degrading in previous years. The warming at Disko is mainly attributed to a winter and spring warming (fig. 4). In this period, atmospheric temperatures have less direct impact on active layer thaw depth and permafrost due to an insulating snow cover. However, we also observe a summer warming on the same order of magnitude as the temperature increase of MMGT, and in this period, an atmospheric warming will have direct effects on ground temperatures.

Looking back on the GEM monitoring period, the long-term air and ground temperature changes required to observe thawing permafrost is being captured, but equally important are the manual probing or georadar surveys necessary in order for spatial assessments of the permafrost state to be made. The combined time series allow for new studies related to changing permafrost conditions such as: what impact does permafrost thaw have on the soil organic carbon pool? How does it alter hydrology and thereby redistribution of nutrients and water for vegetation? And where is the permafrost likely to disappear in Greenland during the coming decade, with implications for infrastructure?

Manual probing is critical for a spatial assessment of local permafrost condition. Photo: Christian Juncher Jørgensen.



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ADVANCING SPATIO- ESTIMATES WITH THE GEM

Surface- and soil moisture have a fundamental effect on the abiotic processes determining for example photosynthesis, respiration, nutrient uptake and earth surface processes. The moisture levels in the soil are important to understand the complex ecosystem dynamics under a changing climate (Aalto et al., 2013). However, soil moisture varies significantly in both time and space, and it is essential to have frequently sensed data in order to capture the dynamic process. At the same time, the ecosystem processes linked to soil moisture often vary locally, underlining the relevance of a detailed spatial resolution. In line with the Remote Sensing efforts in GEM, work has therefore started on developing a calibrated Topographic Wetness Index driven from satellite data and calibrated with GEM *in-situ* ***measurements.***

Here we show work in progress exemplified from Blæsedalen, Disko. There is no publicly available product that offer both a high temporal and spatial resolution, but MODIS (daily overpasses) and the MSI aboard Sentinel-2 (10 m spatial resolution) fulfill each of the demands independently. With the help of the Enhanced Spatial and Temporal Adaptive Reflection Fusion Model (ESTARFM) we are able to create synthetic Sentinel-like imagery with the temporal resolution of MODIS data (Fig. 1). The method, developed by Zhu et al. (2010), aims at predicting surface reflectance based on spectral, temporal and spatial information from a set of input images. Initially, the algorithm selects similar neighboring pixels, then weights are calculated for similar pixels, and subsequently a conversion coefficient is calculated for the calculation of reflectance of the central pixel. As this method usually is applied in phenological analyses, we also explore the model's applicability in snow cover mapping. The resulting snow depletion curve, based on snow cover classifications (based on Normalized Difference Snow Index, NDSI) from the synthetic sentinel data, indicates that the model performs adequately (Fig. 2).

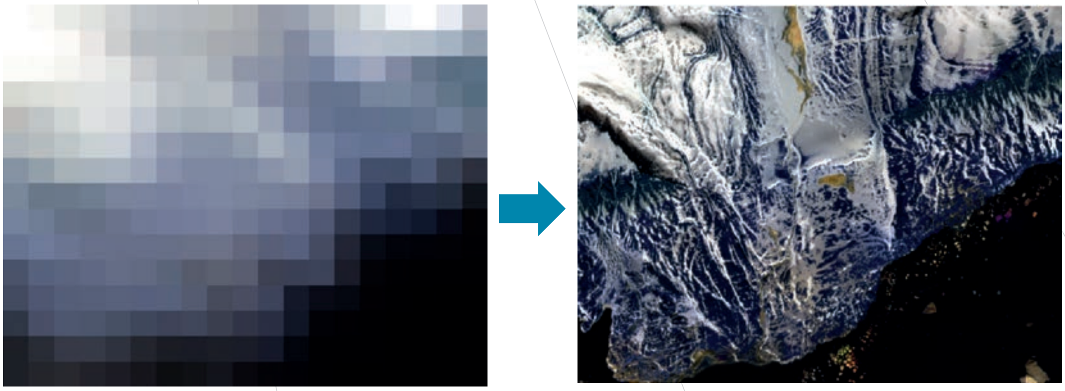

Figure 1. Green, red, and near-infrared band composite of May 3rd 2019 from MODIS at 500 m resolution (left), and synthesized 10 m resolution image aligned with Sentinel-2 (right). The downscaled image is created using ESTARFM.

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Data source:

GEM GeoBasis, BioBasis and the Remote Sensing initiative

Data can be accessed on: https://data.g-e-m.dk/

TEMPORAL SOIL MOISTURE
REMOTE SENSING INITIATIVE

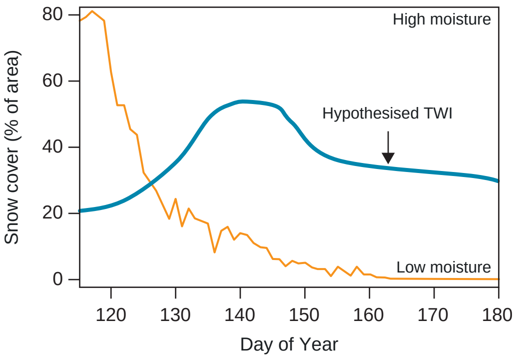

Figure 2. The combination of actual Sentinel-2 scenes (up to bi-weekly overpasses) and synthesized images based on MODIS allow for a high temporal resolution snow depletion based on NDSI and corresponding modelled meltwater runoff (full orange line). The snow melt results in elevated surface moisture, which translate into increased topographic wetness index (TWI, blue line), which is used to estimate soil moisture. We hypothesise a delayed temporal pattern compared to the snow melt water.

Topography plays a dominant role in controlling soil moisture and several terrain-based topographic wetness indices (TWIs) have been proposed to predict the spatial variability of soil moisture. The main limitation to these indices is their static nature and thus their inability to assess the temporal variability of the soil moisture (Temimi et al., 2010). A solution to this issue is the use of ancillary data, such as satellite imagery. In the Arctic, soil moisture in the early summer is directly influenced by snow conditions and snow melt in the spring. Due to this, a wetness index applicable in the Arctic could benefit from including information of where the flow of the melted snow has accumulated which we have previously modelled at very high resolution in Blæsedalen (Westergaard-Nielsen et al. 2020). Additionally, NDVI – an index for quantifying green vegetation – gives us insight into where the landscape is green. This is valuable information because a healthy, green vegetation indicates a higher moisture content in the soil during the summer growing season. With the inclusion of the flow accumulation of melt water and the greening of vegetation, the proposed topographic wetness index is expected to greatly improve its applicability in the Arctic zone as a proxy for soil moisture (Fig. 3) compared to previous formulations.

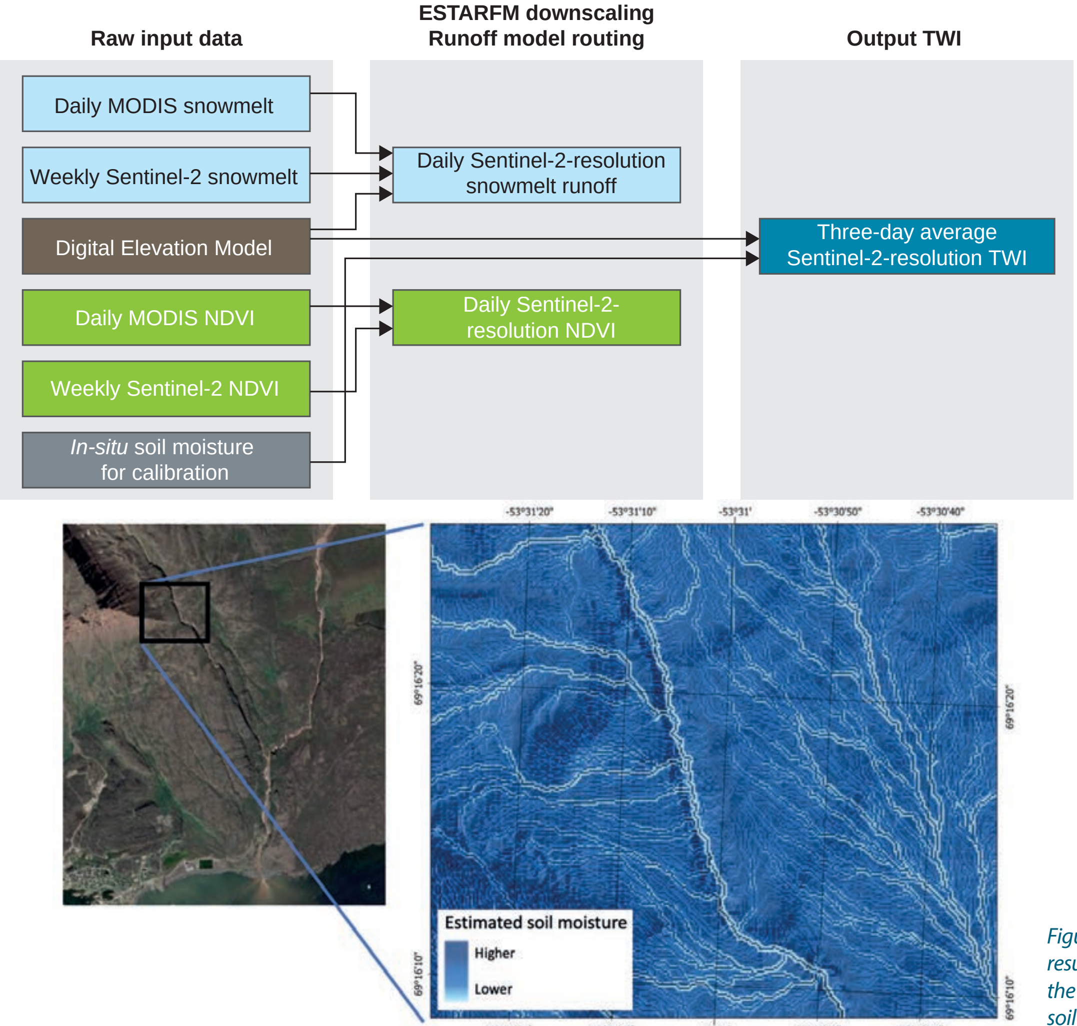

Figure 3. Input data, workflow and output result from May 3rd 2019, as an example from the edge of Blæsedalen, Disko. The estimated soil moisture is resulting from a calibration of the TWI with in-situ soil moisture data.

