Greenland Ecosystem Monitoring

ANNUAL REPORT CARDS 2023

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GREENLAND ECOSYSTEM MONITORING

ANNUAL REPORT CARDS 2023

GEM

Greenland Ecosystem Monitoring

GEM INTRODUCTION

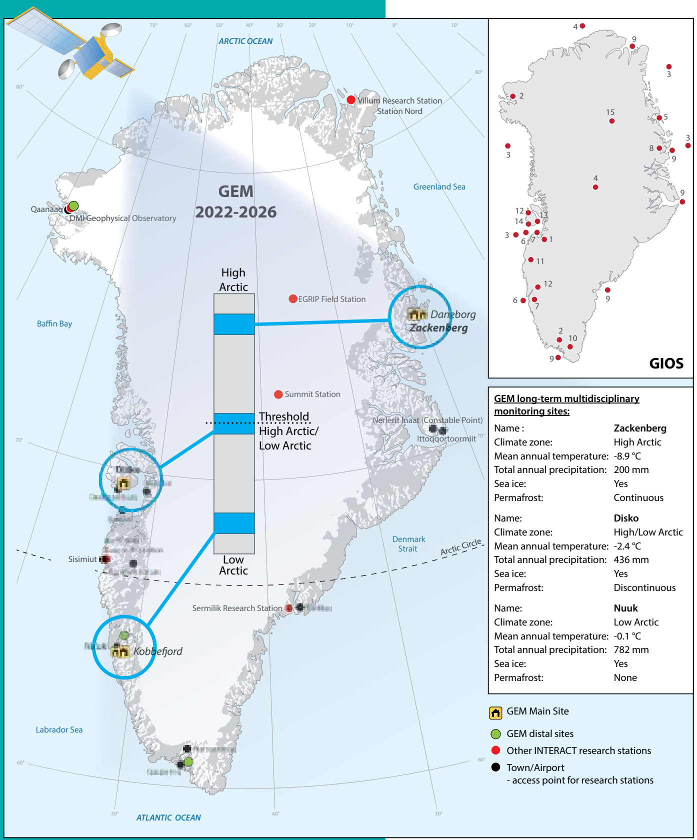

Figure 1. The GEM programme combines intensively studied ecosystems at three main sites (Disko, Nuuk and Zackenberg) with remote sensing and distal sites located along environmental and climatic gradients. The complementary study sites of Greenland Integrated Observing System (GIOS) also shown.

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 has since then been monitoring essential climate and ecosystem variables. Throughout the years GEM has contributed to the working groups of the Arctic Council (AMAP and CAFF) 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 (Figure 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 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."

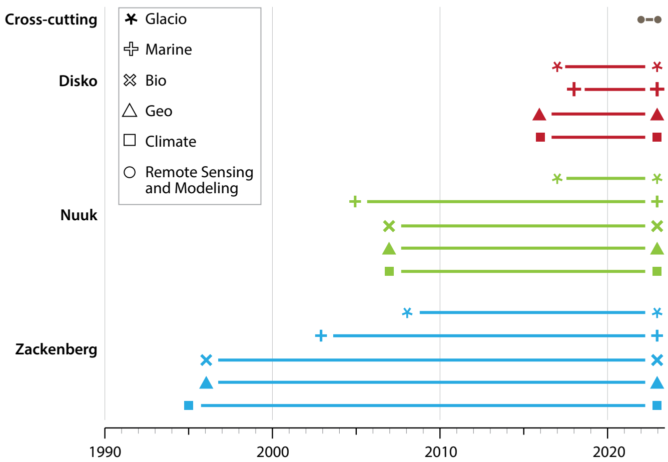

Figure 2. The GEM programme was initiated in 1995 as the Zackenberg Ecological Research Operations (ZERO). In the years 2005-2007 a new main site was established around Nuuk, and in 2016-2018 Disko area was included. All 5 Basisprogrammes are now funded at all three main sites, except for BioBasis at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

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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), 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.

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 (AMAP and CAFF) 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 is making an active effort to help educate the next generation of scientists, with several university courses using GEM data, and associated Ph.Ds and Post Docs. GEM scientists work actively reaching out to students in schools and high schools through course and information materials based on GEM knowledge and data. This all combined with international cooperations reaching a wide arctic audience. GEM work to create 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. 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/

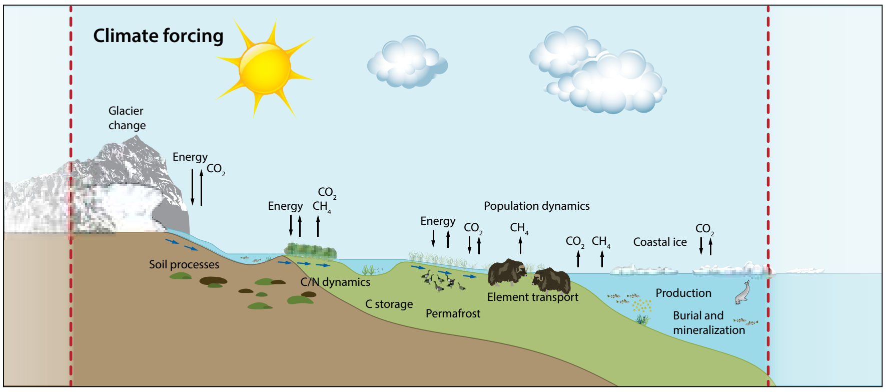

Figure 3. The GEM domain covers the glaciological, terrestrial, limnic and coastal marine compartments of the ecosystem.

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

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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.

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Results and achievements

Infrastructure and green transition

In 2023, significant strides were made at our main study sites to enhance infrastructure, aligning with GEM's commitment to smarter, more energy-efficient, and sustainable operations.

Arctic Station on Disko Island underwent a comprehensive renovation, expanding its capacity to accommodate more scientists and research activities. Another achievement was the completion of the solar panel park at Zackenberg. Preliminary estimates indicate that it will surpass expectations by generating over 50% of the station's electricity annually. This milestone represents a significant step towards our goal of more sustainable operations. Also, in Kobbefjord, sustainable energy is the primary power source. The flux measurement in Kobbefjord was supported by the installation of new power-container facilities in 2023. This initiative aims to enable year-round operation, bolstering our capacity to collect vital data across all seasons.

In 2023 we also saw the introduction of internet access at Zackenberg through a Starlink connection. The end of our internet isolation era opened doors to a new phase of connectivity crucial for both scientific research and logistics. This change allows us to transmit data instantly, monitor instruments remotely, and greatly improves how efficiently we work.

Solar panels are important in the transition to make the GEM monitoring more sustainable. Here are solar panels in Kobbefjord.

Torben Røjle Christensen,
Scientific leader of GEM

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2023

GEM
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The Danish Minister for Research and Education, Christina Egelund (second to left), visited Kobbefjord in August. During her visit, she was introduced to the ecosystem monitoring taking place in Kobbefjord. Photo: Thomas Juul-Pedersen.

Outreach

The Danish Minister for Research and Education, Christina Egelund, visited Kobbefjord in August. During her visit, she inspected various aspects of the GEM facilities and tried the new bridge that replaced the one washed away during a heavy rain event in 2022. In September, the Danish Minister for Climate, Energy, and Utilities, Lars Aagaard, also visited Nuuk and the Greenland Institute of Natural Resources to learn about the GEM programme and its activities.

GEM Principal Investigators (PIs) attended the annual meeting of the INTERACT network held at Toolik Lake, Alaska. During the event, they had the chance to exchange experiences regarding monitoring activities at similar stations, such as Toolik Lake, in comparison to GEM's main sites. Additionally, as a result of this meeting, the GEM scientific leader was invited to join the advisory board for monitoring activities at Toolik Lake.

GEM received significant exposure in both national and international media throughout the year. For instance, GEM's research findings that Spring in the Arctic not necessarily starts earlier and earlier - instead the effects of gradual warming have been rivalled by extremely variable weather which is not good news for species such as Musk-oxen. One notable feature discussing this was published in the Danish newspaper Weekendavisen.

International collaboration

The ongoing war in Ukraine continued to impact Arctic Council-oriented activities within GEM throughout 2023. Despite this, progress was made between the working groups AMAP and CAFF on a collaborative ecosystem-oriented assessment. A special issue of Frontiers in Environmental Research was launched to kickstart this initiative, with 17 committed first-authors. Submissions for this issue are expected by mid-2024, with completion anticipated by late 2024. Several papers within this issue will feature GEM data and studies.

Additionally, GEM scientists led an effort to study and quantify the impact of the exclusion of all Russian stations from the INTERACT network on the circumarctic understanding of climate change impacts. This research resulted in a paper published in Nature Climate Change in January 2024.

High school students from Nuuk (GUX) visit Kobbefjord to learn about the GEM programme and conduct their own vegetation analysis. Photo: Marie Frost Arndal.

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The Danish Minister for Climate Lars Aagaard visited Greenland Institute of Natural resources. Head of Department Mie Winding introduced the field work and the valuable monitoring and research carried out by the GEM programme, partly financed by klimastøtten. Photo: Christian Klindt.

Education

The GEM-affiliated University of the Arctic-funded project BEFLUX continued its PhD schools, hosting one in Nuuk in June. The visit proved highly successful, drawing 13 international students who carried out project work in Kobbefjord. Moreover, Copenhagen University organized several courses utilizing GEM data. As part of the Arctic Science Study Program, jointly conducted by Aarhus University and the Greenland Institute for Natural Resources, courses incorporating GEM data are now regularly held in Nuuk.

The Novo-Nordisk funded educational project, aimed at producing GEM-based data and teaching materials for high schools in Greenland and Denmark, maintained its momentum. In Kobbefjord, one week was dedicated to fieldwork, capturing footage of GEM researchers conducting their monitoring activities. The project will be completed in 2024, offering a comprehensive package of educational resources.

GEM at a glance 2023

- Active Basis Programmes in 2023: 15
- Scientists in the field: 79
- Scientific publications: 34
- Conference with GEM representations: 9
- Conference presentations: 2
- Courses using GEM data: 16

GeoBasis snow monitoring in Disko. Photo: Charlotte Sigsgaard

2023

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GEM database

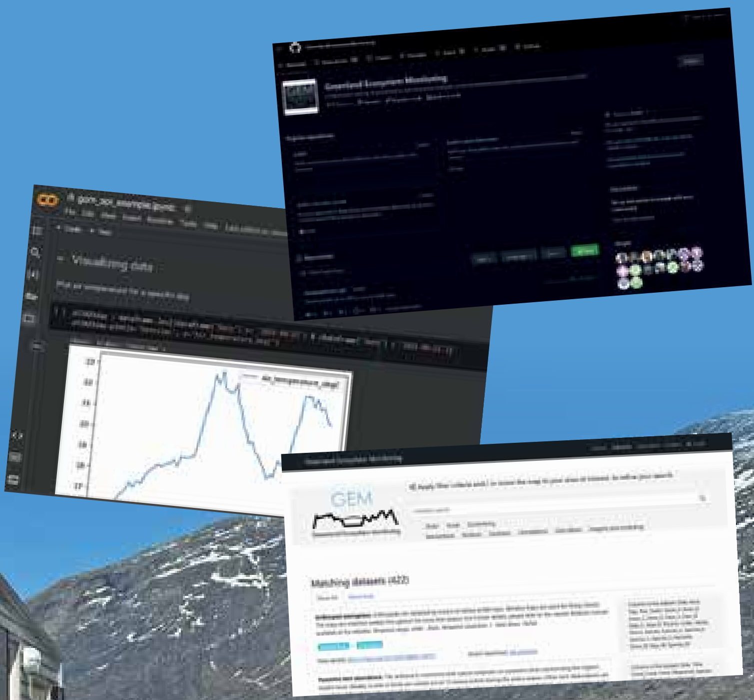
In 2023, users of the GEM database downloaded a total of 1,314 dataset packages for their research and study activities. While slightly fewer than in 2022, this figure remains the second highest since we began tracking download activity in 2017. The decrease is attributed primarily to the intense course activity in 2022 utilizing GEM data. Currently, we provide 425 datasets, with 13 added since 2022, containing long-term monitoring data of key ecosystem elements from the GEM research stations in Disko, Nuuk, and Zackenberg.

Furthermore, in 2023, 232 new users joined the GEM database, bringing the total number of registered users to 1,890.

In 2023, the GEM database work focused on two key areas: 1) Maintenance and cleanup of the database, along with importing new data from the sub-programs, 2) Software development efforts aimed at constructing an Application Programming Interface (API) and renew the open data website. These efforts were driven by the need to meet modern standards, community expectations, and enhance accessibility to GEM's open data.

The software development process within GEM has become more efficient, leveraging GitHub for the entire workflow, including source code control, collaboration, documentation, and building and releasing new versions. Both the API and the new website are currently undergoing testing and finalization, with plans to make them available by mid-2024.

To increase awareness of the GEM database and its valuable information among researchers and students, we initiated new international collaborations in 2023. These collaborations include projects like QGreenland and the new EU-funded infrastructure project from 2024; POLARIN. These collaborations align with our commitment to open data and FAIR sharing initiatives. Through QGreenland, our datasets will be featured in the US DataONE portal https://www.dataone.org/ (expected mid-2024), and later, they will be incorporated into the POLARIN data catalogue: https://cordis.europa.eu/project/id/101130949 (expected in 2025).



PhD students from the BEFLUX project conduct fieldwork in Kobbefjord as part of a successful summer school in Nuuk. Photo: Torben Røjle Christensen.

Climate &

Cryos-phere

Photo: Thomas Juul-Pedersen.

Annual Report Card 2023

OBSERVED THINNING
OF A.P. OLSEN ICE CAP

Glaciers worldwide are thinning and retreating. The local glaciers in Greenland, i.e. all ice excluding the main ice cap, are disproportionately contributing to sea level rise relative to their size. This is due to climate change affecting smaller, coastal glaciers more rapidly. Thinning of glaciers is an indicator of their health. In this report card, we present the different methods of observing glacier thinning at the A.P. Olsen ice cap. As something new this year, we have now incorporated satellite observations. Our observations provide evidence of significant thinning from 2008 to the present.

The lower melt and weather station at A.P. Olsen Ice Cap, upon installation in 2008. Photo: Michele Citterio

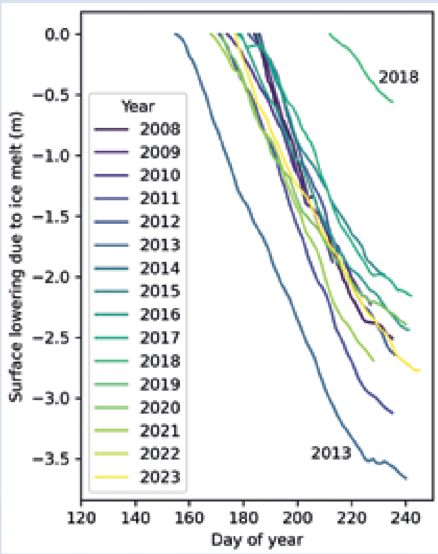


Figure 1. The surface lowering (ice melt) observed at the lower melt and weather station at the A. P. Olsen Ice Cap.

At the A.P. Olsen ice cap, a transect of three ice melt and weather stations (ZAC_L, ZAC_U, ZAC_A) forms the core of our glaciological monitoring. These stations measure ice melt continuously throughout the melt season. As shown in Figure 1, annual ice melt at ZAC_L indicates surface lowering ranging from 0.5 m to 3.5 m, but most years averaging around 2.5 m. Since the beginning of the glaciological monitoring at Zackenberg in 2008, we have observed a total surface lowering of approximately 40 m, up to and including 2023. Due to ice flow, this observed lowering translates to an actual glacier thinning of about 27 m, which is evident from the station's GPS data. The difference between these two numbers arises because melted ice is partially replenished with new ice flowing into the site. In a stable climate, the flow of ice would precisely balance the snow surplus in upper areas with the ice loss in lower areas. Climate changes manifest as glacier thinning or retreating, or conversely, thickening and advancing. Therefore, thinning is a clear sign of a climate becoming less favorable for maintaining glaciers, or put simply, a glacier in poor health. Climate observations from Zack-

A stake after one and a half melt season, the surface around the stake has lowered more than three meters. Photo: Daniel Binder

Authors:

Signe Hillerup Larsen & Anja Rutishauser

Geological Survey of Denmark and Greenland, Copenhagen

Data source:

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

Data source: GlacioBasis, ice melt data: https://doi.org/10.17897/N7HY-AA16, ICESat-2 data doi coming soon

GEM

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enberg indicates rising temperatures for the past few decades which, among other things, has resulted in a longer melt period and thus we expect to see a reaction to this on the glacier shape.

Glacier thinning is observable from space. Data from the ICESat-2 satellite mission (Ice, Cloud, and land Elevation Satellite-2), a NASA mission launched in September 2018, provides precise measurements of Earth's surface elevation, including glaciers. Figure 2 illustrates ICESat-2's observational tracks, which by coincidence pass near both the lower and upper melt and weather stations (ZAC_L and ZAC_A) at A.P. Olsen ice cap. Near the lower station ZAC_L, ICESat-2 has recorded glacier thinning of nearly 10 m over a four-year period (2019-2023).

Combining data from GlacioBasis in situ monitoring of surface elevation, with the with the satellite observations provide a strong documentation and evidence of a thinning glacier.

In summary, the surface near the ZAC_L melt and weather station has lowered approximately 27 m from 2008 to 2023, with 10 m of this total occurring in the last four years – a clear indicator of a glacier in decline. This could be attributed to reduced snowfall, increased melt caused by rising air temperatures, which affect both precipitation patterns and temperatures. The total heat content in the Zackenberg area (measured as the average number of positive degree days) has increased since the establishment of the research station in 1995 (Figure 3), likely contributing to the retreat.

The ICESat-2 mission provides valuable data on the state and health of glaciers. Thus, the glaciological monitoring in Zackenberg now includes surface elevation data from the ICESat-2 mission in the GEM database.