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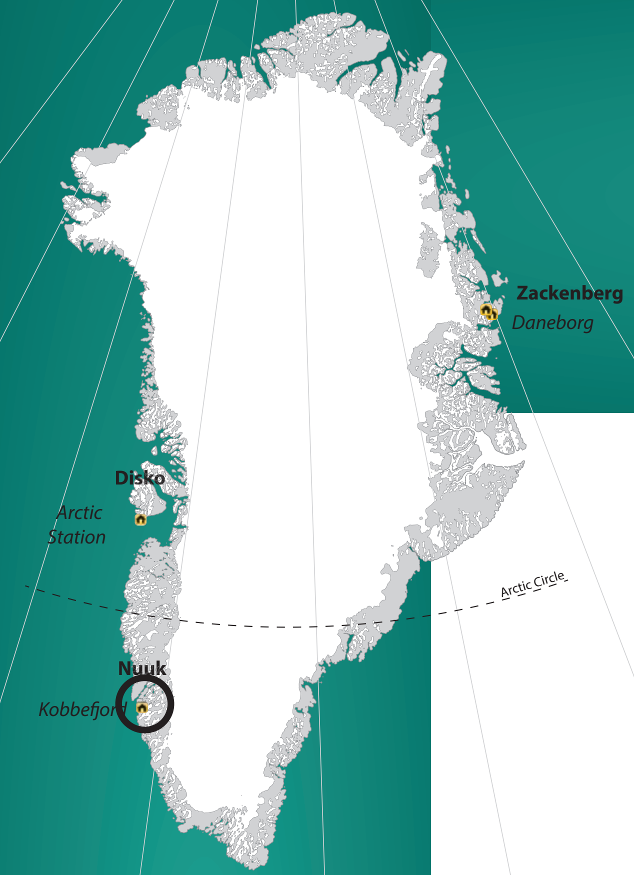

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HOW MUCH WATER FLOWS
SURPRISES FROM KOBBEFJORD,

The higher the resolution of our data gets, the more we learn about the complexity of the systems we study. Discharge in Kobbefjord is a good example of this in that we recently showed that both the magnitude and timing of discharge in four neighbouring catchments (less than 15 km apart) vary a great deal. We understand the drivers and plan to use this knowledge to statistically improve our spatial understanding of discharge variability in Greenland.

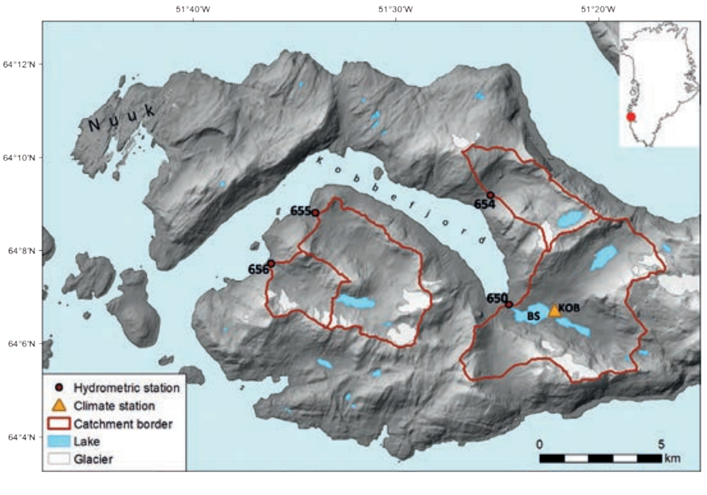

Figure 1. The study area with the studied catchments outlined in red. Digital Elevation Model Data stem from Porter et al. (2018). Kobbefjord climate station (KOB), lake Badesø (BS) and the location of the discharge stations (650, 654, 655, 656) are shown.

When we began monitoring in Kobbefjord 15 years ago, our intention was to improve our understanding of the ecosystem in that fjord and use it as a role model to show the complexity in ecosystem compartments in Greenland. Freshwater is vital in this context because it is the nourishing vein that leads from all terrestrial areas to the marine ecosystem. The choice of a measurement location was easy. One clear priority was the main river that drains the basin, where all other basin programmes are established at the head of the fjord. In addition, however, we chose to measure discharge at three further streams that were less than 15 km apart and feed into the fjord (see Fig. 1). After many years of autonomous data collection, coupled with vital manual discharge measurements, we are now able to present the water balance for the entire fjord. With this, we are able to a) relate runoff characteristics to catchment characteristics in general, b) assess spatial differences in climate and c) study differences in the diurnal freshwater input into the fjord.

Prior to these measurements, no one could answer the following apparently simple question: at what time of the day does most water flow in the rivers, and is that the same for all catchments? We can now state with high confidence that this is very complicated. During sunny days, the maximum discharge arrives around 6–11 hours later at the fjord bottom (650) than it does, for instance, at 654. However, this varies considerably throughout the season, and snow melt, in particular, impacts this shift. Locals and sailors know that the weather changes a great deal between Nuuk and the inner part of Kobbefjord. This notion is backed up by our data, and we show that total discharge is far higher in the outer part of the fjord than the inner part. Although we do not have a high density of precipitation measurements, we can deduce this part of the water balance from the discharge measurements. In the future, further land ice will be lost in Greenland. Catchments that are highly ice-covered now will, in the future, more and more resemble the situation in Kobbefjord. In that sense, we can understand our work as a space-for-time analogy and expect the complexity of discharge generation seen to occur in many areas in Greenland in the future.

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Data source:

GEM ClimateBasis

Data can be accessed on: https://data.g-e-m.dk/

AT WHAT TIME OF THE DAY?

A LOW ARCTIC FJORD IN GREENLAND

Catchment characteristics:

Fig. 2 shows the different catchment characteristics and indicates heterogeneity in hypsometry, position of lakes, aspect and slope.

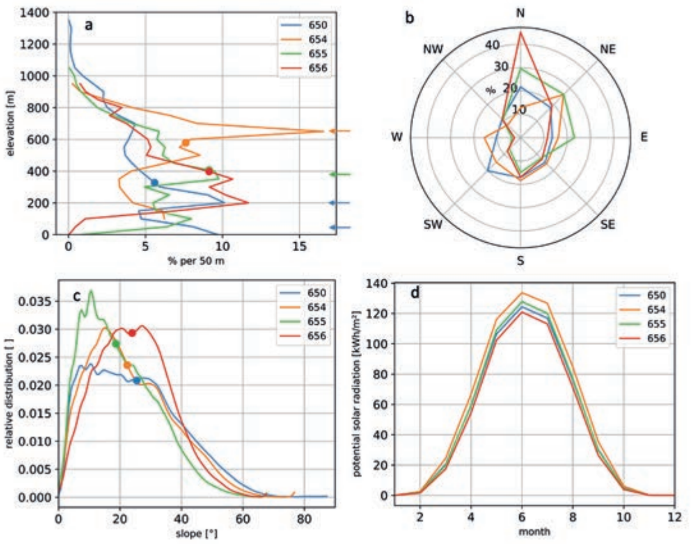


Figure 2. a) Relative hypsometry (i.e., the measurement of land elevation) of the studied catchments in 50 m bins based on the ArcticDEM; the respective median elevation is marked with a dot; heights above mean sea level are shown. The coloured arrows indicate the elevation in which a lake of a respective catchment is situated. Note that the two lower lakes of catchment 650 are in the same elevation band; hence, a single arrow indicates both those lakes. b) Polar diagram of each catchment's relative aspect distribution in % per aspect segment. The grouping was made in 45° increments around the eight cardinal and intercardinal directions. 'NE' means, for instance, that the respective area is directed toward the NE, which is, in this case, the pixels with an azimuth of between 22.5° and 67.5°. c) Slope distribution (°); the median slope is marked with a dot. d) Average potential incoming solar radiation (kWh/m²) for each catchment, averaged for each month of the year.

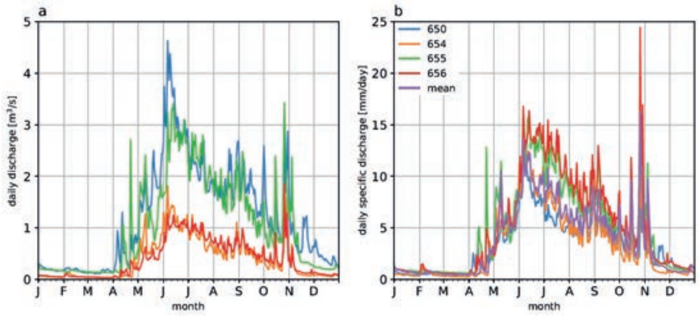


Figure 3. Average annual cycle for the 2008–2019 period for a) daily discharge (m³/s) and b) daily specific discharge (mm).

Spatial differences in climate

Precipitation measurements are scarce and prone to large errors, particularly when snow and/or wind is involved. Discharge is directly connected to precipitation in a given catchment. In Fig. 3 we show that both absolute and specific discharge vary strongly. While absolute discharge is less of a surprise because the individual catchments have different sizes, the differences in specific discharge are more interesting. Spatial differences in precipitation are the main influences and provide more discharge for the catchments closer to the coast. Late in the season, when the impact of snow melt becomes weaker, these differences are also reduced.

Difference in timing of diurnal freshwater input

Finally, with the data that we have, we can show that a time-lag between maximum discharge peaks among the catchments exists in the range of up to 11 hours during fair-weather days (Fig. 4) and slightly less for strong precipitation events. This is surprising and highly relevant for several ecosystem-relevant processes. We recently compiled the main findings of this study into an overview article and plan to use the improved knowledge of spatial and temporal heterogeneity in an upscaling context at the Greenland scale.

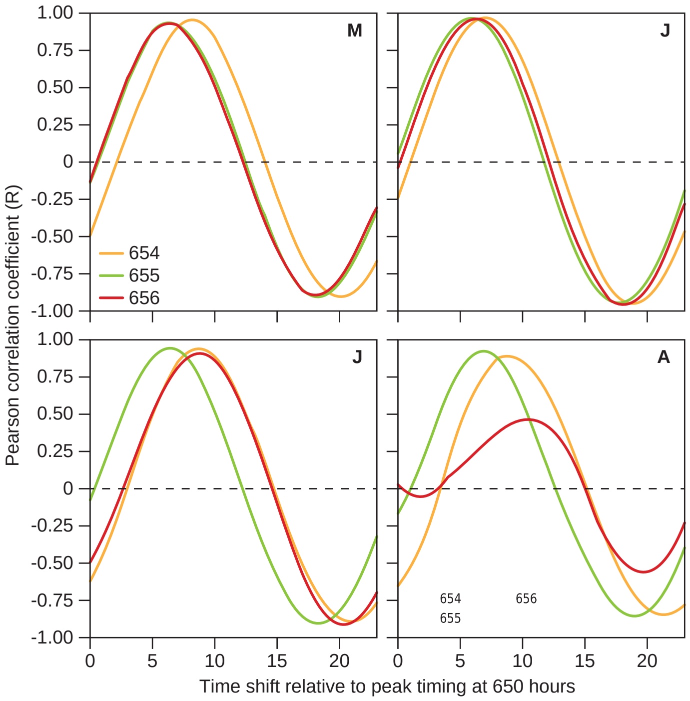
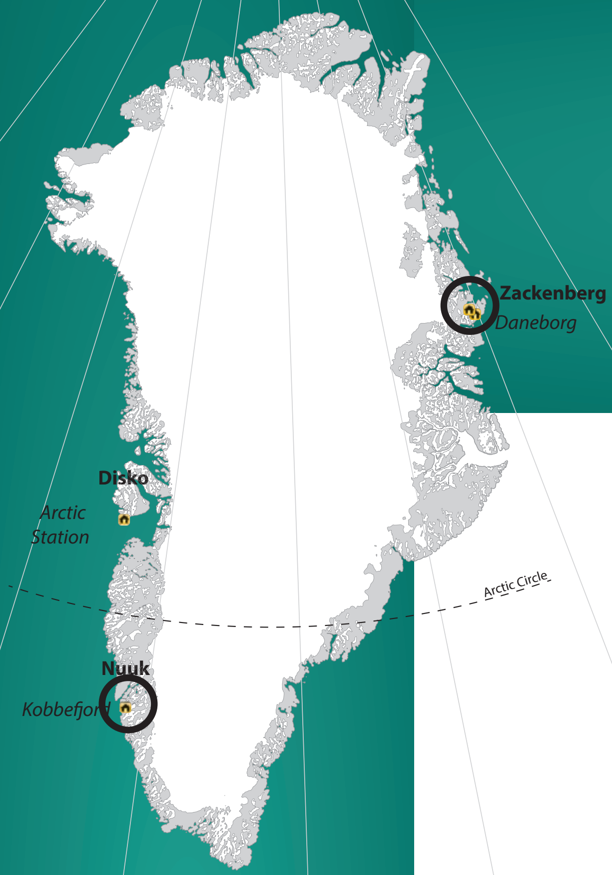


Figure 4. Pearson's correlation (R) between 650 and the other catchments, depending on a temporal cross-correlation of 650 for the months from May to August for discharge during 'fair-weather' days. The maximum of R reflects the time lag of 650 relative to the respective station. A time shift of 10 means, for instance, that the median values of discharge are shifted 10 hours earlier.



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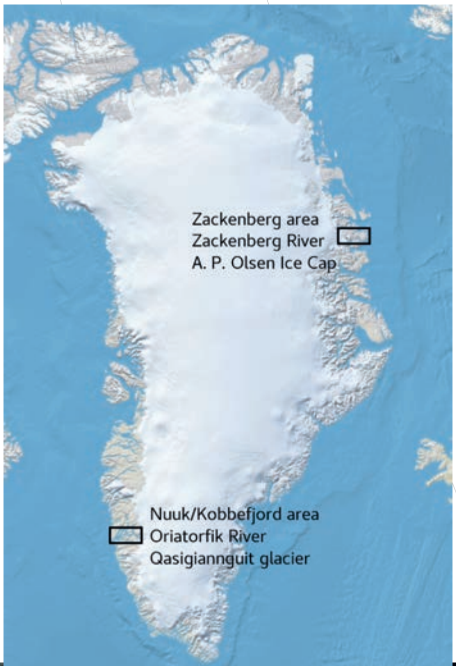
THE ROLE OF
IN RIVER DISCHARGE

Glaciers act as a freshwater reservoir in glaciated catchments, storing excess snow accumulation in the form of ice over years to millennia. The presence of glaciers in a catchment ensures a baseline supply of freshwater throughout the melt season. In dry periods, glaciers may be the only water supply. Runoff affects not only the ecosystem on land but also the fjord/oceans, where sediments and nutrients are ultimately transported along with the glacier meltwater. By combining the field measurements from the past decade with modelling, we show how the fraction of discharge in glaciated catchments in Zackenberg (NE Greenland) and Kobbefjord (SW Greenland), which is sourced from the glacier meltwater, varies seasonally and over the course of the year.

The water discharge in the Zackenberg River includes meltwater from several glaciers in the catchment, of which A.P. Olsen ice cap (APO) is by far the largest (Fig. 1a). The runoff from APO mostly drains directly into the river, where it, c. 15 km downstream, passes into the Store Sødal lake and, after a further 20 km, flows by the hydrological station at Zackenberg research station and out into Young Sound. A small part of the meltwater from the ice cap is temporarily stored in a glacier-dammed lake. Glacier lake outburst floods (GLOFs) from this lake occur at irregular intervals but approximately once a year. In Kobbefjord, the glacier Qasigiannguit lies within the upper reaches of the Oriatorfik river catchment (Fig. 1b), also referred to as site 654 (see also page 20-21). At both locations, the glacier and river have been monitored closely by the GlacioBasis, ClimateBasis and GeoBasis programmes. The third GlacioBasis site, Chamberlin Glacier on Disko Island, is not included here due to the shorter time series.



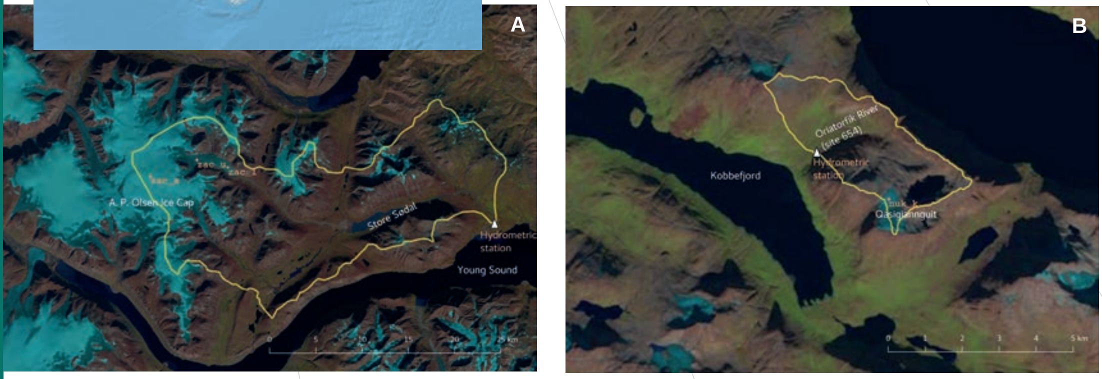


Figure 1. A) Zackenberg river catchment showing the location of the automatic weather stations (zac_l and zac_a) and the hydrometric station where the river discharge is monitored. Precipitation is measured at the ClimateBasis station, close to the hydrometric station. B) Oriatorfik river catchment showing the location of the automatic weather station (nuk_k) and the hydrometric station where the river discharge is monitored. Precipitation is measured at the ClimateBasis station, at the head of the fjord.