A stake upon installation, it is being measured using long ruler to determine the height above surface to be around 20 cm. Photo: Signe Hillerup Larsen.

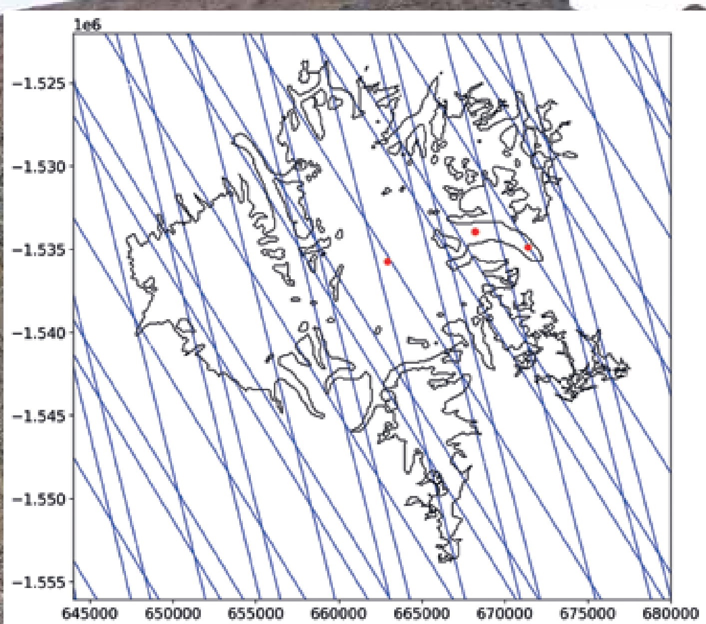


Figure 2. Map of observational tracks of the ICESat-2 (Ice, Cloud, and land Elevation Satellite-2, NASA mission).

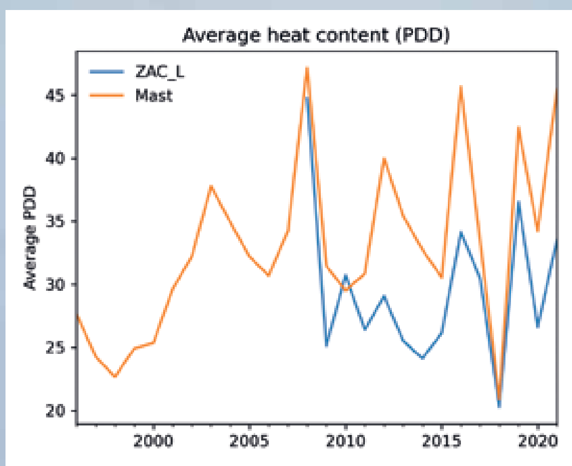
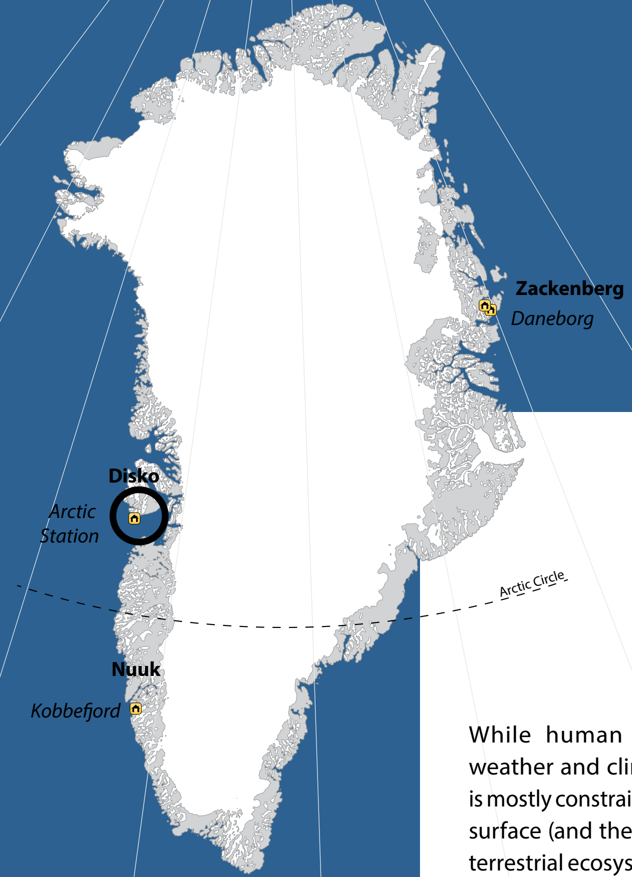


Figure 3. The average annual heat content at the lower melt and ablation station on A.P. Olsen Ice Cap (ZAC_L) and the climate mast (mast) at Zackenberg research station. The heat content is defined by the average number of degree days.

THE VERTICAL STRUCTURE AND ITS CONNECTION TO



What the full spectrum of atmospheric disturbances which can occur in the Arctic – and some of which may lead to severe weather and precipitation – looks like is subject to ongoing research and debate. ClimateBasis instrumentation can provide valuable data to study the physical processes involved in creating and amplifying such disturbances.

While human experience of weather and climatic variability is mostly constrained to the earth's surface (and the same is true for terrestrial ecosystems), a comprehensive understanding of the mechanics of the climate system requires studying the full depth of the atmosphere and ocean. Precipitation, including the record amounts observed on Greenland's west coast in 2022 (Sigsgaard et al., 2023) and 2023 (see this issue), occurs as a result of complicated processes happening throughout the lower atmosphere; energy is redistributed around the globe by all layers of the atmosphere. Understanding the local vertical structure of the atmosphere is important to distinguish between the effects and changes induced by large-scale climatic processes, such as the transport of moisture and heat from lower latitudes into the Arctic, and those caused by local conditions such as the pre-sence or absence of sea ice or snow.

At the Disko GEM site in Qeqertarsuaq, ClimateBasis is operating a radiometer which reconstructs vertical atmospheric profiles of temperature and humidity at high temporal resolution by measuring microwave emissions of oxygen and water molecules (the HATPRO Humidity And Temperature PROfiler). The Disko Bay area is known as one of the ecologically most diverse regions of Greenland and has a varied geography which incorporates many elements of the Arctic climate system. The climate at Disko Bay has been undergoing pronounced changes since at least the 1990s.

We are currently using the profiler to study the atmospheric processes leading to precipitation in Disko Bay. How much precipitation owes its occurrence to the passage of fronts associated with synoptic (mid-latitude) cyclones, and how much occurs due to more localized atmospheric disturbances? Does the moisture come from local sources or is it transported from further away in atmospheric rivers? How do these processes vary from year to year and over the long term? The local moisture supply is expected to increase (with implications for the local ecosystems) due to the disappearance of sea ice and the warming oceans (Bintanja and Selten, 2014), but also due to an increase in the frequency of atmospheric river landfalls in Greenland (Zhang et al., 2024). Atmospheric rivers are narrow zones embedded in mid-latitude cyclonic disturbances along which the largest part of atmospheric moisture transport occurs.

Figure 1 shows vertical profiles of atmospheric temperature and humidity obtained with the HATPRO profiler in June 2019, together with observations of surface temperature, precipitation and wind direction from the nearby ClimateBasis climate station. Several episodes of arrival of warm air and moisture near the surface, followed by precipitation and the arrival of cold air can be discerned. Are these precipitation events associated with the arrival of midlatitude fronts or due to more local disturbances? To answer this question, we look at the larger scale picture as simulated by a numerical model of the atmosphere, the CARRA reanalysis (Schyberg et al., 2020). Figure 2 shows the northward progression of a small-scale disturbance in surface pressure and associated wind fields over Qeqertarsuaq on June 13, 2019. An objective detection algorithm (Parfitt et al., 2017) for meteorological fronts has been applied to the model fields and shows relatively jumbled and occluded streaks. Note, however, that the algorithm is trained on typical mid-latitude cyclones and may not be too informative in higher latitudes; in fact, what is being labeled as fronts may well be more akin to atmospheric waves which act as triggers for the development of the small-scale depression.

Global cyclone tracking datasets show no major cyclone activity near the Greenlandic west coast in June 2019 (not shown). The occurrence of smaller scale atmospheric disturbances, sometimes referred to as "Arctic lows", has been known for several decades and even inspired a research program termed the "Norwegian Polar Lows Project" in the mid-1980s. Their precise nature – whether

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Data source:

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

GEM data from ClimateBasis Disko

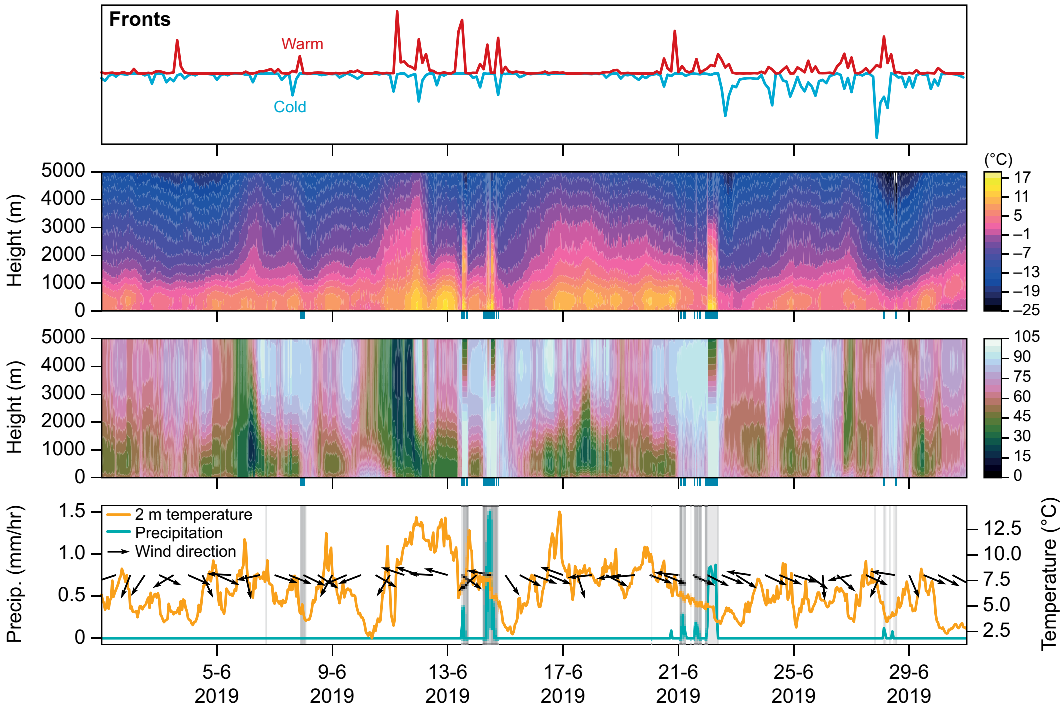

Figure 1. Vertical profiles of atmospheric temperature (second row) and humidity (third row) aquired by the HATPRO instrument, together with surface level meteorological observations (fourth row). The arrows in the fourth row indicate wind direction in the conventional compass orientation with north at the top. Blue marks under the plots and gray shading in the fourth row indicate when rain is falling; at these times, the HATPRO data are not usable. The top row shows a qualitative indication of frontal activity in the vicinity of Qeqertarsuaq as derived from the frontal detection algorithm of Parfitt et al. (2017).

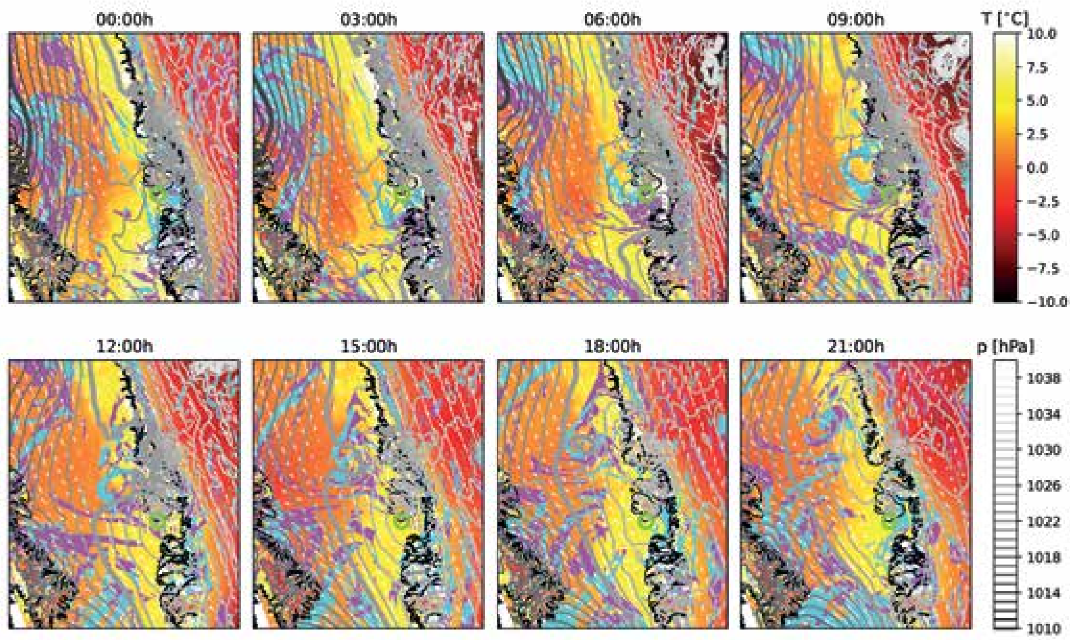

Figure 2. Selected CARRA model fields in 3-hourly intervals for June 13, 2019. The shading represents 2 m atmospheric temperature, the contour lines correspond to mean sea level pressure (thick lines indicate 1015, 1025, and 1035 hPa). The magenta / cyan shading indicates where the frontal parameter of Parfitt et al. (2017) detects a warm / cold front. Arrows show wind direction and are scaled according to speed. The location of Qeqertarsuaq is indicated by the open green circle.

they are similar to mid-latitude baroclinic disturbances or rather due to convective instabilities triggered by oceanic heating – and how to classify and predict them, is subject to ongoing debate (Rasmussen, 2003). ClimateBasis data can make valuable contributions to the understanding of these phenomena, which affect local communities and ecosystems and are sometimes the cause for episodes of severe weather, and thereby contribute to enhancing the resilience and adaptability of Greenlandic society.

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Photo: Charlotte Sigsgaard

Annual Report Card 2023

DOCUMENTING THE ECOSYSTEM RESPONSE TO

While there are many papers referencing the fact that the Arctic has warmed at a rate 3-4 times higher than the rest of the planet (Rantanen et al., 2022) this warming is by no means uniform across the Arctic. The warming is in fact heterogeneous, that is scale and location dependent (Westergaard-Nielsen et al., 2018). Hence, depending on the location and scale, climate change and its ecological implications may be very different from the general picture in the Arctic.

16 years of monitoring; documenting the highly variable picture of climate change

In Kobbefjord, GEM monitoring has been conducted since 2008 and now 16 years of data are available. The long-term monitoring data provides insight into some of the complex dynamics of climate change, as some of the measured variables show changes over the monitoring period, while others do not. In Zackenberg directional changes in seasonality and temperature were detected already in the early years of the monitoring. Revisiting those data and combining them with data collected since show high levels of variation and little to no directional changes (Schmidt et al., 2023).

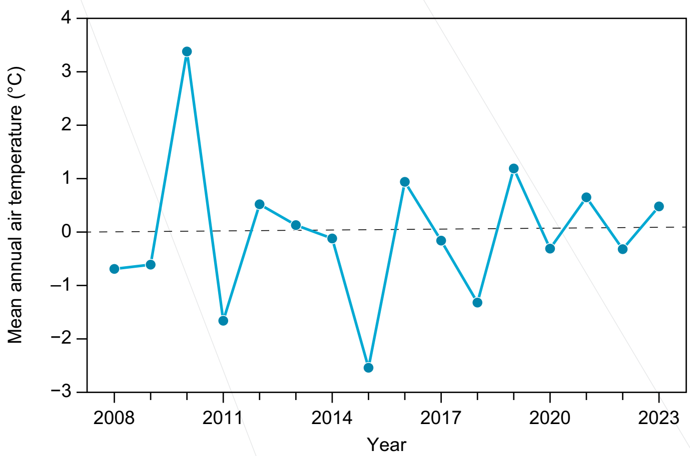

Figure 1. Mean annual temperature per year (°C) during the monitoring period from 2008 – 2023. Mean annual temperature across the monitoring period is −0.02 °C.

No significant change in annual average temperatures

In Kobbefjord, air temperature shows no significant trend during the monitoring period (Figure 1), but high levels of variability, especially in the winter and spring months (Figure 2).

Notably both April and October have had above average temperatures in the last 5 years.

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Data source:

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

GEM data from BioBasis Kobbefjord

Salix phenology: https://doi.org/10.17897/5E9Y-7844

Total flowering: https://doi.org/10.17897/J6EK-FR47

Temperature: https://doi.org/10.17897/PGN3-7597

HIGHLY HETEROGENEOUS
CLIMATE CHANGE

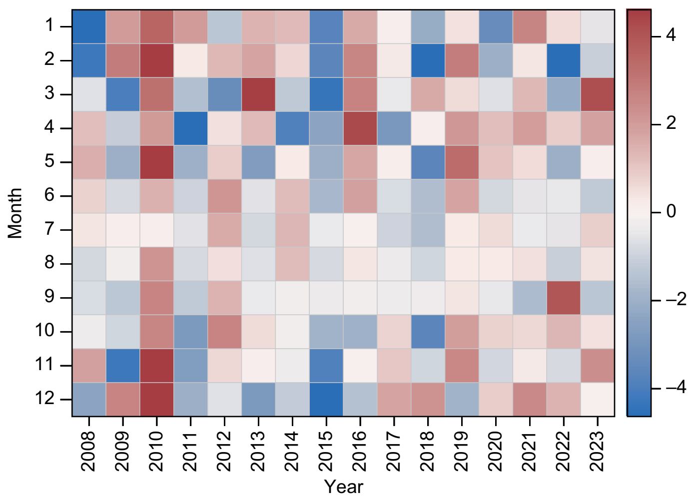

Figure 2. Mean monthly air temperature anomaly (°C) compared to the reference period (2008-2023). Stronger colors (red and blue) indicating higher deviation from the mean, are more common in winter and spring than in summer.