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Data source:

GEM GlacioBasis

Data can be accessed on: https://data.g-e-m.dk/

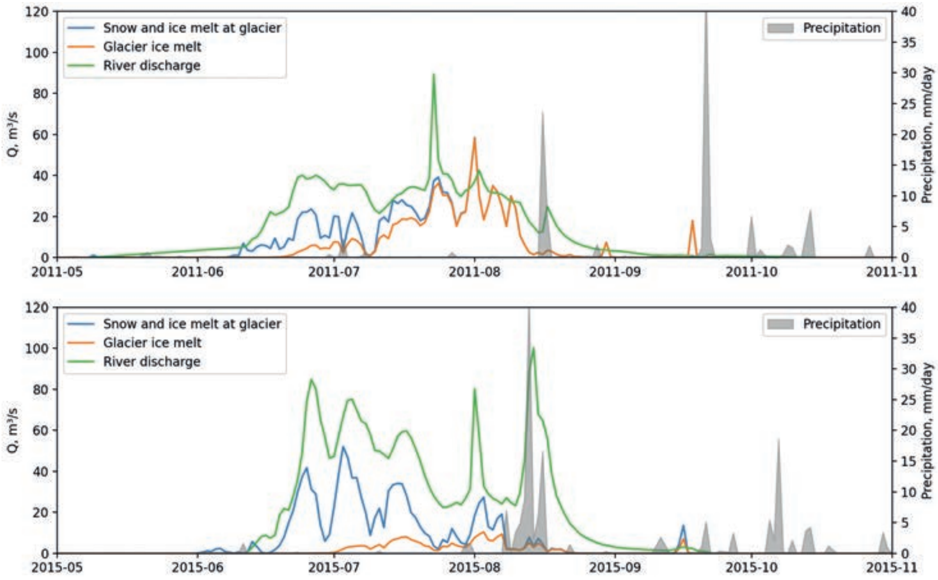

Figure 2. Calculated melt at A.P. Olsen ice cap divided into total melt (blue) and ice melt (orange) as compared with observed discharge in the Zackenberg River and precipitation observed near the hydrometric station.

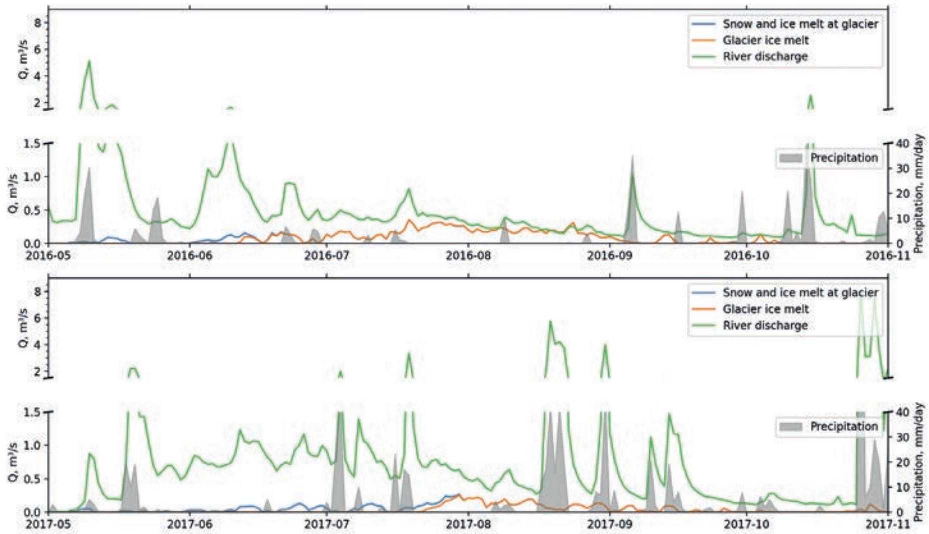

Figure 3. Calculated melt at Qasigiannguit glacier divided into total melt (blue) and ice melt (orange) as compared with observed discharge in the Oriatorfik River and precipitation observed in Kobbefjord.

Glacier runoff, from melting of snow and ice on the glaciers, is calculated using the statistical relationship between temperature and snow/ice melt (as in Hock, 2003). The model utilises daily mean temperatures observed at the automatic weather stations on the glaciers (zac_l and zac_a, on APO and nuk_k on Qasigiannguit) and is calibrated using automatic point observations of glacier snow and ice melt. The approach calculates the combined amount of snow and ice melted for the area of the two glaciers that drains into the monitored rivers. There are, in the presented calculations, no considerations of the intermediate storage of the water or transport time from the ice cap to the discharge observation site.

On average, meltwater from APO is estimated to be responsible for around 40% of the annual discharge from The Zackenberg River, and meltwater from Qasigiannguit totals around 8% of the Oriatorfik River catchment near Nuuk. The fraction is usually smallest in June (around 27% at Zackenberg and 8% in Nuuk), when the river discharge is dominated by snowmelt from the entire hydrological catchment. There is an increasing fraction of meltwater originating from the glaciers through July and August. The glacier meltwater contribution to discharge in August averages around 50% at Zackenberg and 14% at Nuuk; however, for some years, these numbers reach up to 61% and 74%, respectively. The years when meltwater from glaciers contributes most to river discharge are those with little winter accumulation. Examples of this are shown in Fig. 2 for the Zackenberg River and Fig. 3 for the Oriatorfik River. For the Zackenberg River, the low winter accumulation year of 2011 (Fig. 2, top panel) is compared with a year with high winter accumulation, 2015 (Fig. 2, lower panel), and for the Oriatorfik River, the low accumulation year of 2016 (Fig. 3, top panel), is compared with the high accumulation year of 2017 (Fig. 3, lower panel). It is clear, for both sites, that meltwater from glaciers provides an important contribution to the river discharge in late July and August and even dominates in low accumulation years.

In broad terms, this means that both the Oriatorfik and Zackenberg Rivers would be significantly smaller or even dry for periods of the late summer if there were no glaciers. Thus, the present ecosystem, both on land and in the fjord, is highly influenced by the presence of glaciers and, thus, also changes in the meltwater runoff from these. The global warming trend has been seen, in many regions, to reduce the area of glaciers, resulting in a decreasing amount of meltwater from glaciers. Thus, it is essential to understand glacial changes in order to understand how future climate changes will impact the ecosystem.

References:

Hock, R. (2003). Temperature index melt modelling in mountain areas, Journal of Hydrology 282, doi:10.1016/S0022-1694(03)00257-9

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GEM CLIMATEBASIS

The ClimateBasis programme monitors climate and hydrology in Zackenberg, Kobbefjord and Disko and is run by Asiaq - Greenland Survey. The collected data build base-line information on climate variability and trends for all the other sub-programmes within GEM and serve as a trustworthy foundation for adaptation strategies for the Greenlandic society. The stations are embedded in Asiaq's extensive climate and hydrology monitoring network. Furthermore, the runoff data is delivered to the World Hydrological Cycle Observing System (WHYCOS) and the Global Runoff Data Centre (GRDC) networks. Atmospheric parameters are collected redundantly at each location on two separated masts with individual energy supplies in order to be able to treat data gaps and sensor biases consistently. Hydrometric parameters are monitored on various automated stations. Emphasis is placed on the establishment of reliable stage-discharge relations, a challenging task since their temporal stability depends on the river bed. At the river Zackenberg for instance, repeated glacier outburst floods require an updated stage-discharge relation every year, where the related field work is performed together with the GeoBasis sub-programme.

In 2020, the annual mean temperature deviated only slightly from the 2008-2020 average at the three GEM sites (-0.2°C, 0.2°C and 0°C at Kobbefjord, Disko and Zackenberg respectively). It was on average a cooler year on the West coast (Kobbefjord and Disko) compared to 2019, while on the East coast (Zackenberg), the mean annual temperature has been approximately constant since 2017. The temperature record highlights the very different temperature regimes found at the 3 locations with mean annual temperatures way below zero at Zackenberg, a few degrees below zero at Disko and around zero in Kobbefjord. The interannual variability in Zackenberg is notably less than at the other two stations, especially in the last 4 years.

At all sites, temperatures in April and May were above average, and for the second year running, Zackenberg experienced the warmest April since 2008. However compared to all years in the GEM database, there were no record months with respect to temperatures at any of the stations in 2020.

Monitored parameter groups

- Air Temperature
- Air Humidity
- Air Pressure
- Precipitation
- Radiation
- Wind
- River hydrology
- Snow properties
- Fractional cloud cover
- Column-integrated water vapour

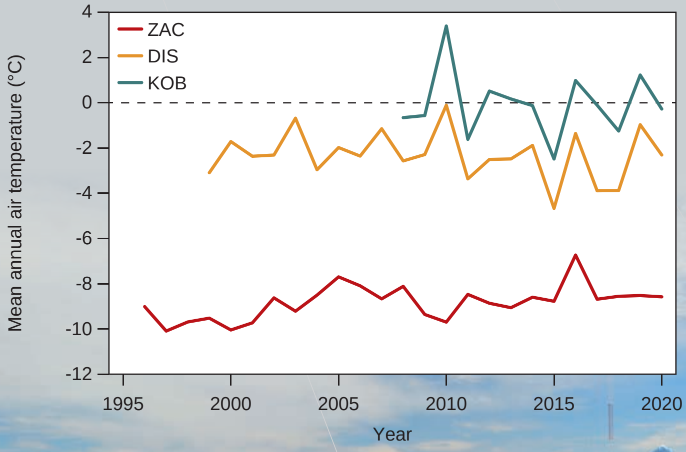

Figure 1. Mean annual air temperature at the three GEM sites Zackenberg (ZAC), Disko (DIS) and Kobbefjord (KOB).