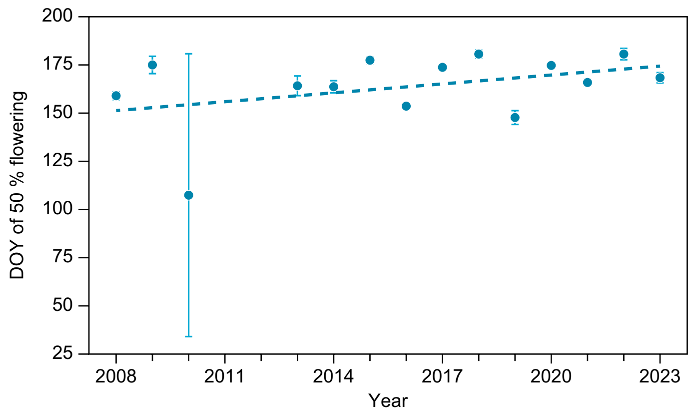

Figure 3. Day of year (DOY) at which 50 % flowering is reached for Salix glauca *(both males and female). 50 % flowering refers to when half the total number of catkins is flowering. Catkins are clusters of flowers i.e., the reproductive unit monitored in* Salix.

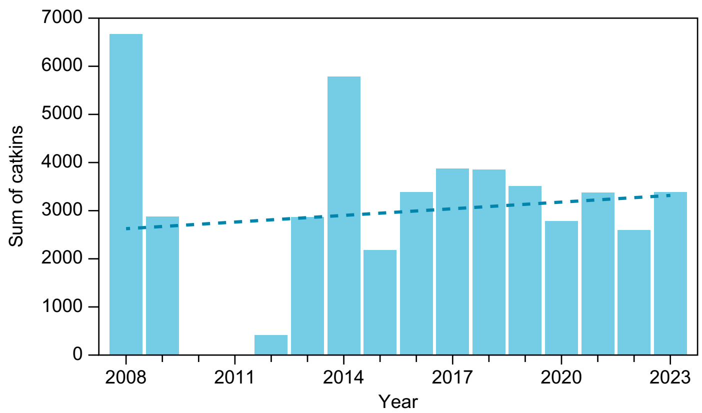

Figure 4. Total number of flowering catkins in Salix glauca*. The summed total counts of* Salix glauca *catkins across all plots in Kobbefjord. Catkins are clusters of flowers i.e., the reproductive unit monitored in* Salix.

Based on the same temperature data we calculate the growing season start and end based on the first and last 5 day consecutive period with temperatures above 5 °C. Again we see no significant change in the growth season timing, but some years (2010, 2012, 2016 and 2019) with approximately 40 days longer growing season indicating some extreme years.

A trend of delay in the 50 % flowering phenology of *Salix*

Flowering phenology in grey willow (*Salix glauca)* from 2008 to 2023 show a slight delay in the day of year at which 50 % flowering (males and females) is reached (Figure 3). This is in accordance with the lack of change in temperature, as grey willow is expected to flower earlier under warming (Post et al., 2008).

Increase in the summed total number of flowering *Salix* catkins

There is a trend towards an increase in the total number of catkins of *Salix glauca* (Figure 4). This is in accordance with trends observed looking at flowering density (m^{-2} $year^{-1}$) (Becker-Scarpitta et al., 2023). It is important to note the lack of flowering in 2011 and 2012. This was due to an outbreak of the noctuid moth *Eurois occulta* in 2010 and 2011 (Lund et al., 2017). This outbreak had a massive impact on the monitoring area, and it is immensely important to consider that all plant monitoring might still reflect the effects and implications of this outbreak.

The temperature trends in Kobbefjord do not follow the warming trends seen elsewhere in the Arctic but highlight the heterogentity of climate change on a local to regional scale. For this reason, it remains very important to continue the long-term and *in-situ* monitoring to document these heterogeneous dynamics and implications for the impacts of climate change.

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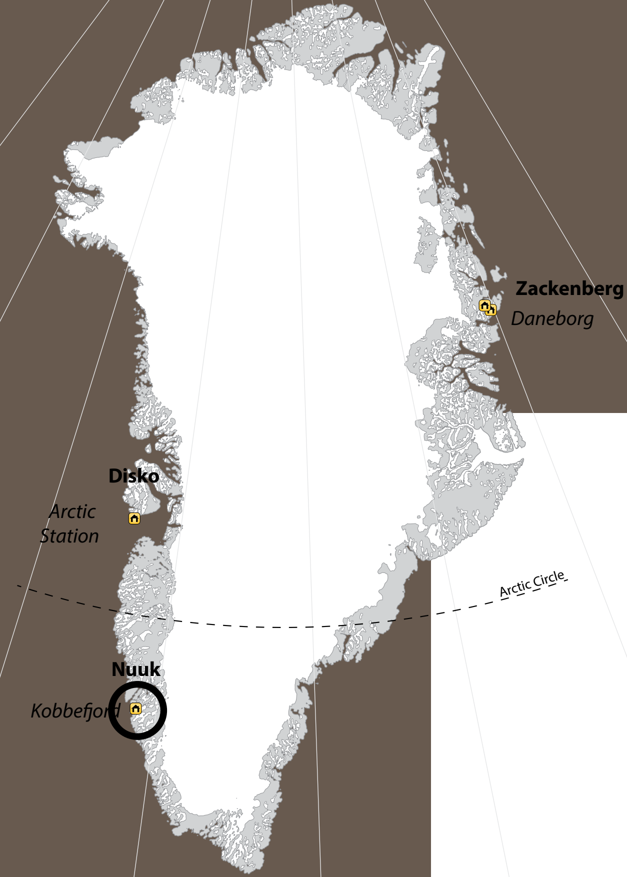

Annual Report Card 2023

BOOST TO INSTRUMENTATION IN

Power is the backbone of long-term climate monitoring. However, harsh Arctic weather conditions are wearing and tearing on both instrumentation and power supplies to the climate and greenhouse gas flux stations. Investments in a greater power capacity and new instrumentation for CH_4 and CO_2 flux measurements at the main GeoBasis monitoring sites in Kobbefjord will secure a more stable data collection and allow valuable eddy covariance CO_2 flux measurements to run continuously throughout the year in the future.

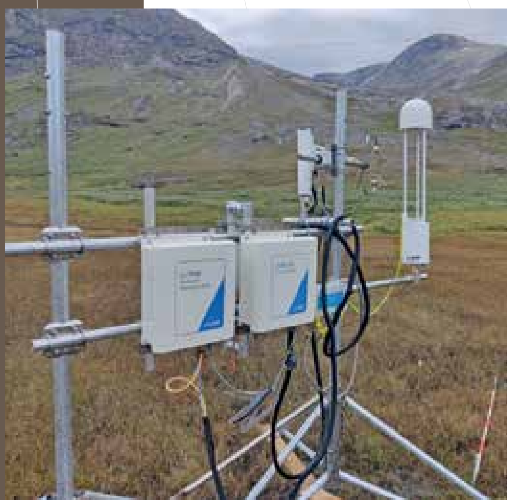

Photo: Karoline Nordberg Nilsson.

It is a continuing challenge to obtain a stable power supply to our monitoring instrumentation due to the harsh Arctic conditions, remote locations, and periodically large power consumption. Storms have broken several windmills, and the freezing winter temperatures and short daylight hours reduce the power capacity and solar power charging potential to the station's batteries. Previously, during summer, the power consumption has been more than 20 times higher than during winter due to power consuming gas flux measurements (CO_2 and CH_4) running in the growing season. Despite long summer days, the input to the batteries can be sparse in periods with dense cloud cover and low winds. In the summer of 2021, strong anomalies with extensive cloud cover and low winds resulted in low power delivery to e.g. the GeoBasis climate and greenhouse gas flux stations. Figure 1 displays a case of data loss due to this combination of high instrument consumption and limited power input occurring in 2021.

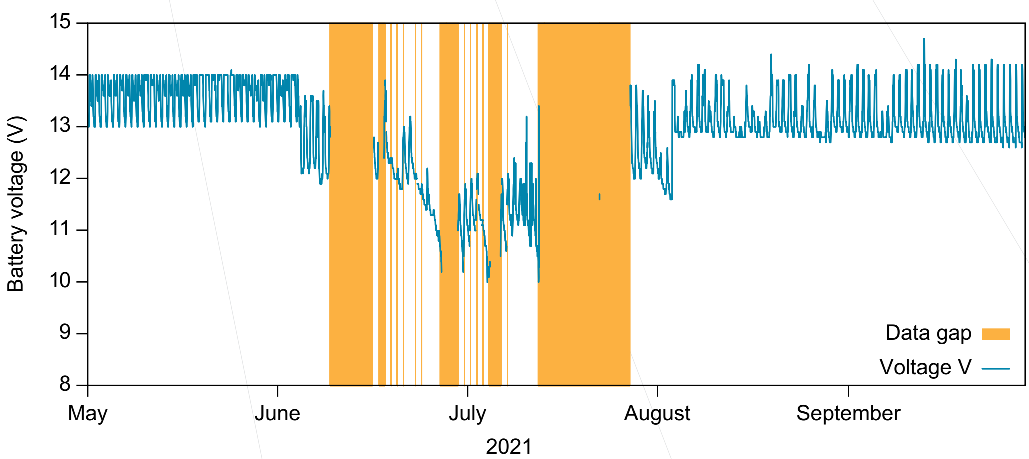

Figure 1. Battery level measured at the Fen station in the anomalous growing season in 2021 with extensive cloud cover and low winds, displaying the associated data gaps.

Authors:

Karoline Nordberg Nilsson[1] & Andreas Westergaard-Nielsen[2]

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Data source:

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

GEM GeoBasis Nuuk – meteorological station Fen: https://doi.org/10.17897/9PZ3-WW15

GEOBASIS
KOBBEFJORD

GEM
Greenland Ecosystem Monitoring

Photo: Karoline Nordberg Nilsson.

Photo: Karoline Nordberg Nilsson.

To secure the future data collection and mitigate risks for data gaps, we are excited to report that 2023 has brought the opportunity to invest in less power consuming instruments for measuring CH_4, and in new power setups for GeoBasis Nuuk. The power supplies were replaced at the two main monitoring sites in Kobbefjord, at the fen and the heath station. Moreover, we are excited to be able to replace a worn-out CO_2 gas analyzer with a new instrument. Based on well-documented experience with integrated power solutions housed in containers (Rysgaard et al. 2022), the new setup consists of two insulated 6 ft shipping containers, each with 3 solar panels and a windmill installed charging six 180 Ah batteries.

The investments in instrumentation and a new power solution at the greenhouse gas measurement sites are key to meet the ambitions of GeoBasis to extend the timeseries of our CO_2 flux measurements to include the entire year. Increasing the temporal coverage of the flux dataset will close a knowledge gap of especially the shoulder season fluxes and, provide valuable information on gas exchange during the freeze-in and thaw period in a low arctic environment as Kobbefjord.

Photo: Karoline Nordberg Nilsson.

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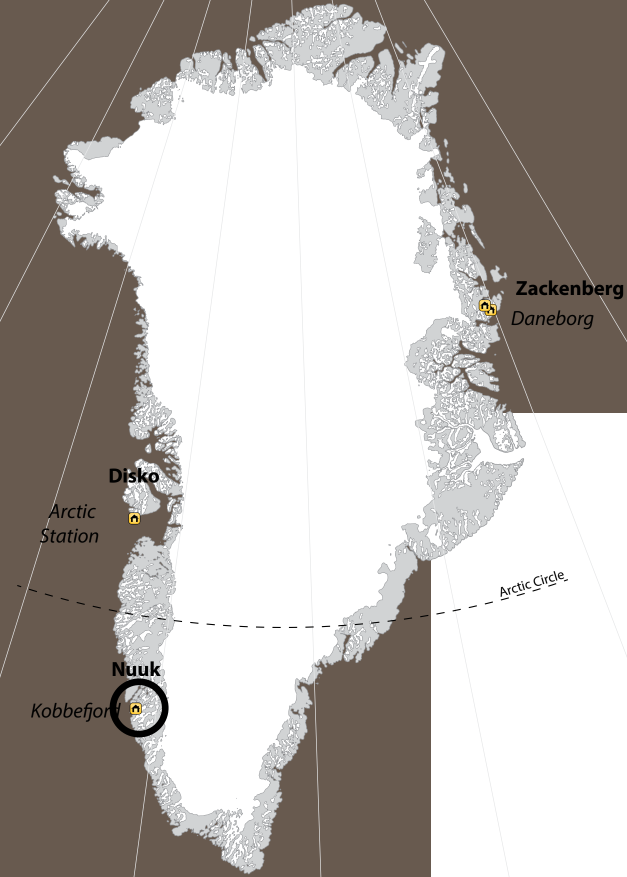


COMBINING MONITORING

– TRACKING SEASONALITY AND EFFECTS OF INORGANIC AND ORGANIC COMPOUNDS

Climate change in the Arctic affects the freshwater runoff from land to the fjords and the coastal sea around Greenland, as a result of increased melting from the ice sheet and glaciers as well as changes in precipitation amounts. In this innovative study, four GEM sub-programmes combined their activities to elucidate the effects – combining monitoring efforts and data on lateral transport of organic and inorganic compounds, across river-lake-fjord compartments in Kobbefjord, SW Greenland.

Authors:

Thomas Juul-Pedersen[1], Ida Bomholt Dyrholm Jacobsen[1,2], Tobias Vonnahme[1], Katrine Raundrup[1], Efrén López-Blanco[2], Lorenz Meire[1], Karoline Nordberg Nilsson[3], Dorthe Petersen[3] & Kirsty Langley[3].

[1]Greenland Institute of Natural Resources

[2]Aarhus University

[3]Asiaq – Greenland Survey

Data source:

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

GEM programme elements: Climate-, Geo-, Bio- and Marine-Basis-Nuuk

ClimateBasis-Nuuk; River hydrology, Discharge: https://doi.org/10.17897/H2MR-PP28

ClimateBasis-Nuuk; Precipitation: https://doi.org/10.17897/SXJ8-WA79

Data Source (Land2Fjord Project):

BioBasis-Nuuk; Badesø Lake, Conductivity.

GeoBasis-Nuuk; Kobbefjord River; Conductivity.

MarineBasis-Nuuk; Kobbefjord St. 1 & 2; Conductivity

The changing climate is affecting runoff from land by increased glacial melt and altered precipitation patterns. The altered freshwater discharge also changes the transport of compounds across land, lakes and rivers towards fjords and coastal waters in Greenland. While terrestrial carbon exchange in vegetation, snow and ice dynamics, and marine primary production are well understood, the links between them are not. The lateral flow, residence times, and sources across compartments are necessary for understanding the processes affecting nutrients, carbon and their effects on the different ecosystem compartments.

Map illustrates sampling locations across ecosystem compartments in Kobbefjord, SW Greenland. Background satellite image retrieved from Bing Aerial Images, Microsoft (Available online: http://www.bing.com/maps/ - accessed on 8 April 2024).

RAIN EVENTS ON THE LATERAL TRANSPORT OF FROM LAND TO FJORD

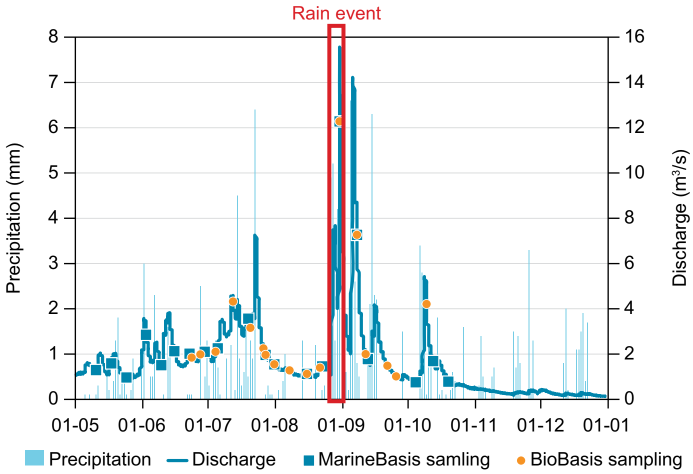


Figure 1. Time of sampling by MarineBasis- and BioBasis-Nuuk plotted with hourly precipitation values [mm] and river discharge [m³/s] from the Kobbefjord River into Kobbefjord.

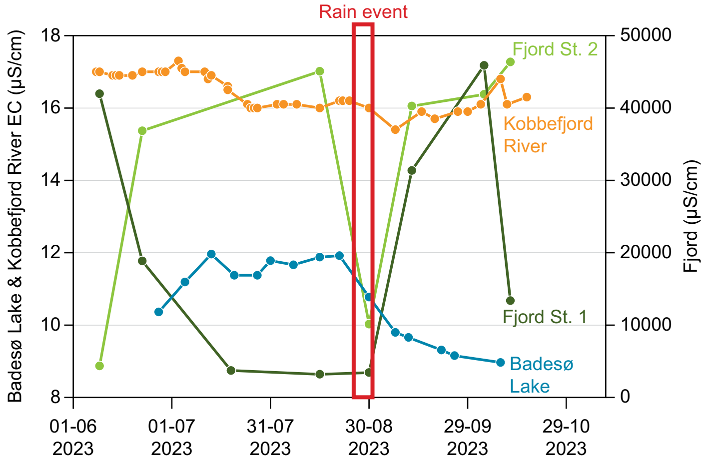


Figure 2. Conductivity values (µS/cm) from Badesø Lake (15 cm below surface), Kobbefjord River and the two innermost Kobbefjord Stations (5 cm below surface).

This study implemented a novel approach combining the efforts of four GEM subprogrammes in studying the seasonal lateral transport of compounds across lake-river-fjord compartments, as well as targeting the effects of intense rain events in Kobbefjord, SW Greenland. A coordinated, intensified sampling campaign in the growing season from May to October 2023, across the four subprograms, allowed for a temporal sampling frequency beyond the regular monitoring and increased the comparability between datasets towards higher seasonal resolution and facilitating detection of pulse events (e.g., heavy rain) and their effects.

Preliminary results highlight the impact of an intense rain event at the end of August. The altered river discharge (Figure 1) could be traced for example in the conductivity measurements (Figure 2) across all ecosystem compartments from land, lakes, rivers, and fjord. Rain events like this not only affect the short-term lateral transport but may also contribute significantly to the overall seasonal and annual transport. The innermost fjord stations highlighted the seasonal freshwater discharge from Kobbefjord River (Fjord St. 1; Figure 2), and while the seasonal signal already diminished by Fjord St. 2 it did reflect the high discharge during intense rain event in late-August (Figure 2).

This project not only employs novel sampling approaches, i.e. stations and timing, but also explores new ways of collaborating within the GEM program. Learning outcomes of this project can be used to evaluate the existing GEM monitoring effort and promote closer collaboration across land-lake-river-fjord ecosystem compartments.

Kobbefjord River photographed on 15-08-2023 (Left) and 30-08-2023 (Right). Photos: Thomas Juul-Pedersen, MarineBasis-Nuuk.

AN UNEXPECTED
TO ARCTIC CLIMATE

At the remote Zackenberg Research Station in Northeast Greenland, we face a powerful force of nature in our pursuit of environmental monitoring data – the iconic polar bear. Driven by curiosity, hunger, or perhaps a playful instinct, the polar bears are increasingly challenging our scientific instruments, leaving behind a series of consequences for the monitoring data.

In the early years of ecosystem monitoring in Zackenberg Valley, encounters with polar bears were rare, but in recent years, polar bear interactions have increased significantly. This may be attributed to the shrinking sea ice in the Arctic. As their traditional hunting grounds diminish, polar bears are forced to venture further onto land in search of food sources, bringing them in closer contact with Zackenberg Research Station and our equipment.

It might sound amusing at first – a polar bear wrestling with a weather station or curiously sniffing at a sensor. But the implications for our research are serious. Every toppled mast, every damaged automatic chamber, and every displaced sensor represents a gap in our precious long-term datasets. Continuous gapless data series are the overarching goal of the GEM programme and these gaps might obscure the very trends we are trying to understand in this changing Arctic environment. The damages aren't always obvious. Even subtle disturbances, such as a slight repositioning of instruments, can skew our readings and mislead interpretations, challenging the integrity of long-term climatic monitoring.

All photos taken by GeoBasis automatic camera.

Authors:
Daniel Alexander Rudd & Mikhail Mastepanov
Aarhus University, Roskilde, Denmark

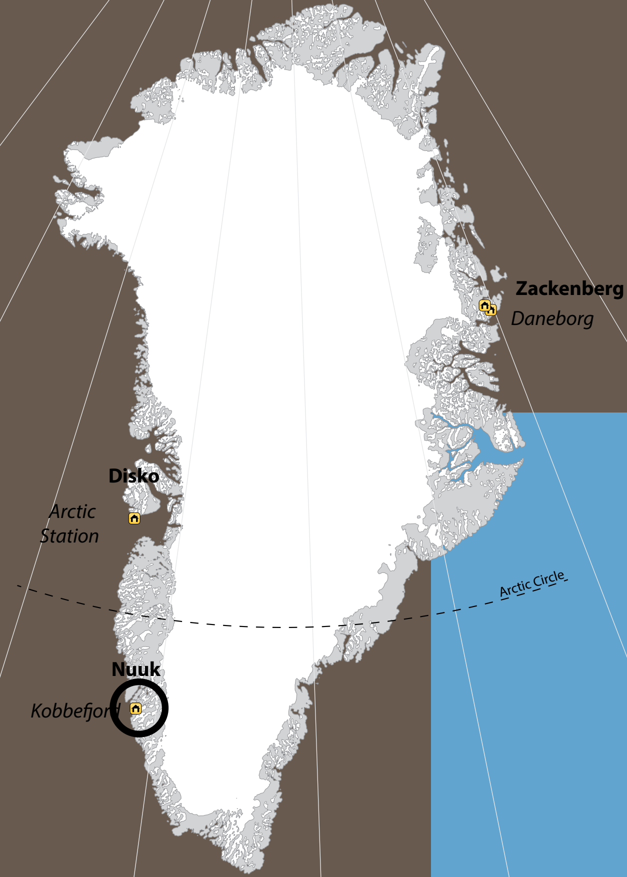
CHALLENGE
RESEARCH

GEM
Greenland Ecosystem Monitoring

Protecting our equipment in this remote and extreme environment is a constant struggle. We've taken measures like encasing wiring in protective panzer tubing to prevent smaller wildlife like arctic foxes to bite the cables for our equipment. However, polar bears are immensely powerful, and we are reluctant to introduce heavy-duty structures that could alter the very environment we are trying to measure with precision. As these bear encounters increase, they underscore the urgent need for innovation: resilient monitoring techniques, redundant systems where possible, and perhaps even a shift towards remote-sensing technologies, where possible. It's a delicate balancing act and this challenge highlights the difficulties of conducting sustained environmental research in the Arctic.

Our encounters with polar bears highlight a broader challenge of Arctic research. It's a reminder of the unpredictable forces at play in this wild and changing region. The climate change mitigation and adaptation depend on reliable data from places like Zackenberg. Every encounter with a curious bear is a testament to the challenges we need to overcome to shed light on the changes in the Arctic, and to the importance of our monitoring programme.

Data of snow depth, greenhouse gas fluxes, and air temperatures are all vulnerable to polar bear interactions, especially during the long, unstaffed winter months where repairs won't be possible until our arrival in spring where the research station opens. These disruptions don't just jeopardize our long-term data; repeated encounters add a significant financial burden to our Arctic research, requiring funds for repairs and, in some cases, the purchase of entirely new equipment when damages are too severe.



Annual Report Card 2023

CATCHMENT

WATER CHEMISTRY AND NUTRIENT

The ecosystems in Greenland are evolving rapidly, with a noticeable increase in vegetation growth, commonly termed "greening." This phenomenon, driven by climate change-induced factors like rising temperatures and altered precipitation patterns, carries significant implications for the region's ecosystems and climate dynamics. Understanding the mechanisms behind Greenland's greening and its effect on biogeochemical cycling is crucial for adapting to these changes effectively.

Streams connect terrestrial ecosystems to coastal areas, e.g., by exporting nutrients and carbon from ice and landscape to sea. In this context, small catchment streams have been suggested to play a disproportionately large role in the land-coast fluxes in the Arctic (Vonk et al., 2023), which highlights the importance of furthering knowledge on nutrient dynamics in small catchments. Therefore, the overall aim of this MSc project is to quantify nutrient dynamics in small low Arctic watersheds during summer, aiming to uncover a possible effect of climate change and greening on nutrient variation in streams.

Recent efforts (Riis et al., 2023) has established a correlation between vegetation dynamics, snow melt, and precipitation in stream catchments and the nutrient composition and variability observed during summer in NE Greenland. This study seeks to extend this understanding by undertaking the following specific objectives: (1) to quantitatively assess the seasonal variation in nutrient concentrations within four streams in Kobbefjord located in Southwest Greenland: (2) to evaluate the significance of catchment characteristics in influencing nutrient concentrations throughout the summer period; and (3) determine the flux of nutrients from the streams to the fjord over the course of the summer season, thus elucidating the role of these streams as conduits for nutrient export from land to coast.

Samples were collected to study water chemistry in three streams with catchments varying in snow cover and Normalized Difference Vegetation Index (NDVI). This was done weekly from June 23rd to August 16th, 2023. Additionally, samples were collected at the outlet to the fjord to estimate the flux of nutrients from the streams to Kobbefjord.

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[1]Aarhus University, Department of Biology, Arctic Research Center, Denmark

[2]Greenland Institute of Natural Resources

[3]Aarhus University, Department of Ecoscience, Arctic Research Center

Data source:

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

River discharge data/GeoBasis https://doi.org/10.17897/H2MR-PP28

Temperature_Air temperature@200cm /ClimateBasis https://doi.org/10.17897/PGN3-7597

CHARACTERISTICS AFFECT
AVAILABILITY IN LOW ARCTIC STREAMS

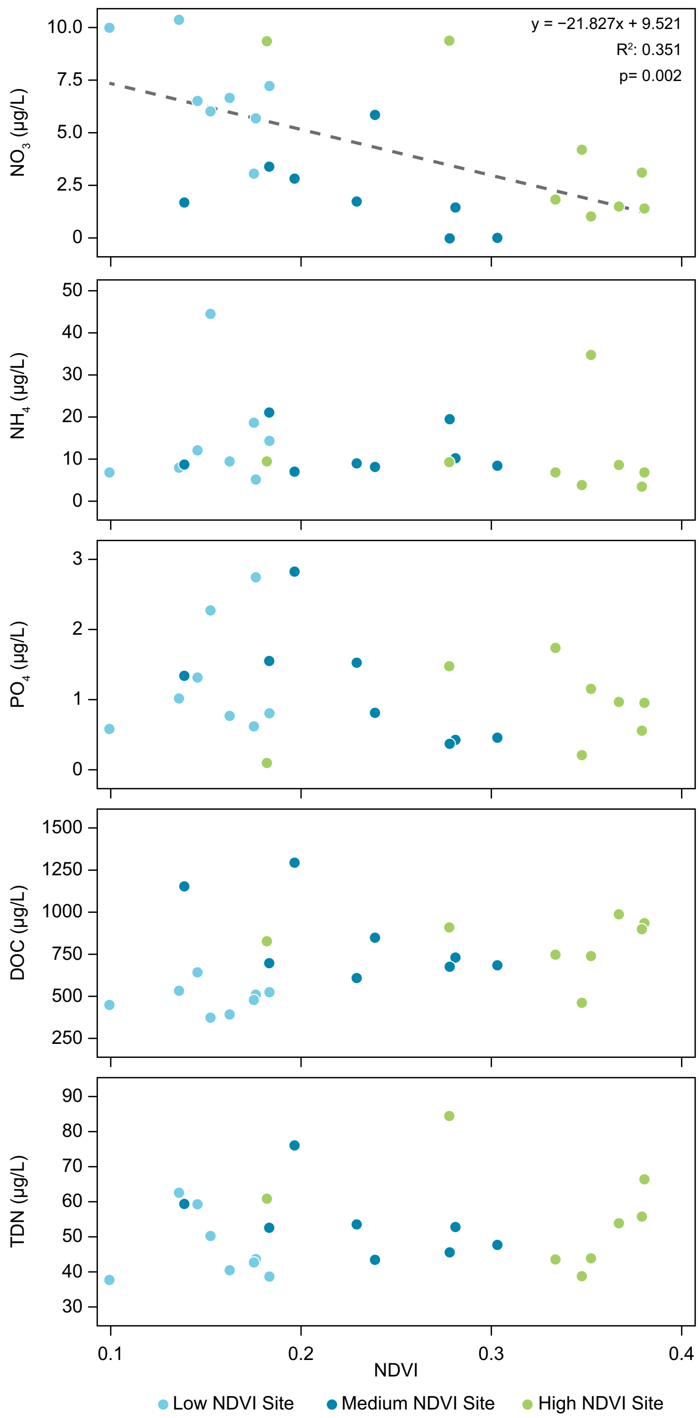
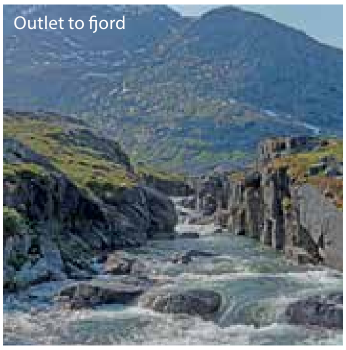


Figure 1. The relationship between the median NDVI for the catchment area of each sampling site and the concentration of nitrate, ammonium, phosphate, dissolved organic carbon (DOC), and total dissolved nitrogen (TDN) in µg per liter. The dashed line shows linear regression (only the statistically significant regression is included in the figure). Each site is indicated by colour.



Preliminary findings reveal a significant negative correlation between NDVI and nitrate (NO_3) concentrations, indicating that potential more vegetation in the catchment (i.e., elevated NDVI) may lead to enhanced nutrient uptake in the landscape and consequently lower NO_3 export (Figure 1). There were no significant relations between NDVI and other water chemistry variables (Figure 1).

This observation suggests that the greening phenomenon in Greenland could potentially influence nitrogen availability in Arctic streams, potentially reducing the nitrogen flux reaching the fjord and causing significant cascading effects on coastal ecosystems. However, further investigation and extended fieldwork are suggested to fully comprehend the discharge dynamics and the consequent nutrient flux towards the fjord. Further investigations should also include comparisons to high Arctic stream systems such as in Zackenberg to increase our understanding of the greening effects on nutrient dynamics and export across different Arctic regions.

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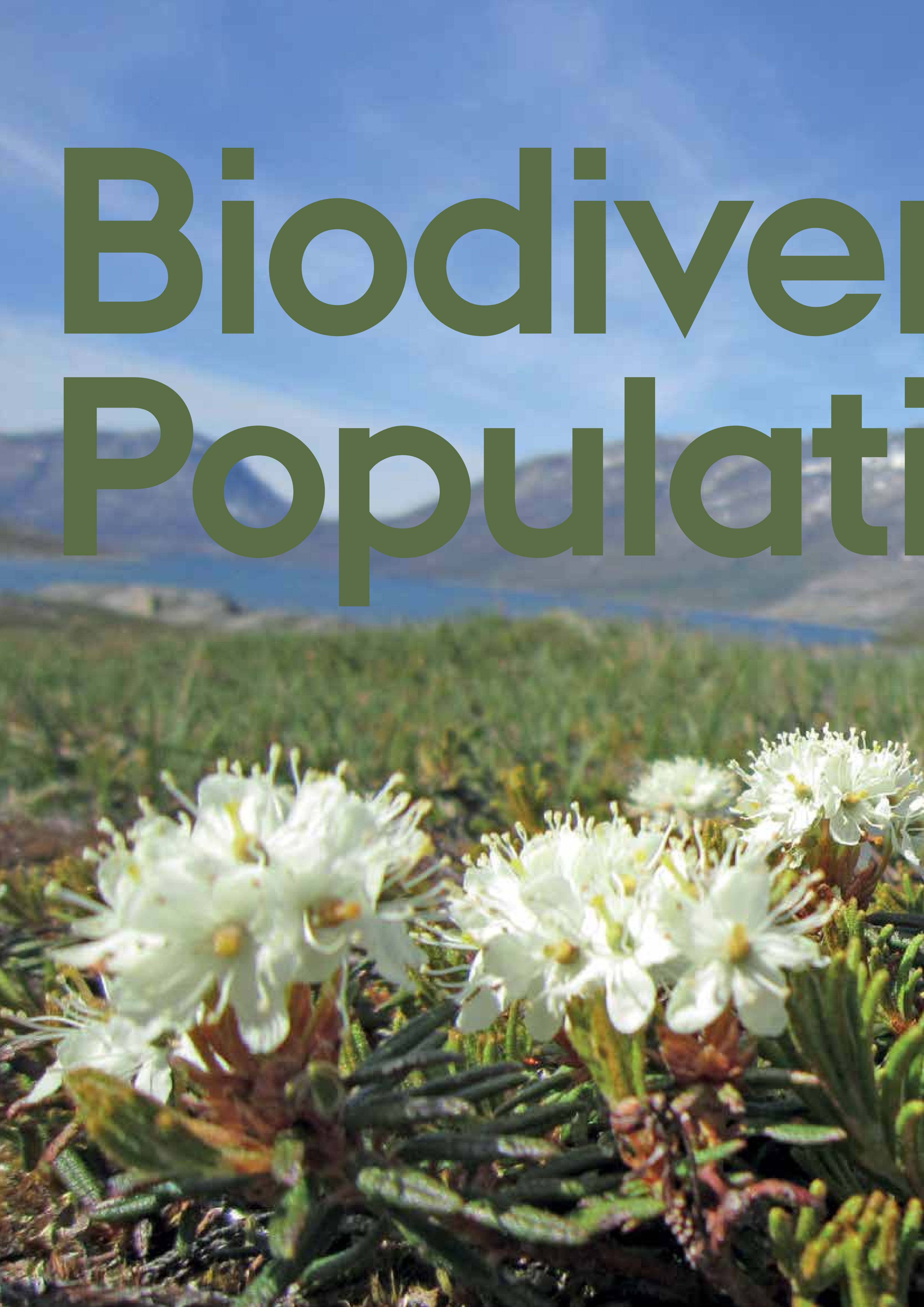

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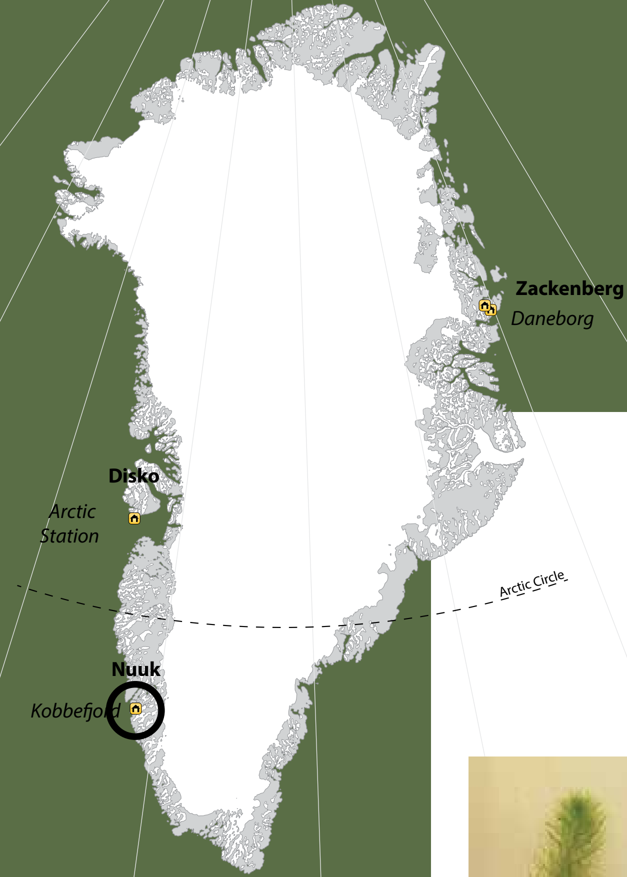
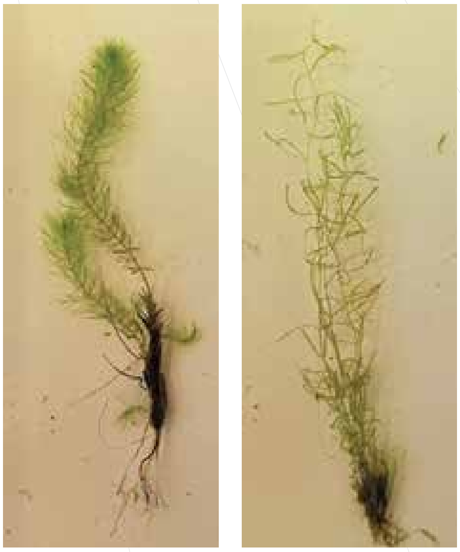
Photo: Katrine Raundrup.