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PROGRAMME DESCRIPTION

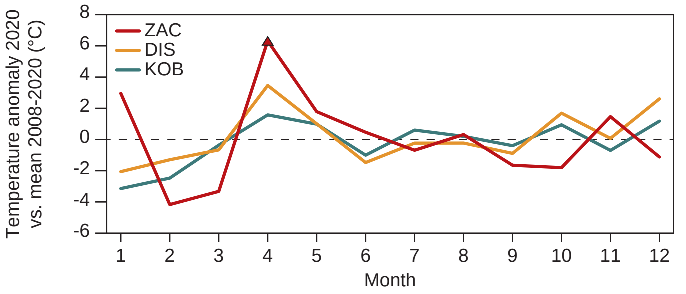


Figure 2. Monthly air temperature anomaly for 2020 compared to the common reference period 2008-2020 for Zackenberg (ZAC), Disko (DIS) and Kobbefjord (KOB). A triangle marks a month whose mean temperature has been more extreme than those of the corresponding month in any other year from 2008-2020. The upward pointing triangle indicates that the month has been the warmest in this period.

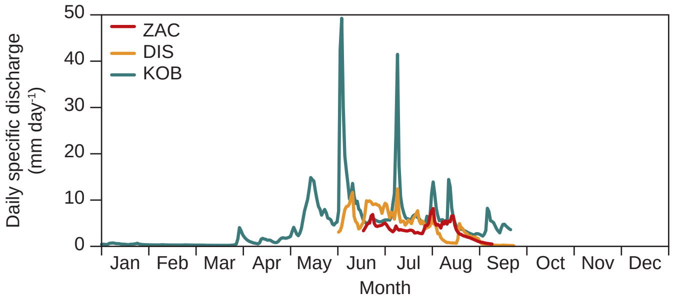


Figure 3. Specific daily discharge (runoff per unit area) at the three GEM sites: Zackenberg (ZAC), Disko (DIS) and Kobbefjord (KOB) for 2020. In winter, ZAC has no flow and DIS no winter instrumentation, while KOB shows year-round discharge. In most years, the specific discharge at Zackenberg is lower than in Disko and Kobbefjord, corresponding to a drier climatic regime.

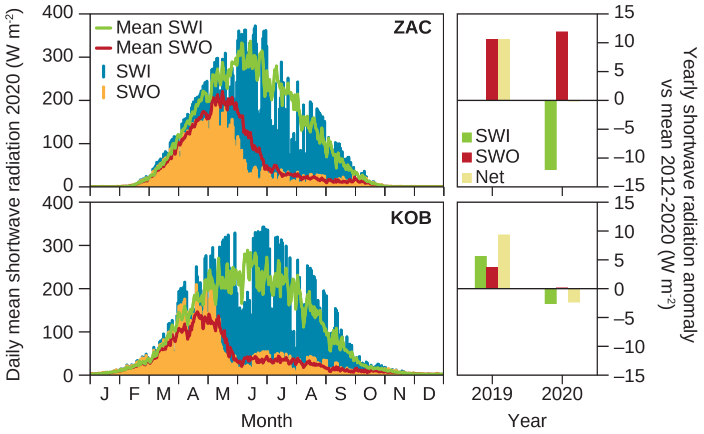
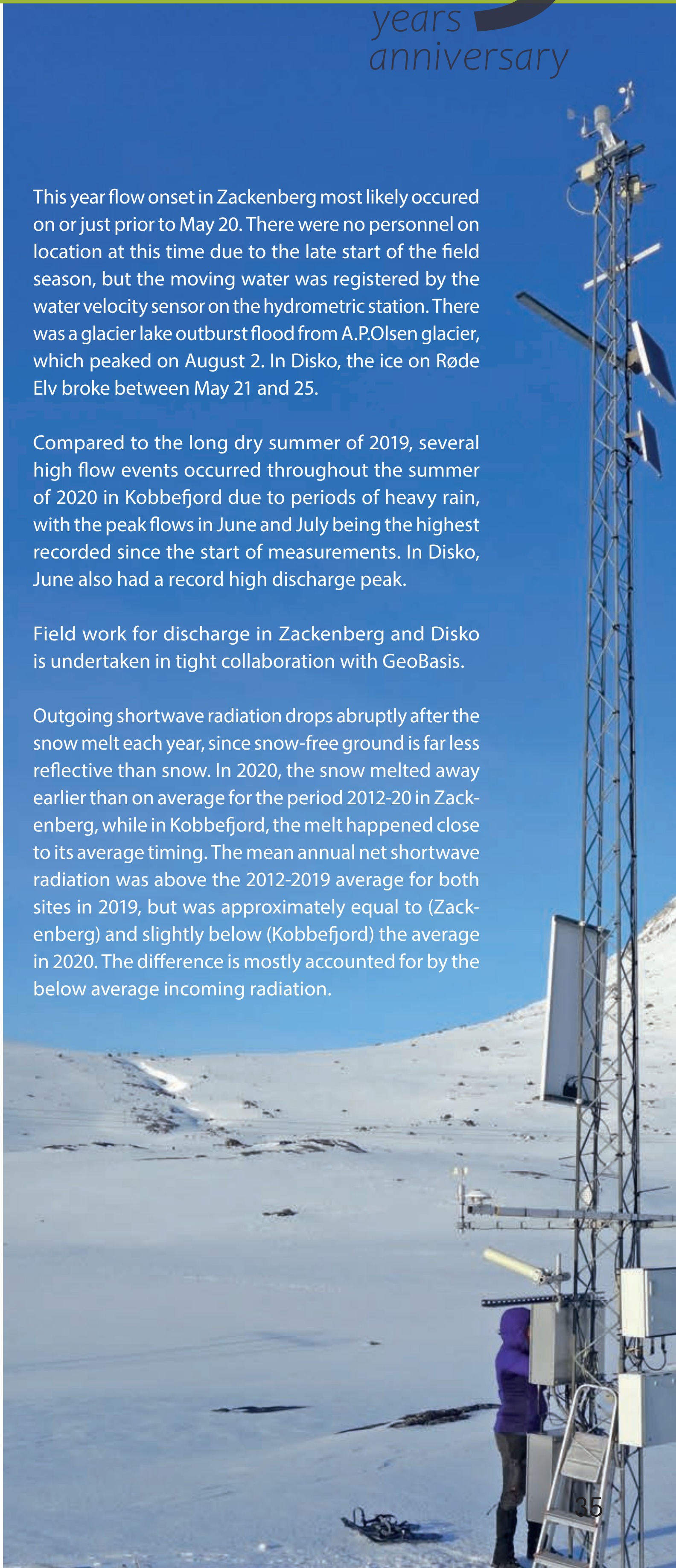


Figure 4. Main plots: Daily mean shortwave incoming radiation (SWI) and shortwave outgoing radiation (SWO) in 2020 with their respective daily means for the period 2012 to 2020 (SWI mean and SWO mean) for Zackenberg (ZAC) and Kobbefjord (KOB). Bar plots (right columns) show yearly mean anomalies for the two most recent years, with outgoing radiation (SWO) taken to be negative, so that the net radiation is simply the sum of SWI and SWO.

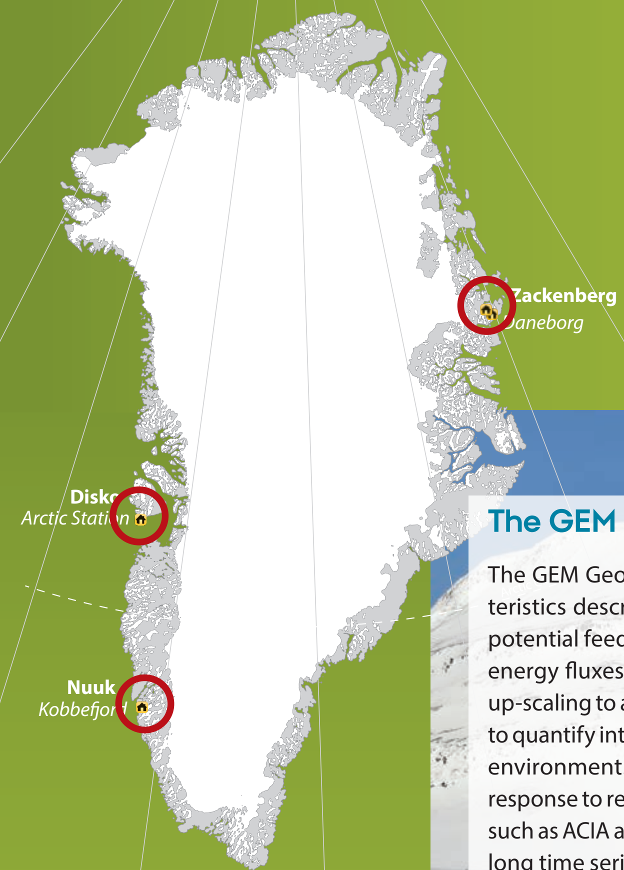


This year flow onset in Zackenberg most likely occured on or just prior to May 20. There were no personnel on location at this time due to the late start of the field season, but the moving water was registered by the water velocity sensor on the hydrometric station. There was a glacier lake outburst flood from A.P.Olsen glacier, which peaked on August 2. In Disko, the ice on Røde Elv broke between May 21 and 25.