EXPLORING THE COMPOSITION IN BADESØ,

Annual vegetation mapping in Badesø, southwest Greenland, reveals a historical composition dominated by **Callitriche hamulate** *(intermediate water-starwort) and moss. However, since 2018, the emergence of* **Myriophyllum alterniflorum** *(alternate watermilfoil) has shifted the vegetation composition.*



Myriophyllum alterniflorum *(left) and* Callitriche hamulata *(right).*

Badesø (Kangerluarsunnguup Tasia) is located in the Kobbefjord catchment area in Southwest Greenland. The submerged vegetation in Badesø is monitored annually through the GEM programme, where the distribution, density and diversity of submerged vegetation is determined. The macrophyte diversity in the lake is very low, and until recently only two species/taxa were observed in Badesø: *Callitriche hamulata* (intermediate water-starwort) and moss. *Myriophyllum alterniflorum* (alternate watermilfoil) was first discovered in Badesø in 2018 and has been present since.

Climate change is expected to result in major changes in the physical and chemical characteristics of arctic lakes. These changes could result in a change in species composition as well as species interactions (Vincent & Laybourn-Parry 2008). It is therefore interesting to investigate the potential competitive relationship between *M. alterniflorum* and *C. hamulata* to assess what the future macrophyte distribution and diversity in Badesø might look like in the light of climate change.

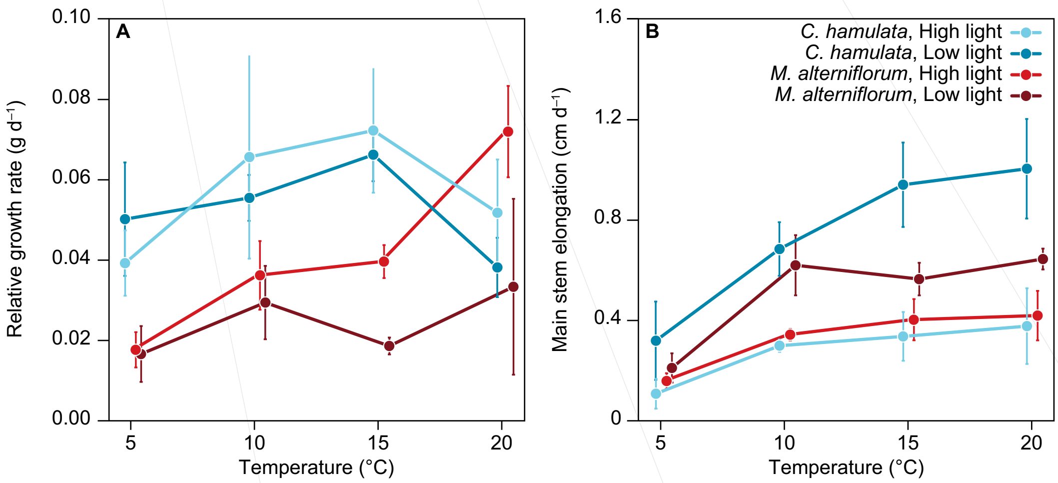


Figure 1. The relative growth rate (A) and main stem elongation (B) of Callitriche hamulata *and* Myriophyllum alterniflorum *grown at four different temperatures (5, 10, 15, and 20°C) and at different irradiance (high and low light) in controlled lab environment for 35 days.*

Authors:

Julie Katzke Simonsen[1,2], Katrine Raundrup[2], Tenna Riis[1] & Torben Linding Lauridsen[3]

[1] Department of Biology, Arctic Research Center, Aarhus University, Denmark

[2] Greenland Institute of Natural Resources

[3] Department of Ecoscience, Arctic Research Center, Aarhus University, Denmark

Data source:

BioBasis Kobbefjord

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

SHIFT IN MACROPHYTE
A LOW ARCTIC LAKE

In this study, the aim is therefore to investigate the difference in growth and photosynthetic response between *C. hamulata* and *M. alterniflorum* at different temperature and light conditions. A further aim is to investigate what determines the distribution and abundance of *C. hamulata* and *M. alterniflorum* in Badesø.

In the laboratory, *C. hamulata* and *M. alterniflorum* were grown at different temperatures and light conditions and their growth and photosynthetic light response were measured.

C. hamulata had a higher relative growth rate than *M. alterniflorum* at temperatures below 20°C. Under low light conditions (representing deeper waters), *C. hamulata* had a higher main stem elongation, especially at higher temperatures (Figure 1). This might infer that *C. hamulata* performs better than *M. alterniflorum* at lower light conditions and at lower temperatures.

The temperature in Badesø in the upper part of the water column (<6m) was 13.5°C in August 2023 (Figure 2), and warmer water temperatures during summer have previously been recorded. If the temperature increases as a consequence of climate change, *M. alterniflorum's* growth conditions may improve. This would result in an expansion of the *M. alterniflorum* population within Badesø, potentially outcompeting the native *C. hamulata*. However, *C. hamulata* performs better under low light conditions, so the future of macrophyte composition in Badesø is also dependent on the future light climate in the lake. If such a change in macrophyte composition will have ecological implications is uncertain, except that in a warmer climate we will expect higher dominance of *M. alterniflorum* at shallow water and dominance of *C. hamulate* at deeper water.

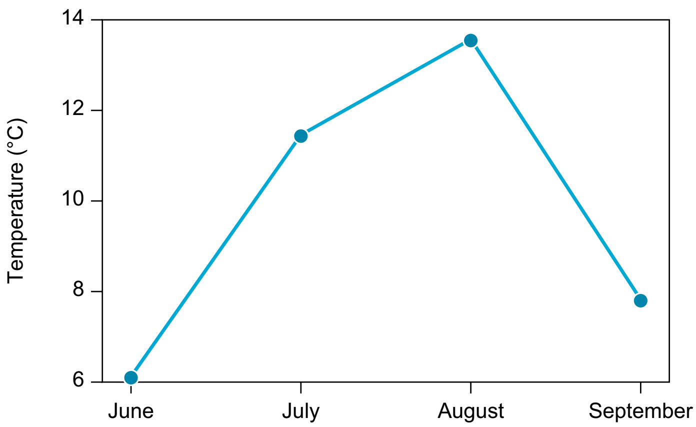


Figure 2. The mean temperature in the upper part of the water column (0-6 m depth) in Badesø during the open water season in 2023.

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THE CHEMICAL TUNDRA INFLUENCES

Access to nutritious forage is key to animal fitness, but the chemical composition of plants vary across the landscape. By combining long-term monitoring data on habitat use and muskox calf recruitment with research data on plant chemical composition, we show that the spatial distribution of essential and non-essential elements in the vegetation across the landscape influences muskox reproduction.

In a recent multi-disciplinary study (van Beest et al., 2023), we investigated linkages between the chemical composition of Arctic tundra vegetation and the reproductive success of muskoxen. Doing so offered new insights into the ecological interactions between herbivores and their foraging environment.

Our study hinges on the premise that the nutritional quality of forage is a critical determinant in herbivore reproduction. However, the spatial heterogeneity of plant chemical composition across a landscape introduces variability in nutrient availability. Our research integrates 25 years of monitoring data on muskox habitat use and calf recruitment with detailed analyses of the chemical composition of tundra vegetation.

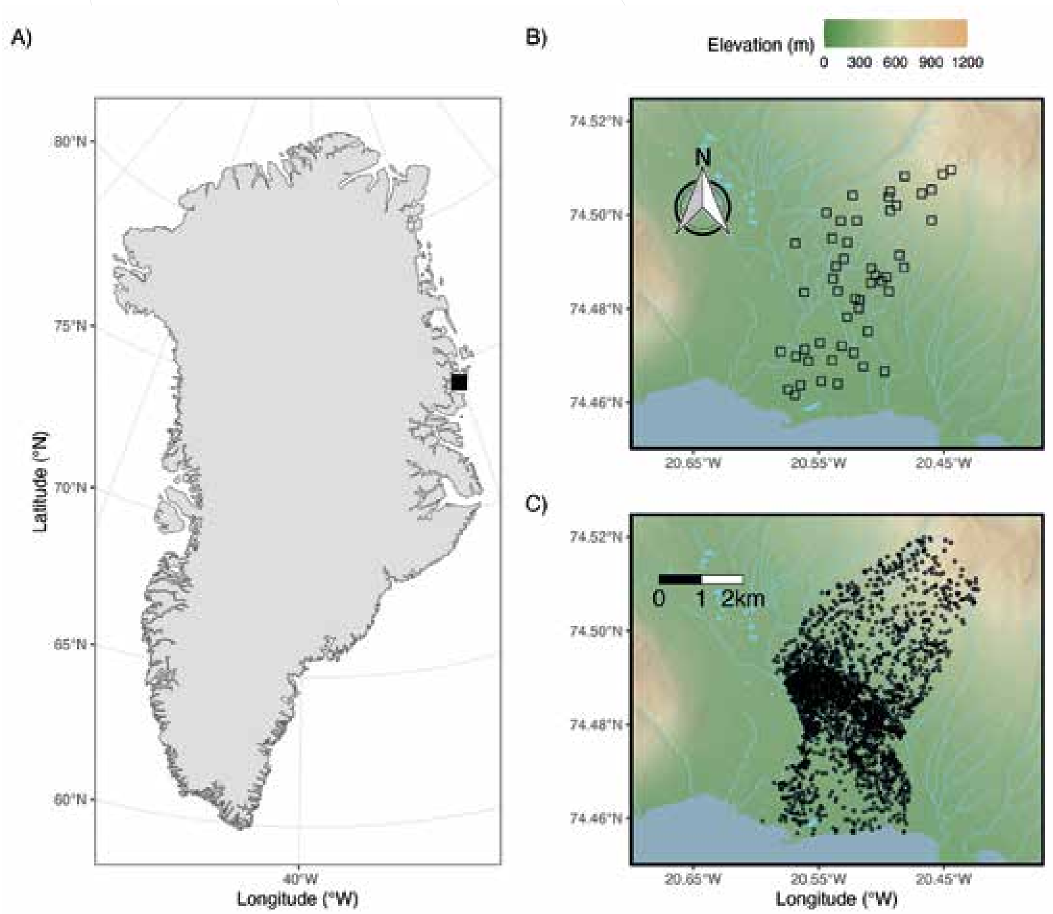

Figure 1. showing in A) Greenland with Zackenberg valley indicated by the black square. B) Elevation map of the Zackenberg valley with the locations of the field plots used to sample plant and soil material. C) Elevation map of the Zackenberg valley with the locations of muskox observations during summer (Jun-Sep) for the years 1996–2021.

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Data source:

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

BioBasis, Research data

COMPOSITION OF THE ARCTIC

GEM
Greenland Ecosystem Monitoring

REPRODUCTIVE SUCCESS OF MUSKOXEN

Conducted in the nutrient-limited ecosystems of the Arctic tundra, specifically in Zackenberg (Figure 1), the study involved collecting plant samples and analyzing them for different elements, categorized into essential (vital for health such as N (nitrogen), copper (Cu), selenium (Se), and zinc (Zn) and non-essential (either not required or potentially detrimental such as lead (Pb), Arsenic (As), and mercury (Hg)). This analysis allowed for the creation of geochemical maps of the landscape, based on environmental factors such as soil moisture, temperature, and elevation with nutrient distribution.

An important aspect of the study was linking these geochemical maps with longitudinal weekly muskox survey data (1996–2021) during July and August (Fig.1). The findings highlighted muskoxen's variable habitat preferences across years, influenced partly by environmental factors like snow cover. Crucially, these habitat choices also correlated with the distribution of essential and non-essential elements in the vegetation.

The study's pivotal discovery was the correlation between muskox reproductive success and foraging behavior. Higher calf recruitment rates were associated with years when muskoxen preferred habitats rich in essential nutrients, particularly nitrogen, copper, selenium, and molybdenum. Conversely, years with higher snow cover forced muskoxen to use areas with higher concentrations of non-essential elements like arsenic and lead, which lowered calf recruitment rates (Figure 2).

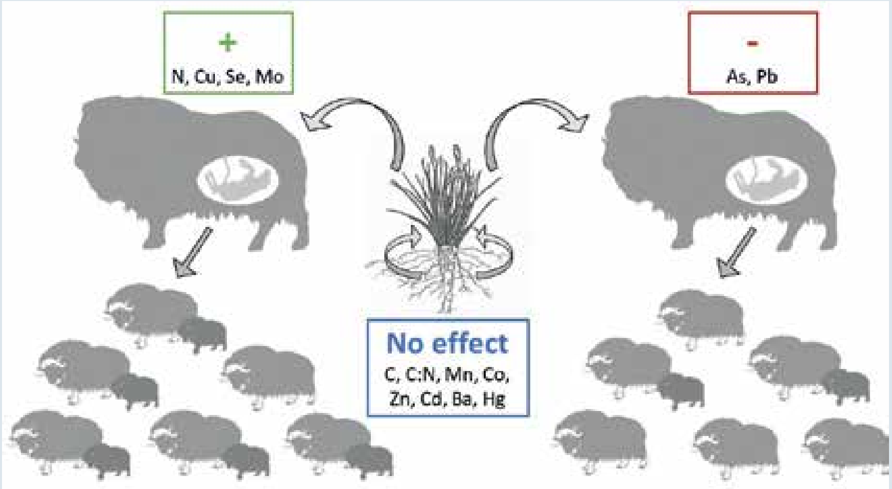


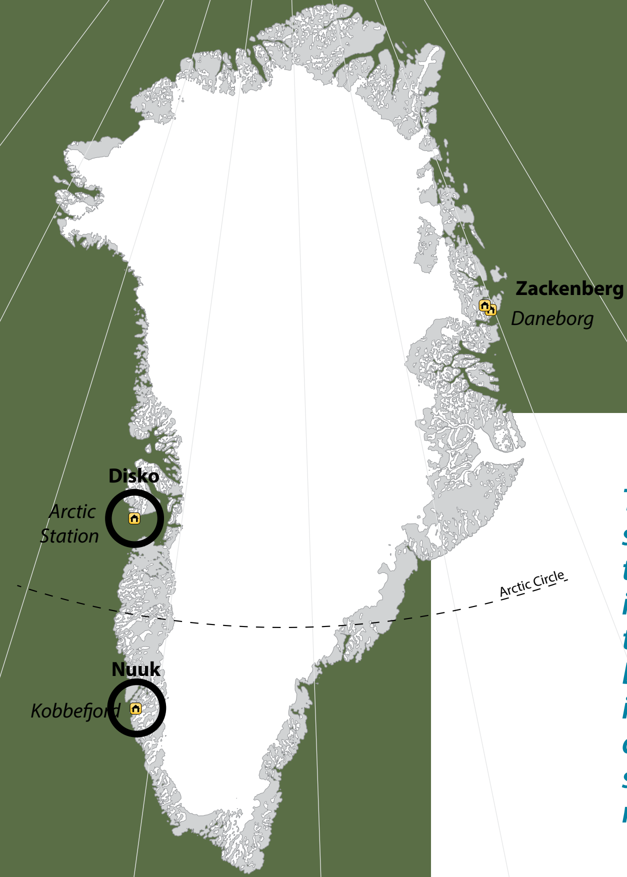
Figure 2. Graphical overview of how the use of geochemical landscapes impacts reproductive success of muskoxen. Essential elements N (nitrogen), Cu (copper), Se (selenium), and Mo (molybdenum) positively influence muskox calf recruitment, while non-essential elements As (arsenic) and Pb (lead) negatively influence muskox calf recruitment. Artwork created by Sophia V. Hansson.

This research underscores the importance of understanding the ecological dynamics between herbivores and their foraging landscapes, particularly in nutrient-limited environments like the Arctic tundra. It also highlights the potential impact of environmental changes (such as permafrost thaw and atmospheric contamination) on the geochemical composition of habitats and their consequent effects on herbivore populations. Our study serves as an example of how ecological and environmental factors intertwine to influence wildlife populations, emphasizing the importance of long-term monitoring data and multidisciplinary approaches in ecological research.

Snowy summers can force muskoxen to forage in nutrient poor areas reducing their reproductive success. Photo: Lars H. Hansen.

References

van Beest, F.M., Schmidt, N.M., Stewart, L., Hansen, L.H., Michelsen, A., Mosbacher, J.B., Gilbert, H., Le Roux, G., Hansson, S.V., 2023. Geochemical landscapes as drivers of wildlife reproductive success: Insights from a high-Arctic ecosystem. Science of The Total Environment 903, 166567. https://doi.org/10.1016/j.scitotenv.2023.166567



REPRODUCTIVE EFFORT
OF DISTRIBUTION OF THE

The intertidal brown alga **Ascophyllum nodosum** *is a habitat-forming species with its northern distribution limit in the Disko Bay. It is expected to expand northwards with climate change, but its reproductive capacity is still unknown for Greenland. We show that* Ascophyllum*'s reproductive effort constitutes 29%-35% of its annual production in the Disko Bay, and increases towards southern, warmer latitudes, suggesting increased reproductive effort with future warming. Furthermore, we quantified a substantial flux of carbon released from the reproductive structures to the surrounding ecosystem at the end of each annual reproductive season.*

The macroalga *Ascophyllum nodosum* inhabits the intertidal areas of rocky shores in the North Atlantic, spanning a wide latitude range, from Portugal all the way to its northernmost distribution limit in Disko, Greenland (Figure 1). In sheltered shores where it proliferates, it creates extensive canopies that provide habitat and resources for the coastal communities (Figure 2a). *Ascophyllum* growth rate increases from North to South, because of the higher temperatures and, in the Arctic, also due to a decrease in ice coverage (Marbà et al., 2017). It is thus believed to expand further north as a consequence of climate change. Given its ecological importance and sensitivity to the changing environmental conditions, the GEM programme gives it a special focus, with the annual monitoring of its vegetative growth. However, no studies have yet addressed the reproductive capacity of *Ascophyllum* in Greenland, which is a basis for its potential to spread. Moreover, as reproduction occurs annually, with the release of high amounts of reproductive vesicles (receptacles, Figure 2b), reproduction contributes to the total production and carbon flux of *Ascophyllum*. As a supplement to the GEM programme, we therefore explored the reproductive effort of *Ascophyllum* at its northern edge of distribution in the Disko Bay (Qeqertarsuaq and Kronprinsens Ejland) and near Nuuk (Kobbefjord) and compared it to data available along the species' distribution range.

Reproductive effort along different latitudes

We quantified *Ascophyllum* reproduction as an add-on to the GEM fieldwork in late summer 2023. The annual reproductive effort was quantified by relating the biomass of the receptacles at the peak of reproduction to that of the annual vegetative growth (at the tips) of the individuals. Our results indicate that reproduction contributes a mean of 29% (Kronprinsen,

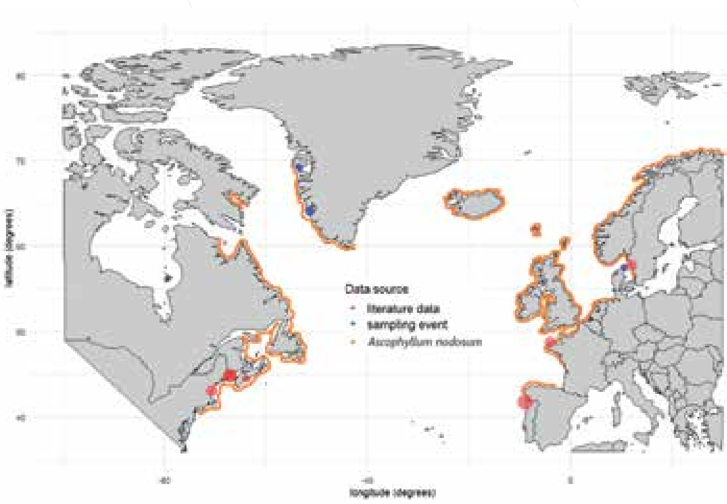


Figure 1. Location of study sites. Red: data was collected from the literature. Blue: sampling sites from this study. The size of the point is proportional to the value of annual reproductive effort of the respective site. Orange line: Ascophyllum nodosum *geographic distribution (based on Pereira L. et al. (2020)).*

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AT THE NORTHERN EDGE

BROWN ALGA

Disko), 35% (Qeqertarsuaq, Disko), and 46% (Nuuk) of *Ascophyllum*'s total annual production (Figure 3). At Qeqertarsuaq, Disko Bay, this corresponds to a reproductive C-flux of 203 (±38) g C m^{-2} yr^{-1}, and at Nuuk to 913 (±233) g C m^{-2} yr^{-1}. Although the reproductive effort at the northern distribution limit in Disko Bay is lower than further south in Greenland, it indicates a potential for reproductive expansion beyond the current northern distribution limit.

When comparing our results with other studies along the whole distribution range we see a decreased reproductive effort with increasing latitude. This finding contradicts a previous hypothesis that *Ascophyllum* populations at the distribution edge allocate relatively more energy to reproduction than those at central distribution range, as an adaptive strategy to cope with the more limiting conditions (Araújo et al., 2015). We propose that the latitude trend may result from the general decrease in temperature and light availability affecting production and that the reduced allocation to reproduction is a result of the species' need to maintain canopy biomass under these growth-limiting conditions. Our results therefore also point at a possible future increase in reproductive effort at the northern distribution edge as temperature increases and ice coverage decreases with global warming.

Figure 2. a) Dorte Krause-Jensen, Constança Albuquerque and Núria Marbà sampling Ascophyllum *at low tide in inner Kobbefjord, Nuuk. B)* Ascophyllum *frond with mature receptacles, collected in Kronprinsen Ejland.*

Ecosystem consequences

Our results document considerable reproductive potential even for the northernmost *Ascophyllum* populations. Our findings also underline that it is important to consider reproduction when estimating this species' annual production and associated carbon flux to the surrounding ecosystems. Part of this carbon flux may support secondary producers in the coastal ecosystem (Josselyn & Mathieson, 1978) and a fraction may potentially contribute to marine carbon sinks (blue carbon). There is evidence for potential contribution of *Ascophyllum* to distant carbon sinks, as high amounts of vegetative biomass have been found floating over considerable distances in Nuup Kangerlua (Ager et al., 2023). To assess how the reproductive biomass may contribute to carbon storage, there is a need to identify degradation rates of receptacles as well as the transportation pathways to potential marine carbon sinks.

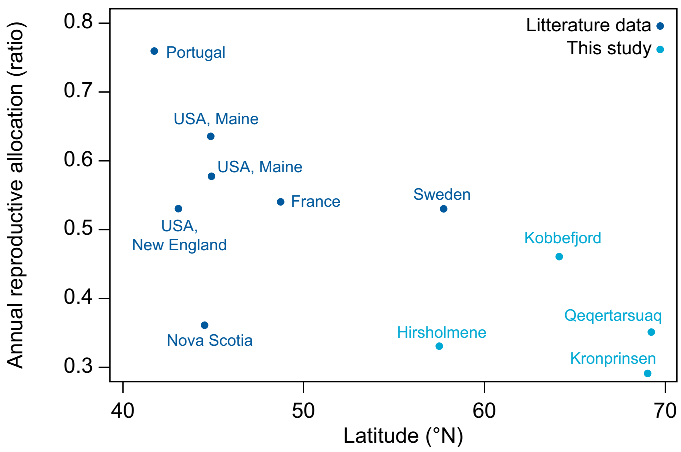

Figure 3. Annual reproductive effort as a function of latitude. Dark blue: sites from which data was collected from the literature. Light blue: sites sampled during this study.

This project was also supported by the EU Horizon 2020 programme (FACE-IT, The Future of Arctic Coastal Ecosystems – Identifying Transitions in Fjord Systems and Adjacent Coastal Areas, contract number 869154).

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FROM DIRECTIONAL TO NOISY INTER-ANNUAL

Photo: Niels Martin Schmidt.

Ten years after the establishment of the long-term monitoring program at Zackenberg, a scientific paper was published, documenting some of the fastest rates of phenological advancement ever observed on the globe. Revisiting the extended data records after another 15 years, we now find that the extreme rates of phenological change have been replaced by a huge year-to-year variation. This shift is attributable to a similar shift in the climate regime, but also to the fact that some species may be approaching the limit of their capacity to track the climatic conditions.

Phenology is the timing of the annual cycles or events of plants and animals, such as flowering or bird nesting. Shifts in the timing of events in response to changes in environmental conditions are well-documented responses to climate change across a wide variety of species. The coherent long-term data series from Greenland Ecosystem Monitoring constitutes a unique source of information from the High Arctic, and over the years, multiple scientific papers documenting phenological responses to climatic variability across a suite of species have been published.

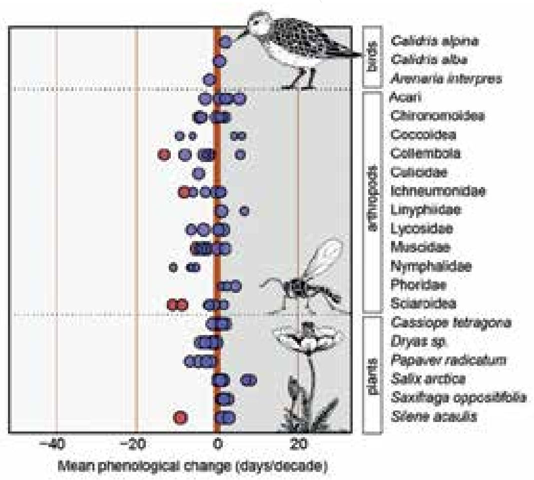

Figure 1. The mean rate of phenological change for plants, arthropods, and birds at Zackenberg 1996-2021. Red dots indicate significant trends, while blue dots show non-significant trends. Dot size indicate the number of years included. Reprinted with permission.

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Data source:

GEM BioBasis

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

CHANGE
VARIABILITY

GEM
Greenland Ecosystem Monitoring


Photo: Jeroen Reneerkens.

In 2007, we examined the phenological responses to climatic variability at Zackenberg during the first decade of monitoring and were able to document unprecedented rates of advancement of spring phenology across a variety of plant, arthropod, and bird taxa (Høye et al. 2007). As one of few from the high Arctic, the paper has been highly cited and has thus been influential for our understanding of patterns in phenological change. However, already in the original publication we acknowledged that the extreme rates of phenological change observed at Zackenberg were unlikely to continue unabated due to limits in the change of climate conditions but also to limits to the plasticity in species phenology. Revisiting the very same time series of phenology after more data has been collected thus appears relevant, to challenge patterns previously unraveled and to update current knowledge.

In 2023, after 25 years of community-wide monitoring at Zackenberg, we re-examined the, now, extended phenological time series (Schmidt et al 2023). Compared to the first decade, rates of phenological change are now very low and close to zero, indicating no directional change in phenology across plants, arthropods and birds at Zackenberg. This shift away from directional trend of continuously earlier spring phenology is attributable to two factors: Firstly, a similar shift in the climate regime has been observed at Zackenberg, with the interannual variation in especially spring snow conditions having increased. Secondly, several taxa appear to be approaching the limits of their phenological plasticity and will thus not be able to track the climatic conditions adequately.

The insights gained from revisiting the Zackenberg time series highlight that variation and not just mean conditions are key to understanding arctic change. Furthermore, even though arctic species are capable of tracking large climatic variability, continued climatic change in the Arctic may decouple some species from their climatic cues, ultimately impacting the function of entire communities. The study also stresses the importance of sustained long-term monitoring and the key role it plays for our understanding of the patterns and processes shaping the responses of arctic ecosystems to the rapid climatic changes in the region.

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Schmidt et al., (2023). Little directional change in the timing of Arctic spring phenology over the past 25 years. Current Biology 33: 3244-3249. https://doi.org/10.1016/j.cub.2023.06.038


Photo: Piotr Lukasik.

PROGR
DESCR

RAMME
IPTION

The program descriptions are restricted to the five data-gathering observational programmes. In addition the Remote Sensing and Modelling programme is now using the observational data from these five programmes for integration.

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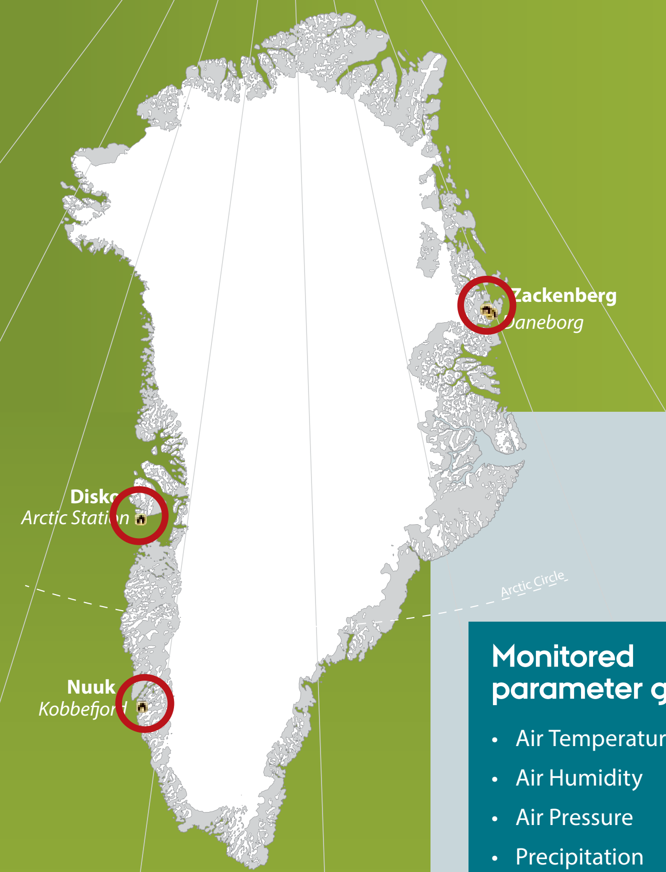
GEM CLIMATEBASIS



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 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 riverbed. 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.

The annual mean temperature in 2023 was close to the longer-term means (2008-2023) at all three GEM sites (+0.5°C, –0.5°C and +0.1°C difference at Kobbefjord, Disko and Zackenberg, respectively).

The two west coast stations at Disko and Kobbefjord exhibited particularly large deviations from their respective long term monthly mean temperatures, synchronously between the two stations but alternating between positive and negative throughout the year. In Zackenberg, on the east coast, the monthly anomalies were less pronounced, but, as is frequently the case, opposite in sign to those on the west coast (see

Monitored parameter groups

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

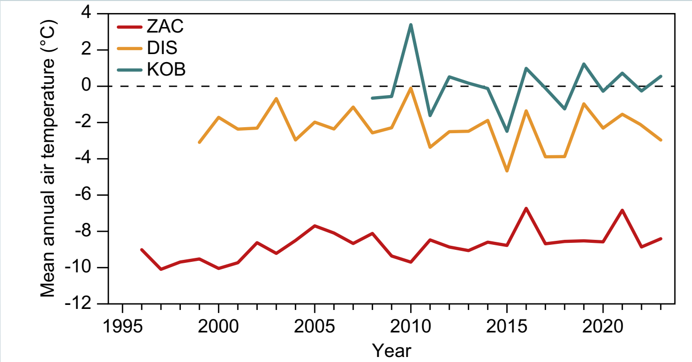


Figure 1. Mean annual air temperature at the three GEM sites Zackenberg (ZAC), Disko (DIS) and Kobbefjord (KOB).

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Disko experienced another very wet year with about 2-3 times the average (2011-2023) rainfall in May-July 2023.

PROGRAMME DESCRIPTION

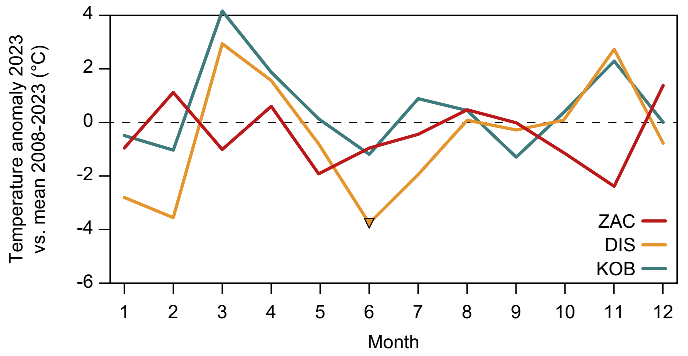

Figure 2. Monthly air temperature anomaly for 2023 compared to the common reference period 2008-2023 for Zackenberg (ZAC), Disko (DIS) and Kobbefjord (KOB). A triangle marks a month whose mean temperature has been more extreme than those of the corresponding month in any other year from 2008-2023. The downward pointing triangle indicates that the month has been the coldest in this period.

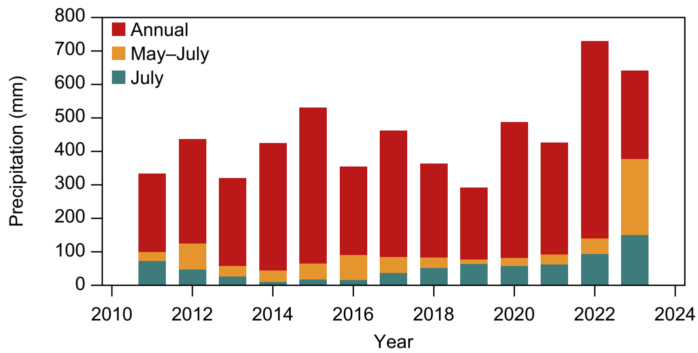

Figure 3. Annual Precipitation for Disko (DIS) showing annual contribution for May-July (orange) and July (green).

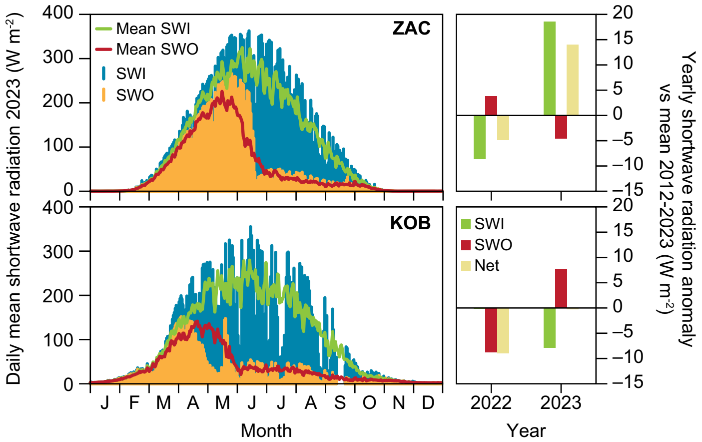

Figure 4. Main plots: Daily mean shortwave incoming radiation (SWI) and shortwave outgoing radiation (SWO) in 2023 with their respective daily means for the period 2012 to 2023 (SWI mean and SWO mean) for Zackenberg (ZAC) and Kobbefjord (KOB). Bar plots (right columns) show yearly mean anomalies for 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.