Compared to the long dry summer of 2019, several high flow events occurred throughout the summer of 2020 in Kobbefjord due to periods of heavy rain, with the peak flows in June and July being the highest recorded since the start of measurements. In Disko, June also had a record high discharge peak.

Field work for discharge in Zackenberg and Disko is undertaken in tight collaboration with GeoBasis.

Outgoing shortwave radiation drops abruptly after the snow melt each year, since snow-free ground is far less reflective than snow. In 2020, the snow melted away earlier than on average for the period 2012-20 in Zackenberg, while in Kobbefjord, the melt happened close to its average timing. The mean annual net shortwave radiation was above the 2012-2019 average for both sites in 2019, but was approximately equal to (Zackenberg) and slightly below (Kobbefjord) the average in 2020. The difference is mostly accounted for by the below average incoming radiation.



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GEM
GEOBASIS

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The GEM GeoBasis Program

The GEM GeoBasis monitoring programme focuses on selected abiotic characteristics describing the state of Greenlandic terrestrial environments and their potential feedback effects in a changing climate (e.g. effects of permafrost thaw, energy fluxes and greenhouse gases). Monitored plot data provides a basis for up-scaling to a landscape level and improvements of ecosystem models to be able to quantify interactions in relation to the atmosphere and also the adjacent marine environment. The GeoBasis program provides an active response to recommendations in international assessments such as ACIA and SWIPA with due respect to maintenance of long time series; and a continuous development based on AMAP and other international recommendations.

Monitored parameters

Snow properties

- Snow properties
- Snow cover
- Snow depth
- Snow density

Soil properties

- Thaw depth/Active layer development
- Soil/ground temperature
- Soil moisture
- Soil water chemistry

Meteorology

- Air temperature and relative humidity
- Wind speed and direction
- Incoming and outgoing long- and shortwave radiation

Flux monitoring

- Eddy covariance measurements of CO_2, water vapor and energy
- Automatic chamber measurements of CH_4 and CO_2

Hydrology

- River water discharge
- River water chemistry and transport of suspended sediment and organic matter

Geomorphology

- Shore line mapping
- Mapping of landscape dynamics and erosional features

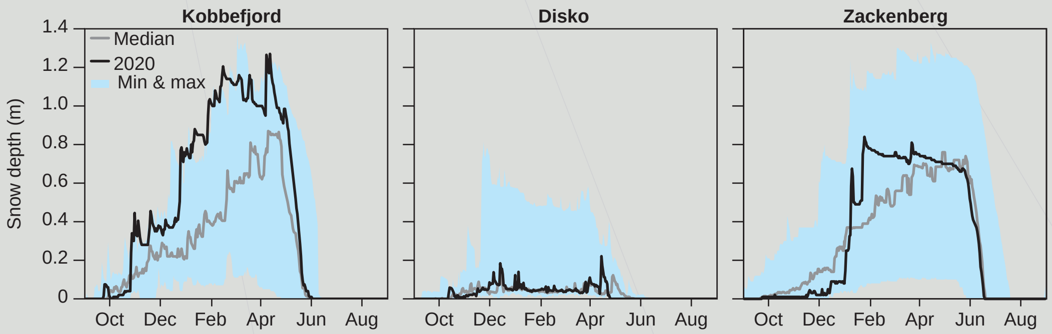

Figure 1. Daily snow depth measurements in 2020. (black lines) compared to min and max for the historical record (shaded area) and the median (gray line). Snow is a key parameter in Arctic ecosystem functioning. Thus, several different monitoring methods are put in place to get information on spatial distribution and temporal patterns in snow cover, across the three GEM sites. Methods include time-lapse photography, transect surveys, snow density measurements and, as shown here, long-term point-based monitoring of snow depth. Data used in the figure: Kobbefjord: 2008-2020, Disko: 2012-2020 and Zackenberg: 1997-2020.

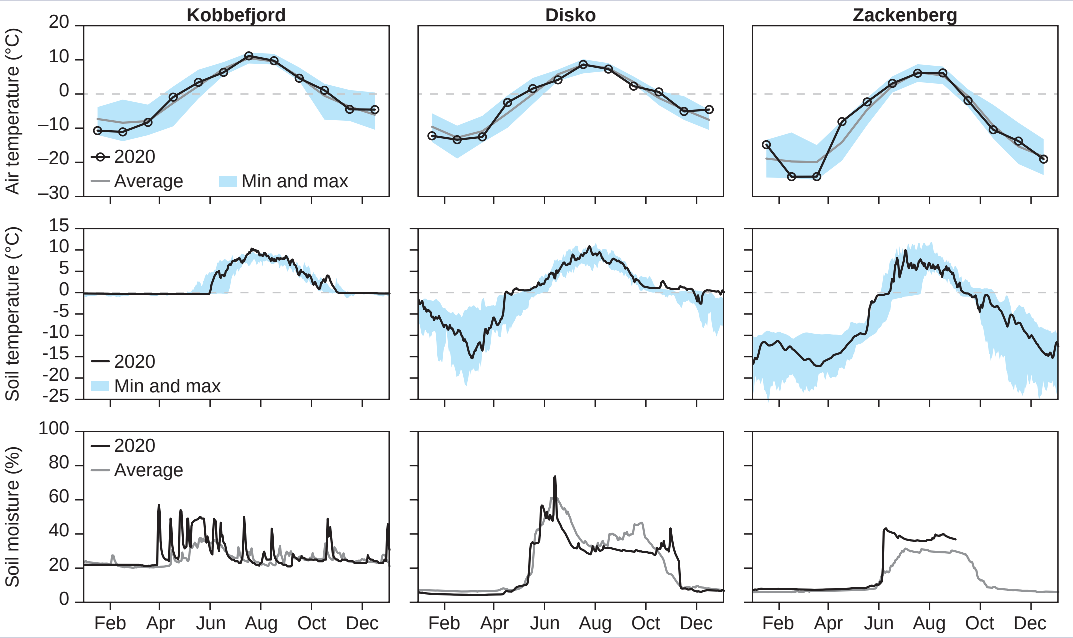

Figure 2. Mean monthly air temperature across sites (top panel) in 2020 compared to average and minimum and maximum (shaded area) in historical data. Heath soil temperatures in 10 cm (middle panel) in 2020 compared with minimum and maximum (shaded area) and soil moisture within the top 10 cm, shown together with long-term average. Soil temperature and soil moisture content are important parameters for plant growth, phenology, permafrost, energy fluxes and carbon exchange. Soil temperature and soil moisture are measured under several different vegetation communities and in a wide range of depths, as part of the GeoBasis programme. Data used in the figure: Top panel: Kobbefjord: 2008-2020, Disko: 2012-2020 and Zackenberg: 1996-2020. Middle panel: Kobbefjord: 2012-2020, Disko: 2012-2020 and Zackenberg: 1996-2020. Bottom panel: Kobbefjord: 2013-2020, Disko: 2012-2020 and Zackenberg: 2005-2020.

While the snow depth of 2019/2020 at Kobbefjord reached new records at times early and late in the winter, the snow depth at Disko was thin. At Zackenberg snow depths were shallow until January, after which they increased rapidly (Fig. 1).

The monthly air temperatures were below average in the first three months of 2020 across all three GEM sites except January in Zackenberg, which was close to maximum. In April and May, air temperatures were high at all three sites (Fig. 2, top panel). An early date of snow-free ground combined with relatively high air temperatures is clearly observed at the Disko and Zackenberg sites in the early onset of positive ground temperatures, as well as an early peak in soil moisture. Zackenberg showed constant above-average soil moisture conditions throughout the summer due to a higher frequency of rain events in 2020. The late freeze-in at Disko was mainly due to October and December being warm . The soil in Kobbefjord hardly freezes during winter due to the insulating effect of the deep snow. This is also why the soil moisture at this site shows a strikingly different pattern than the other sites. (Fig. 2, middle and bottom panel).

In Zackenberg, the mean maximum thaw depth in ZEROCALM-1 was 86 cm, the deepest registered so far (Fig. 3).

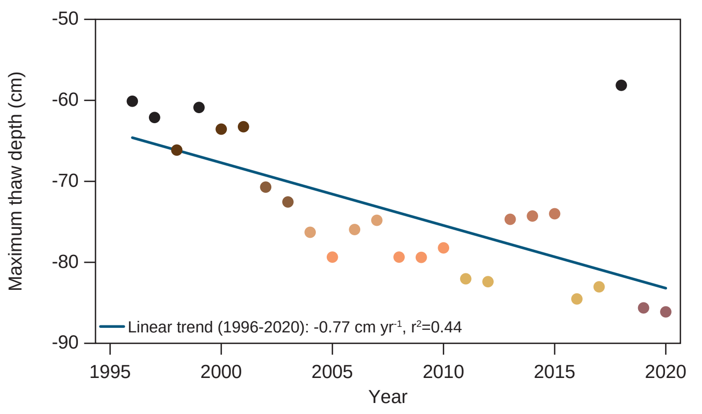

Figure 3. Long-term trend in annual maximum soil thaw depth in Zackenberg Circumpolar Active Layer Monitoring grid # 1 (ZEROCALM-1). Soil thaw and active layer depth are studied under different vegetation types. Monitoring methods include manual probing and borehole temperature recordings.