January-April and October-December in Figure 2). During the summer months, temperatures in 2023 were within 1°C of the long-term mean, with the exception of June. June 2023 was colder than average at all three stations, and in Disko it was the coldest June, not only in the 2008-2023 period, but the 1993. The record began in 1991 and only June of 1992 was colder than 2023.

Disko experienced another very wet year with about 2-3 times the average (2011-2023) rainfall in May-July (Figure 3). On the 7th July, 40% of the total July rainfall fell. This heavy rainfall occurred while there was still snow on the ground. The resultant flooding of Røde Elv destroyed the bridge over the river.

A warm spring resulted in an early snow melt on the West coast, indicated by the drop in outgoing shortwave solar radiation through April, since bare ground reflects less sunlight than snow covered ground (Figure 4). However, renewed snow fall occurred in mid-May both in Kobbefjord and Disko (see GeoBasis report card on the renewed spring snow fall), resulting in another period of snow-covered ground and higher levels of outgoing shortwave radiation.

The incoming shortwave radiation was frequently below average on the West coast, indicating high levels of cloudiness. This is consistent with the below-average June temperatures and high levels of precipitation observed.

Climate station in Kobbefjord. Photo Asiaq.

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GEM GEOBASIS

The GEM GeoBasis Programme

The GEM GeoBasis 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 programme 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.

The season of 2023 was the first year where the four GEM eddy covariance stations have operated as Integrated Carbon Observation System (ICOS) labeled ecosystem stations. Over the past three years the instrumentation, setup, data logging and processing has been standardized across GEM stations to be aligned with ICOS standards, which must be regarded as the eddy covariance community state-of-the-art standards. Zackenberg Fen has been labelled as a Class 2 station, which sets some strict requirements on how the station operates. The other three stations are labelled as Associated Stations, which has a less strict protocol.

The onset of the growing season is closely linked to the timing of snow-melt. At all stations, the growing season (net CO_2 sink) typically begins in late June to early July when snow has disappeared from the ground (Figure 1). The registered snow depth at the three sites for the winter 2022-2023 shows an average seasonal pattern in the snow build up (Figure 2). However, a Føhn-event in beginning of March in Kobbefjord, reaching

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Monitored parameters

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

Landing after UAV survey of snow covered transect in Zackenberg. Photo: Daniel Alexander Ruud.

PROGRAMME DESCRIPTION

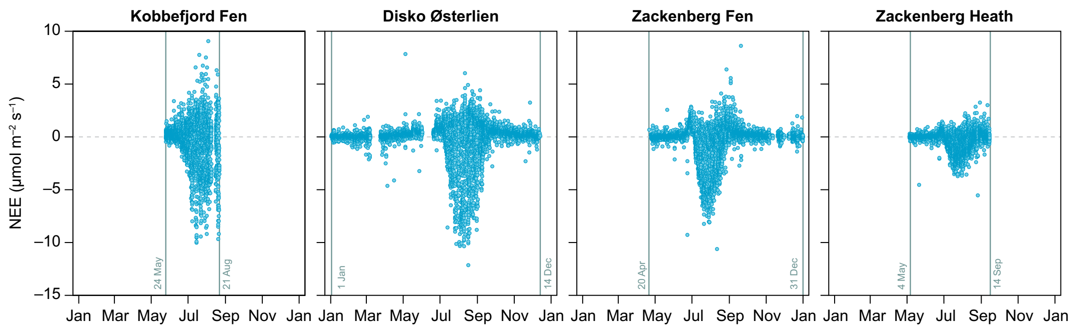

Figure 1. The Half-hourly Net Ecosystem CO_2 Exchange (NEE) is measured at the GEM/ICOS eddy covariance (EC) stations located at Kobbefjord Fen, Disko Østerlien, Zackenberg Fen, and Zackenberg Heath. Negative values indicate a net ecosystem sink of CO_2, while positive values indicate a CO_2 source. Disko Østerlien is the only station connected to grid power, enabling year-round operation. Zackenberg Fen operates on a reliable autonomous off-grid power system during the winter, currently undergoing testing. Kobbefjord Fen and Zackenberg Heath are restricted to operation only when the stations are accessible, affecting data coverage throughout the year (refer to the figure for start and end dates of operation). The range of fluxes varies considerably among ecosystems, with the smallest net CO_2 sink observed at the dry Zackenberg Heath.

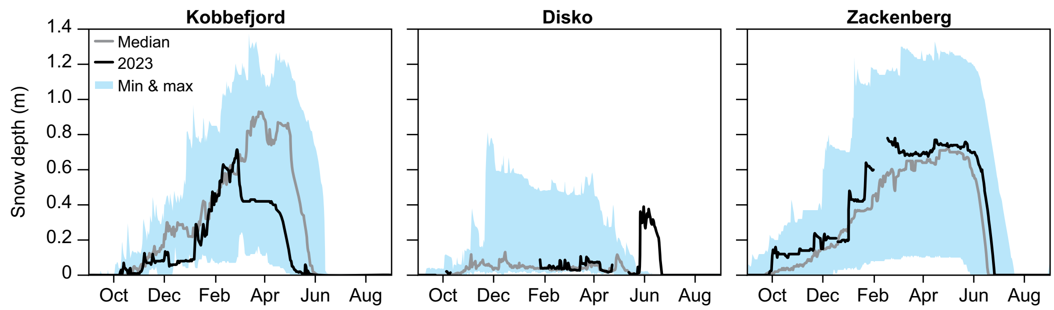

Figure 2. Snow depth measurements in 2023 (black lines) compared to min and max for the historical record (shaded area) and the median (grey line). Snow is a key parameter in Arctic ecosystem functioning. Several different methods are in use to get information on spatial distribution and temporal patterns 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: 2008-2023, Disko: 2012-2023 and Zackenberg: 1997-2023.

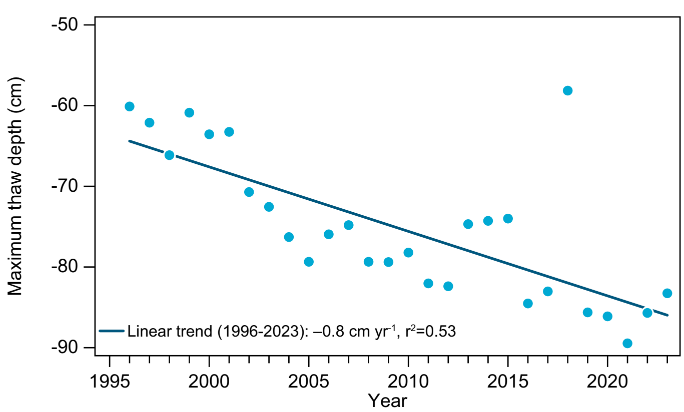

Figure 3. Long-term trend in annual maximum soil thaw depth in Zackenberg Circumpolar Active Layer Monitoring grid # 1 (ZEROCALM-1). Soil thaw and active layer depth are studied under different vegetation types. Monitoring methods include manual probing, as the one shown here, and borehole temperature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

temperatures of 11.8°C, reduced the snowpack by 30 cm in 5 days. With no further snow accumulation apart from a small peak in the end of May the snow disappeared relatively early. At Disko, a heavy snow event in the end of May and early June followed a sparse winter snow cover (Figure 2). Suddenly the area was totally snow covered and snow on the ground lasted until late June. Such an unusual timing and late-lying thick snow cover has a huge impact on other ecosystem processes.

The mean maximum thaw depth of the 110 grid nodes in ZEROCALM-1 reached 83 cm at the end of the summer (Figure 3).

Soil Water sampling from the fen in July 2023. Photo: Karoline Nordberg Nilsson.

Annual Report Card 2023

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 plays a leading role in the development and implementation of their monitoring plans.

Monitored parameters

Vegetation
- Flowering phenology
- Plant community composition
- Plant community distribution and zonation
- ITEX and 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
- Zooplankton abundance and diversity
- Fish stocks

General
- Tissue sampling
- Plot-scale abiotic parameters

All photos: Marie Frost Arndal.

Lead institutions:

Zackenberg:

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Nuuk:

Greenland Institute of Natural Resources

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PROGRAMME DESCRIPTION

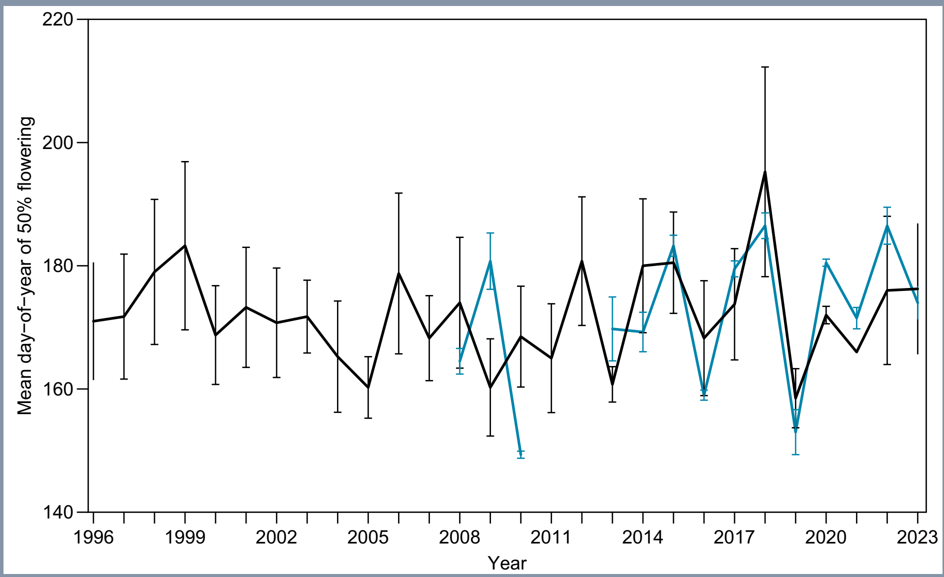

Figure 1. Day of 50% flowering is indicative of the effect of climate variability on the timing of flowering. The timing of plant growth and flowering is important for e.g. insects and herbivorous animals. The graph shows inter-annual variation in mean Salix *flowering phenology during the period 1996 to 2023 in selected permanent plots in Kobbefjord (blue) and Zackenberg (black). Note that no flowering was observed in Kobbefjord in the years 2011 and 2012 due to insect outbreak. Due to the covid-19-induced late arrival to Zackenberg in 2020 and 2021, two out of four plots in 2020 and three out of four in 2021 had reached 50% flowering prior to arrival.*

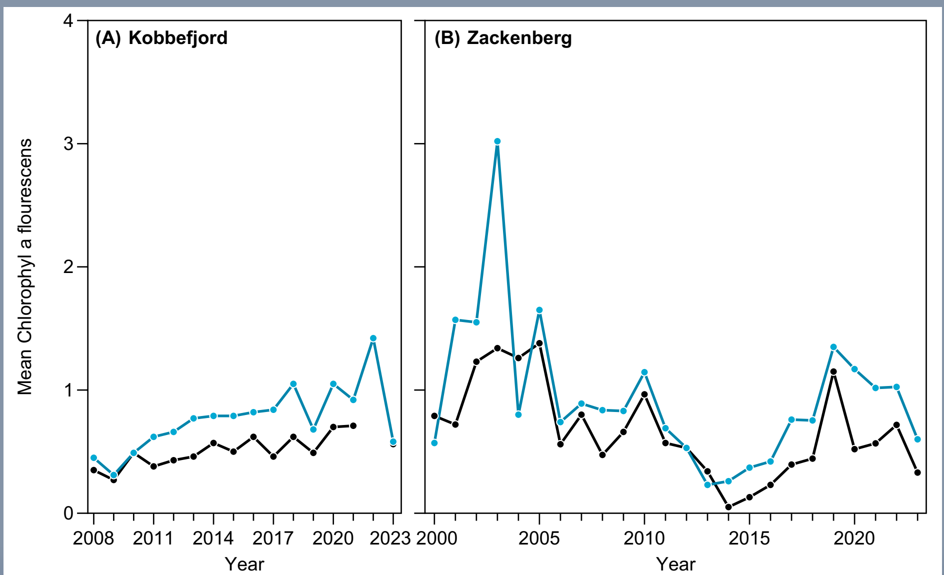

Figure 2. Chlorophyll fluorescence is a measure of productivity in the limnic ecosystem. The graphs show inter-annual variation in chlorophyll fluorescence in lakes at Kobbefjord (A) and Zackenberg (B) 1996-2023. Blue lines indicate lakes with fish, black lines lakes without fish. Note that due to the late onset of the 2020 season at Zackenberg dictated by the covid-situation, only one measurement was conducted in July. In 2022, only one lake in Kobbefjord was sampled due to logistical constrains.

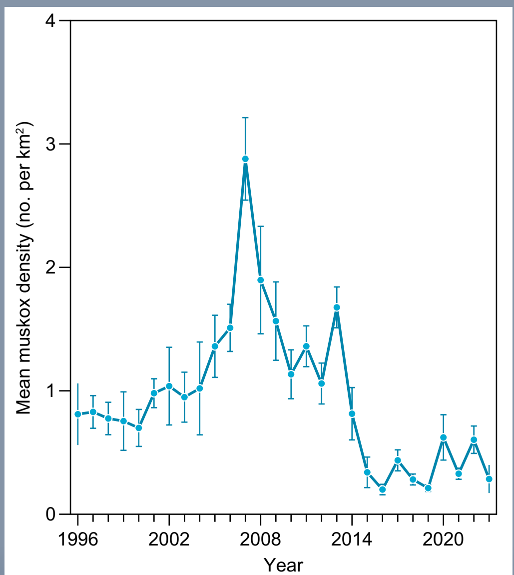

Figure 3. Inter-annual variation in muskox population dynamics (July and August) at Zackenberg 1996-2023.

Annual Report Card 2023

GEM MARINEBASIS

Photo: Christian Sølbeck.

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 working 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).

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

Photo: Christian Sølbeck.

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PROGRAMME DESCRIPTION

GEM
Greenland Ecosystem Monitoring

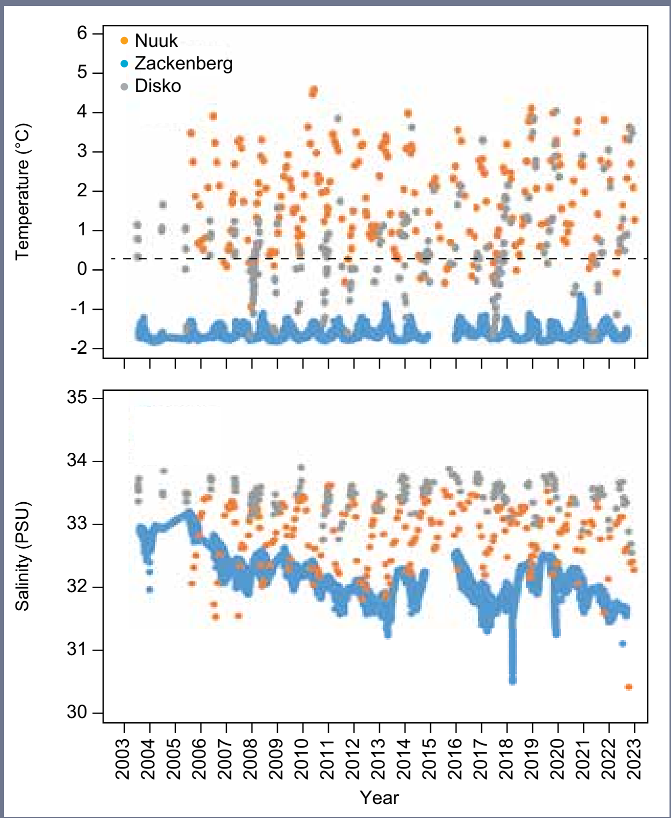
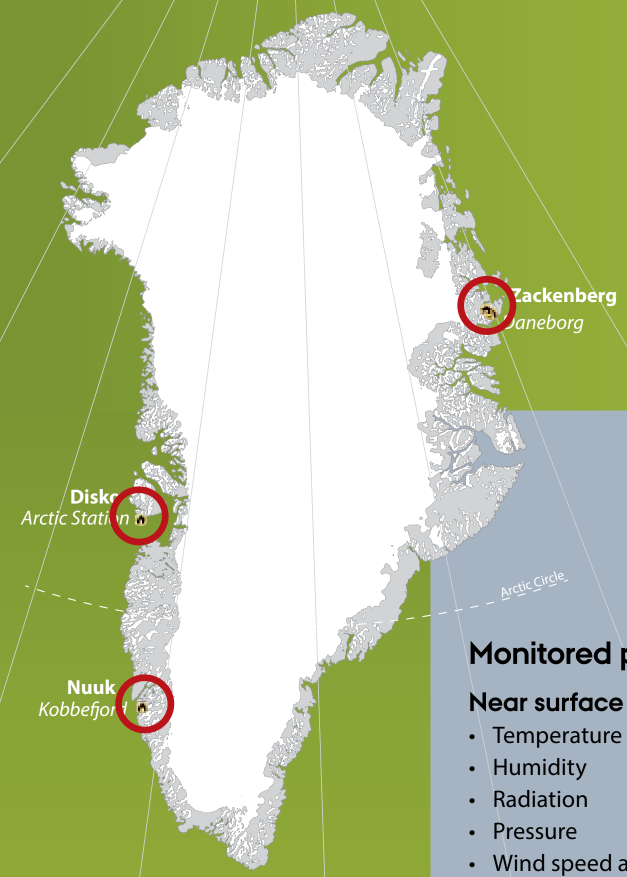


Figure 1. Water temperature and salinity at the permanent monitoring stations in Nuuk, Disko and Zackenberg. The time series from Nuuk and Disko represents one depth (63 m) selected from a monthly profile covering the entire water column. The time series from Zackenberg represents an autonomous mooring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

Photo: Christian Sølbeck.

Photo: Mie Winding.



Annual Report Card 2023

GEM GLACIOBASIS

GlacioBasis primary focus is the monitoring of mass and energy balance of arctic glaciers at the three GEM locations. Through this we aim to provide in situ observations of essential climate variables (identified by AMAP, IPCC, WMO-GCW, WGMS) that enable quantifying the processes that govern the mass balance and the impact of arctic glacier melt processes on future sea-level rise, freshwater inputs into fjord systems and impact on the fjord ecosystem. By addressing the glacier and glacial meltwater runoff components, GlacioBasis contributes to the hydrological monitoring in GEM sites which is essential for understanding linkages between glaciated, freshwater, terrestrial and marine ecosystems. The data are further used for calibration and validation of modeling and remote sensing products such as downscaled temperature from regional climate models, snow extent and discharge modeling.

Globally, ice loss from glaciers is on a par with mass loss from the Greenland ice sheet and accounts for 25-30% of the currently observed rise in sea level (Zemp et al., 2019). Greenland glaciers are the second largest contributor to this global sum. The three GlacioBasis sites are fundamental to the extremely sparse distribution of glacier monitoring sites in Greenland, making up almost half of the existing sites.

GlacioBasis monitors three glaciers: Qassinnguit Sermiat at the Kobbefjord, Nuuk site, Chamberlin glacier at the Disko site and A.P. Olsen Ice cap at the Zackenberg site.

The two West coast glaciers, Kobbefjord and Disko, exhibit similar monthly mean temperature pattern with a warmer than usual March followed by a cooler late spring and warm late summer in 2023 (Fig. 1). Higher temperatures in late summer when the winter snowpack has melted leaves bare ice exposed and leads to greater mass loss. At both sites some melt periods occurred during the winter, visualised with the positive degree days (Fig. 2). Zackenberg also experienced warmer than usual late summer temperatures. The melt season at this site is shorter (tighter temperature curve in Fig. 1), but the total amount of positive degree days was greater by the end of the summer.

Monitored parameters:

Near surface climate:

- Temperature
- Humidity
- Radiation
- Pressure
- Wind speed and direction
- Ice temperature down to 10 m

Surface mass balance

- Snow depth
- Snow water equivalent
- Ice melt *(aws DPT)*
- Winter, Summer, Annual net surface mass balance (stake method)
- Surface elevation change (UAV)

Checking mass balance stakes on Qassinnguit Sermiat, Kobbefjord. Photo: Asiaq.

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Disko:

Geological Survey of Denmark and Greenland

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Nuuk:

Asiaq – Greenland Survey

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GEM
Greenland Ecosystem Monitoring

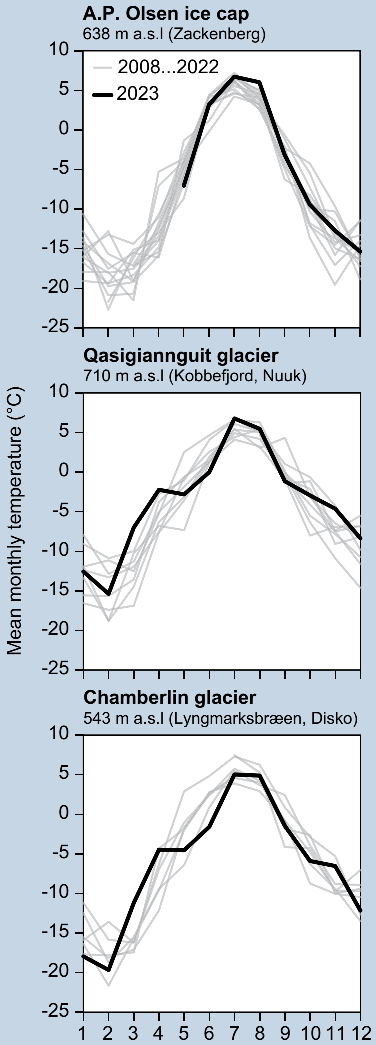


Figure 1. Mean monthly air temperatures from automatic weather stations in the ablation zone of the monitored glaciers at the three GEM sites A.P. Olsen ice cap (Zackenberg), Qassinnguit Sermiaq (Kobbefjord) and Chamberlin Glacier (Disko) in 2023 (black) vs. earlier years (gray).

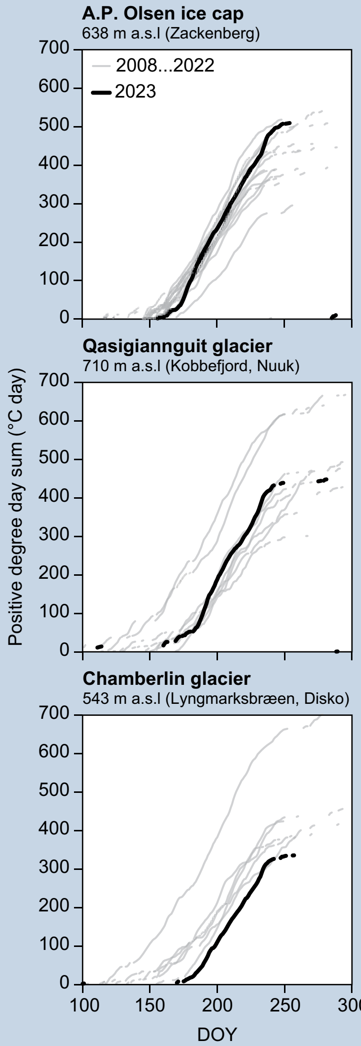


Figure 2. Positive degree day (PDD) sums, indicating melting conditions, from GlacioBasis automatic weather stations in the ablation zone of the monitored glaciers at the three GEM sites in 2023 (black) vs. earlier years (gray). Gaps visible in the curves indicate sub-freezing daily mean temperatures.

Photo:Asiaq

Meltwater channel on the lower tongue of Chamberlin glacier (Lyngmaksbræen ice cap, Disko). Photo: Michele Citterio

Annual Report Card 2023

GEM
REMOTE SENSING PROGRAMME

Ecosystem modelling and remote sensing are key tools for understanding changes and making forecasts for remote and highly heterogeneous arctic landscapes. Since 2022, GEM has implemented several remote sensing and modelling products across the three science thematic structures aligned with the GEM 2022-2026 strategy (see Figure 1) for use by national/international stakeholders and researchers. This new sub-programme helps us to improve the understanding of spatiotemporal trends and variability, uncertainties and feedbacks through the integration of long-term monitoring *in situ* data with established but novel numerical models and remote sensing products. This new sub-programme initially focuses on prototype products and frameworks that are revised, implemented and upscaled across the strategy period once their utility and effectiveness are validated and proven.

Figure 1. Revised schematic illustration from the 2022-2026 GEM strategy showing how each Basis sub-programme (operational structure) explicitly connects with the three new science themes.

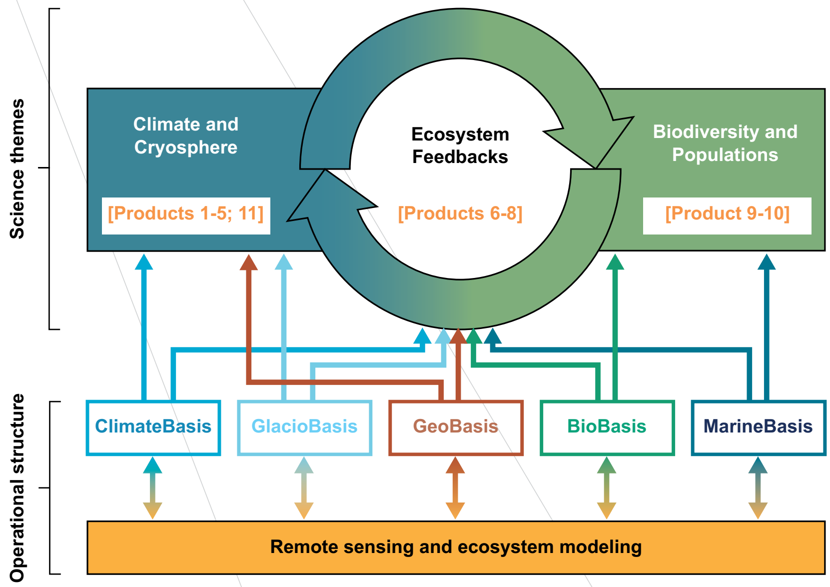
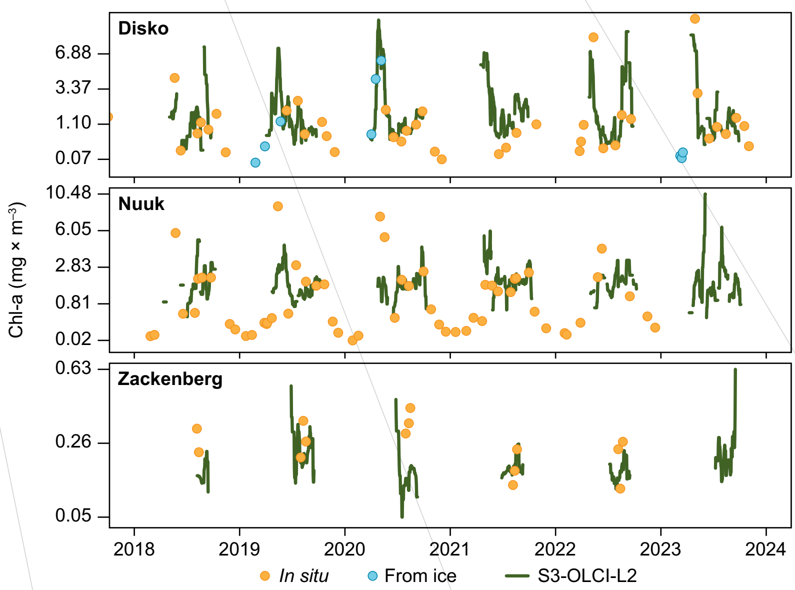


Figure 2. Chlorophyll – a time series for the three GEM sites. Chlorophyll concentration in the ocean is an essential indicator of the presence of phytoplankton, which contributes to the primary production of the system. The remote sensing and modeling GEM subprogramme uses Sentinel-3 Ocean and Land Color Instrument to benchmark the high precision chemical measurements of Chlorophyll-a conducted by the MarinBasis program at the three GEM sites.



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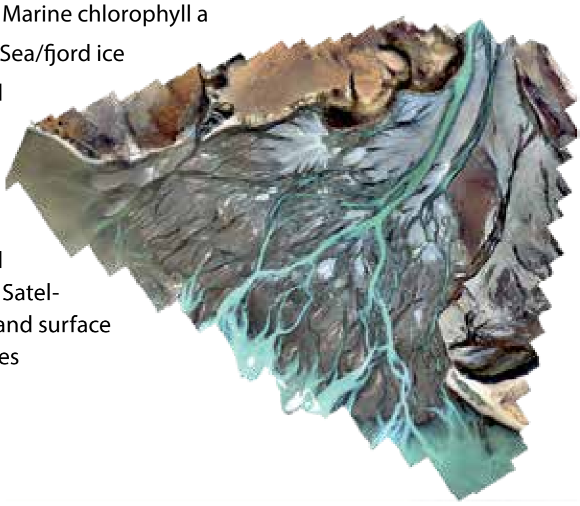
AND MODELING DESCRIPTION

GEM

Greenland Ecosystem Monitoring

Monitored and modeled products in 2023

- Product 1: Satellite-based cloud cover
- Product 2: Downscaled 2m monthly air temperature grids
- Product 3: Skin and sea surface temperature from satellite
- Product 4: Snow depth (snow water equivalent) model
- Product 5: High-resolution snow cover (over land and sea ice) and albedo
- Product 6: Carbon, water, energy cycles modelling
- Product 7: Enhanced high-resolution land-cover classification
- Product 8: Topographic wetness index (TWI)
- Product 9: Spectral and structural canopy diversity
- Product 10: Marine chlorophyll a
- Product 11: Sea/fjord ice
- Operational product 12: Satellite-based NDVI
- Operational product 13: Satellite-based land surface temperatures



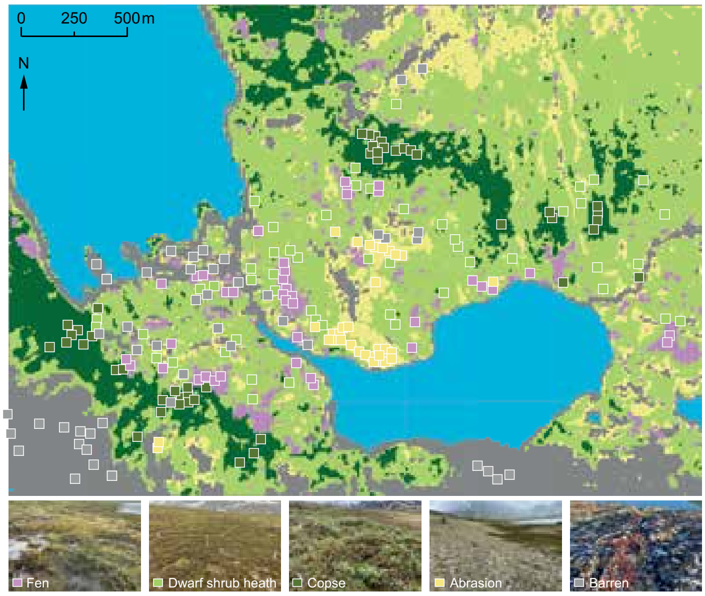
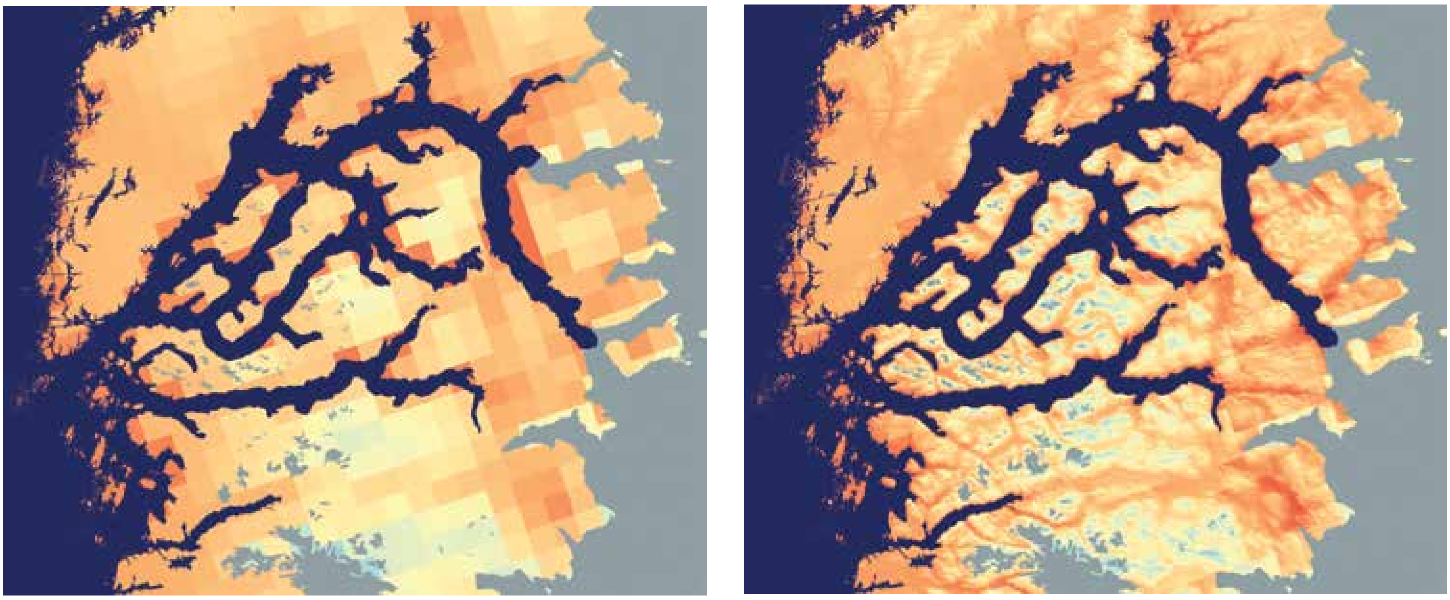


Figure 3. Veg(M)app: vegetation classification mapping. These maps are crucial for expanding our understanding of vegetation types, even though they often come with considerable uncertainties that are not easily resolved. To address this, 264 new ground reference data (GRD) points were collected to enhance the vegetation classification map generated by Google Earth Engine using modern machine learning techniques. The joint effort between the Biobasis, Geobasis, and remote sensing and modeling sub-programmes has resulted in a more detailed and accurate vegetation map for Kobbefjord, and has the potential to help future crosscutting spatial upscaling exercises.

Figure 4 illustrates a downscaled example from a Regional Climate Model, providing mean temperature grids at a spatial resolution of 100 meters and monthly time steps. These grids are downscaled from the Regional Climate Model HIRHAM5 used by the Danish Meteorological Insitute (DMI). The data generated from this endeavor encompasses glaciers, land, and water across the three GEM sites. This level of data resolution enables the correlation of local ecosystem processes and surface mass balances with temperatures from the regional climate model.



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

AARHUS UNIVERSITY

GEUS

ASIAQ

Grønlands Naturinstitut

DTU Technical University of Denmark

UNIVERSITY OF COPENHAGEN

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.

The GEM Remote Sensing and Ecosystem Modeling programme supports the the identification of extreme events, potential tipping points and quantifies processes across a full spatial domain from site to landscape and regional scale.