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GEM BIOBASIS

The GEM BioBasis programme is the biodiversity component of the GEM programme. The program studies key species and key processes across plant and animal populations and their interactions within the terrestrial and limnic ecosystem compartments in Kobbefjord/Nuuk (low Arctic) and Zackenberg (high Arctic). The main focus of BioBasis is on biodiversity in general, and abundance and community composition in particular, of the most important flora and fauna components in the tundra biome. Central to the programme is the monitoring of status and trends of selected focal species, phenology of their life history events and rates of reproduction and predation. Through these monitoring activities, BioBasis documents the intra- and inter-annual variation in central biotic parameters, their resilience towards biotic and abiotic perturbations, as well as their long-term trends. The long time series and the interdisciplinary approach of GEM provides in-depth knowledge of ecosystem structure and function, and the status of key biodiversity elements in a changing Arctic. BioBasis has strong linkages to Arctic Council's Circumpolar Biodiversity Monitoring Program (CBMP) and play a leading role in the development and implementation of their monitoring plans.


Photo: Katrine Raundrup.


Photo: Katrine Raundrup.

Monitored parameters

Vegetation

- Flowering phenology
- Plant community composition
- Plant community distribution and zonation
- ITEX and UV-B effect monitoring

Arthropods and microarthropods

- Abundance
- Emergence phenology
- Herbivory rates

Birds

- Abundance
- Reproductive phenology
- Reproduction and predation rates

Mammals

- Abundance
- Spatial distribution
- Reproduction and predation rates

Lake flora and fauna

- Phytoplankton abundance and diversity
- Distribution of submerged macrophytes
- Zooplankton abundance and diversity
- Fish stocks

General

- Tissue sampling
- Plot-scale abiotic parameters

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Photo: Katrine Raundrup.

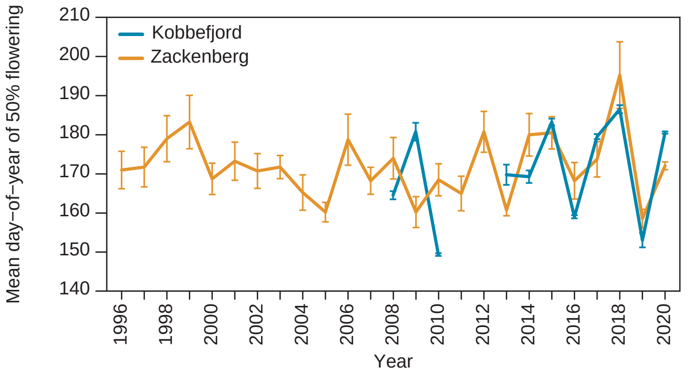

Figure 1. Day of 50% flowering is indicative of the effect of climate variability on the timing of flowering. The timing of plant growth and flowering is important for e.g. insects and herbivorous animals. The graph shows inter-annual variation in mean Salix *flowering phenology in selected permanent plots in Kobbefjord and Zackenberg 1996-2020. Note that no flowering was observed in Kobbefjord in the years 2011 and 2012 due to insect outbreak, and due to the covid-19-induced late arrival to Zackenberg in 2020, two out of four plots had reached 50% flowering prior to arrival.*

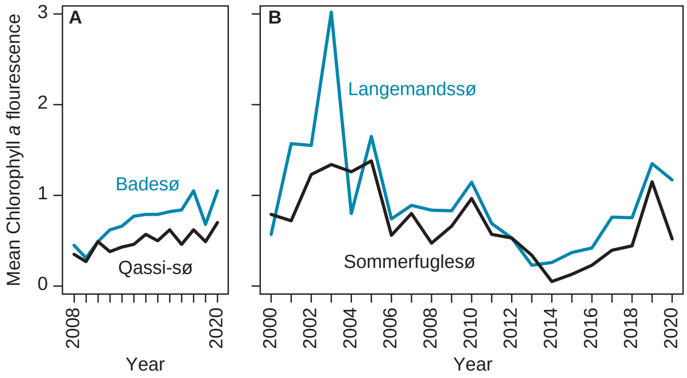

Figure 2. Chlorophyll fluorescence is a measure of productivity in the limnic ecosystem. The graphs show inter-annual variation in chlorophyll fluorescence in lakes at Kobbefjord and Zackenberg 1996-2020. Blue lines indicate lakes with fish, black lines lakes without fish. Note that due to the late onset of the 2020 season at Zackenberg dictated by the covid-situation, only one measurement was conducted in July.

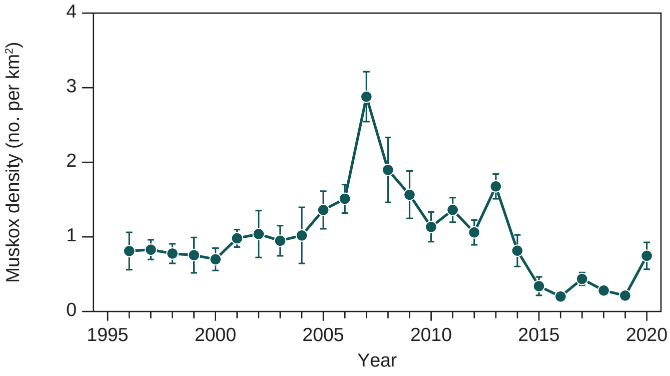

Figure 3. Inter-annual variation in muskox population dynamics (July and August) at Zackenberg 1996-2020.

Photo: Katrine Raundrup.

Annual Report Card 2020

GEM
MARINEBASIS


Photo: Mie Winding.

The GEM MarineBasis programme collects physical, chemical and biological data from the Greenland coastal zone. Work is focused in three fjord systems (Godthåbsfjord, Disko Bay and Young Sound) all influenced by glaciers from the Greenland Ice Sheet. The programme provides long-term data for identification of trends and improved understanding of ecosystem function, both of the physical environment (such as sea ice cover, water temperature, salinity and nutrient concentrations) and of the biotic environment (such as primary production and marine biodiversity). Data from the program feed into several work groups under the Arctic Council, i.e. the Circumpolar Biodiversity Monitoring Programme (CBMP) under the Conservation of Arctic Flora and Fauna (CAFF) and the Arctic Monitoring and Assessment Programme (AMAP).

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Monitored parameters:

- Sea Ice and Snow Conditions
- CTD Measurement
- pCO_2
- DIC
- TA
- Nutrients
- Chlorophyll a Concentration
- Phaeopigments Concentration
- Particulate Pelagic Primary Production
- Particulate Sinking Flux
- Plankton
- Fish Larvae
- Benthic Vegetation
- Marine Mammals
- Sea Birds

PROGRAMME DESCRIPTION

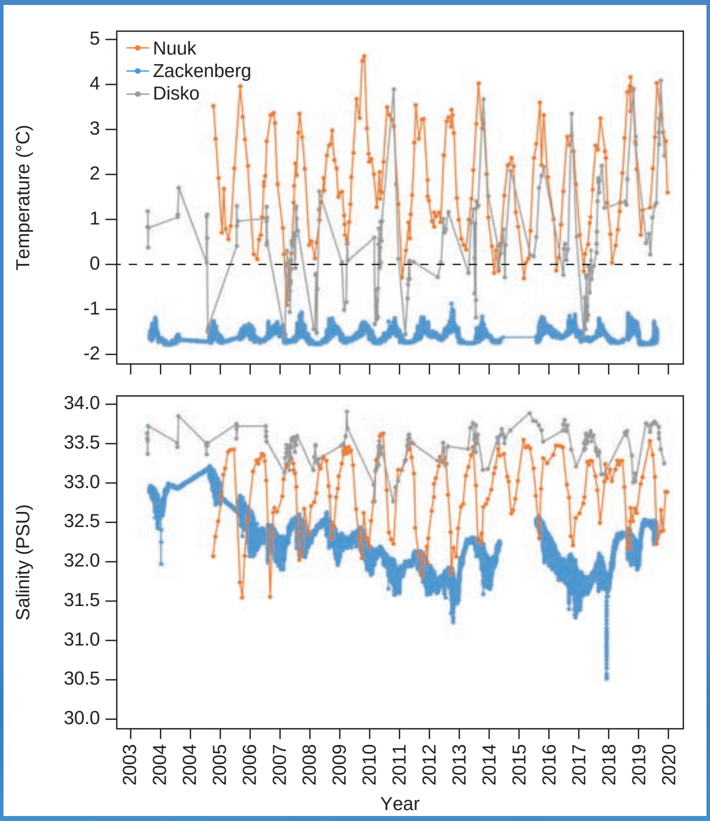

Figure 1. Water temperature and salinity at the permanent monitoring stations in Nuuk, Disko and Zackenberg. The time series from Nuuk and Disko represents one depth (63 m) selected from a monthly profile covering the entire water column. The time series from Zackenberg represents an autonomous mooring deployed at an average depth of 63 m.

Photo: Mie Winding

Annual Report Card 2020

GEM GLACIOBASIS

The highest automatic weather station on Chamberlin Glacier, Disko, on 21 August 2020. The dark surface and lack of snow indicates that virtually all Lyngmarksbræen experienced negative surface mass balance in 2020. Photo: Michele Citterio, GEUS.

Monitored parameters:

- Glacier surface mass balance
- Glacier weather and surface energy budget
- Glacier surface elevation
- Glacier surface velocity
- Snow depth and density

GlacioBasis monitors the surface mass balance and the surface energy budget of glaciers at the Zackenberg, Kobbefjord and Disko GEM sites to quantitatively understand the climatic drivers of glacier change. Glaciers and ice caps distinct from the Ice Sheet account for 14-20% of Greenland's total contribution to global sea level rise. At the river catchment scale, glacier runoff is a key component of the hydrological balance and contributes to the freshwater input to the sea (see "The role of glacier meltwater in river discharge" at page XX). GlacioBasis activities started in 2008 at the A.P. Olsen ice cap in Zackenberg, followed by Qasigiannguit glacier in Kobbefjord (since 2012/2013) and Chamberlin glacier, a sector of Lyngmarksbræen ice cap on Disko Island (since 2015/2016). GlacioBasis manual and automatic in situ observations implement standardized protocols and best practices from WMO GCW (World Meteorological Organization's Global Cryosphere Watch) and WGMS (World Glacier Monitoring Service). The GlacioBasis time series provide in situ calibration and validation data for the GEM Remote Sensing Initiative and offer a platform for external project like EU-H2020 INTAROS. GlacioBasis is operated by GEUS (Zackenberg and Disko) and Asiaq – Greenland Survey (Kobbefjord) in collaborationn with the other GEM Programmes, PROMICE, DMI, ZAMG (Vienna) and is represented in the Steering Group of WMO Global Cryosphere Watch.

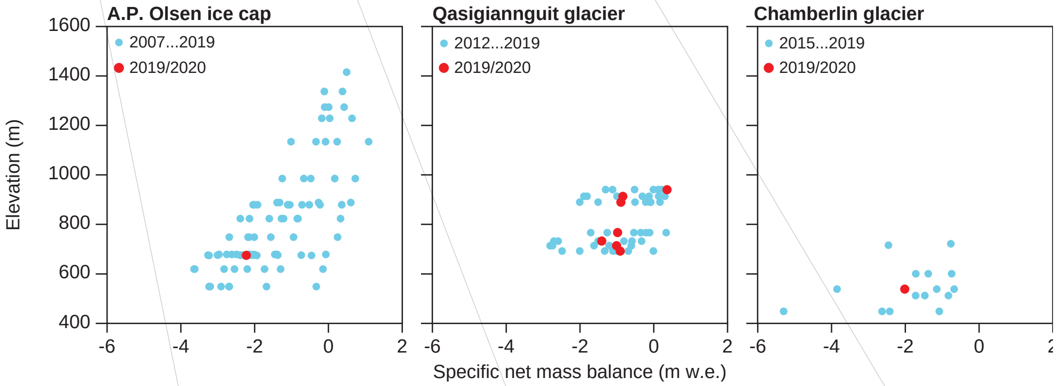

Figure 1. Glacier surface mass balance vs. elevation at the stakes on A.P. Olsen ice cap (Zackenberg, 14 stakes), Qasigiannguit glacier (Kobbefjord, 9 stakes) and Chamberlin Glacier (Disko, 7 stakes).

The travel limitations during 2020 due to the Covid-19 pandemics resulted in the loss of several manual measurements.

The 2019/2020 was a moderately more negative mass balance year than average since the start of GEM glaciological monitoring observations at the different sites. The automatic weather stations operated without interruptions, providing vital measurements of both near surface weather as well as the accumulation and ablation terms of the surface mass balance. However, both in Zackenberg and on Disko it was not possible to maintain the normal schedule of stake measurement and redrilling, which resulted in many stakes melting out and falling. Due to constraints in safely accessing the sites, this loss of ablation stakes may also impact the 2021 campaign especially if the 2021 spring season start is going to be delayed, as stakes will need to be reestablished in at the earliest opportunity in 2021. This data loss is mitigated by 2020 not having been an extreme year, which makes it less uncertain to interpolate based on earlier years.

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Disko:

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2020 remained within the range of most of earlier years at all three sites, though with a warmer than average early spring season. This contrasts with a colder than usual March at both A.P. Olsen and Chamberlin Glacier.

Positive degree day (PDD) sums provide a simple tool highlighting the interannual variability in the intensity and timing of snow and ice ablation. The differences of climate at the three GEM sites is clearly reflected in these plots, even though the length of the Qasigiannguit and Chamberlin weather time-series is still rather short. At all sites the 2020 ablation season saw moderate melt conditions, with the main melt season ending earlier than the average on record. Interestingly, all sites witnessed episodes of positive daily average temperatures both earlier and later in the season than in most years, approximating or exceeding the overall significantly warmer years 2019 and 2016.

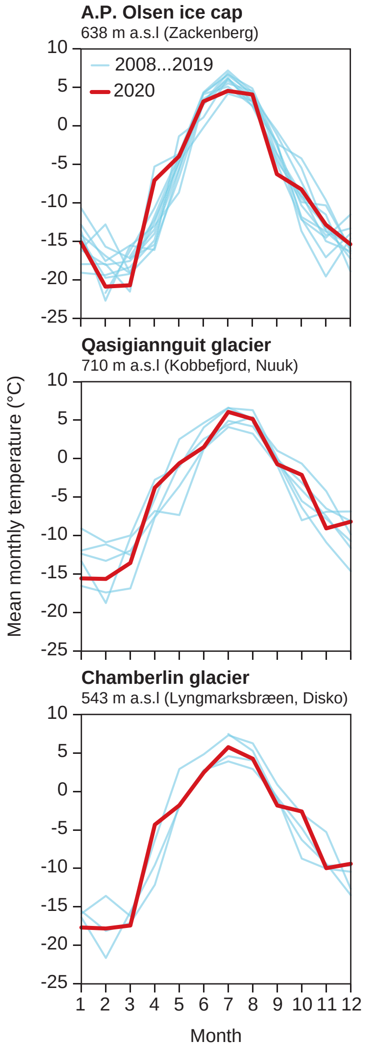


Figure 2. Mean monthly air temperatures from automatic weather stations in the ablation zone of the monitored glaciers at the three GEM sites in 2020 (red) vs. earlier years (light blue).

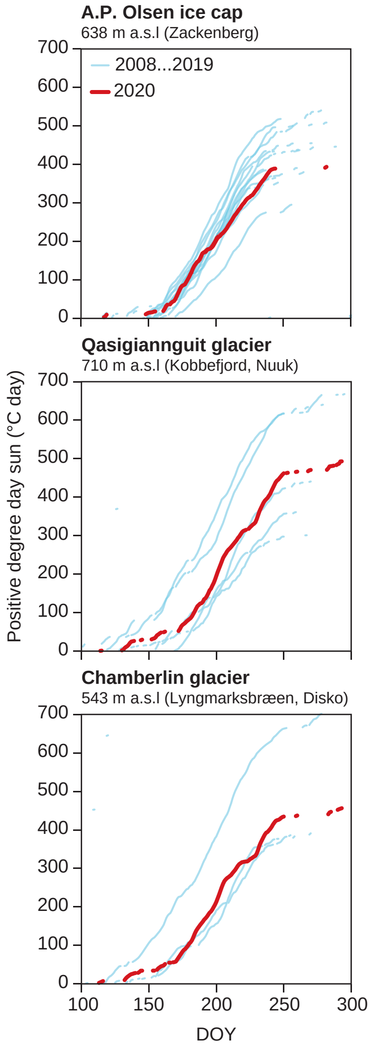


Figure 3. Positive degree day (PDD) sums from GlacioBasis automatic weather stations in the ablation zone of the monitored glaciers at the three GEM sites in 2020 (red) vs. earlier years (light blue). Gaps visible in the curves indicate sub-freezing daily mean temperatures.

One of the surviving ablation stakes at A.P. Olsen ice cap in Zackenberg on 1 July 2020 when snow has completely disappeared. Photo: Ylva Sjöberg, KU.

Greenland Ecosystem Monitoring

Greenland Ecosystem Monitoring (GEM) is an integrated monitoring and long-term research programme on ecosystem dynamics and climate change effects and feedbacks in Greenland.

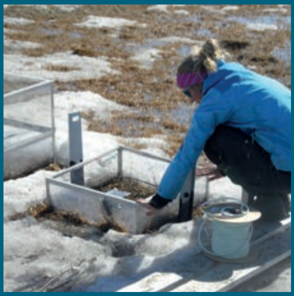
www.g-e-m.dk

ClimateBasis Programme

The GEM ClimateBasis Programme studies climate and hydrology providing fundamental background data for the other GEM programmes.

GeoBasis Programme

The GEM GeoBasis Programme studies abiotic characteristics of the terrestrial environment and their potential feedbacks in a changing climate.



BioBasis Programme

The GEM BioBasis Programme studies key species and processes across plant and animal populations and their interactions within terrestrial and limnic ecosystems.

MarineBasis Programme

The GEM MarineBasis Programme studies key physical, chemical and biological parameters in marine environments.

GlacioBasis Programme

The GEM GlacioBasis Programme studies the response to climate of Greenland's glaciers and ice caps independent from the ice sheet.

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