Greenland Ecosystem Monitoring

ANNUAL REPORT CARDS 2022

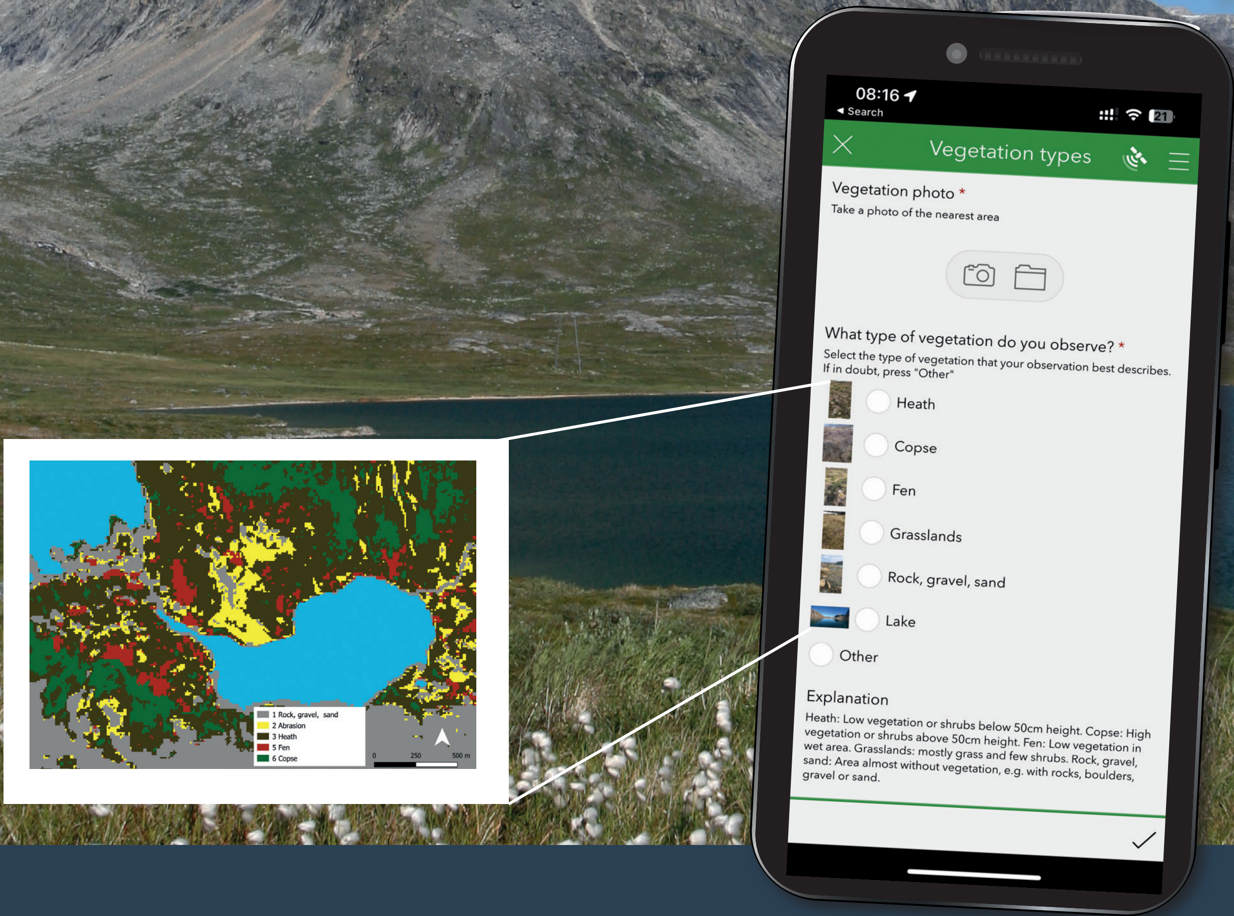

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Photo by Katrine Raundrup.

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GREENLAND ECOSYSTEM MONITORING

ANNUAL REPORT CARDS 2022

GEM

Greenland Ecosystem Monitoring

GEM INTRODUCTION

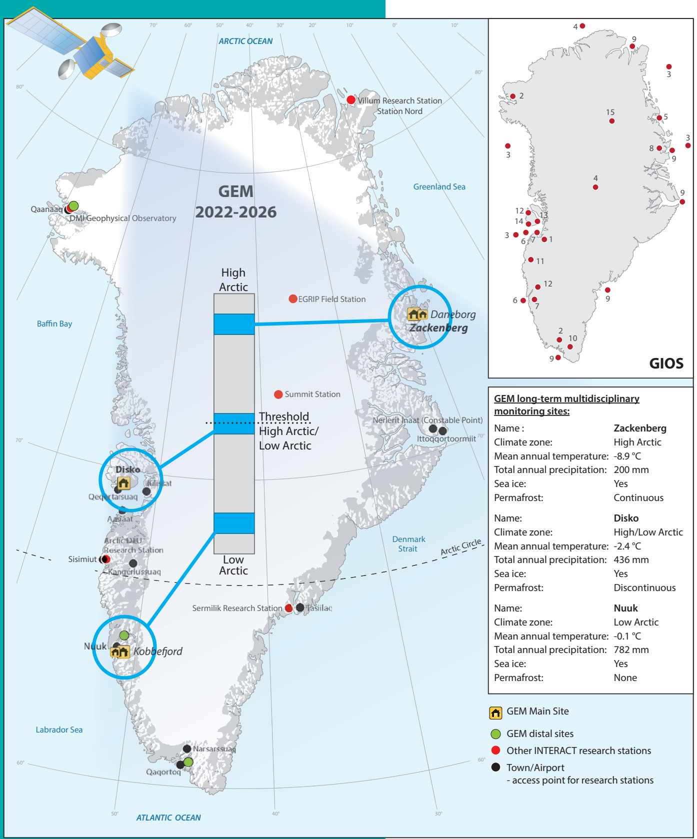

Figure 1. The GEM programme combines intensively studied ecosystems at three main sites (Disko, Nuuk and Zackenberg) with remote sensing and distal sites located along environmental and climatic gradients.

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 (Fig 1).

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

The 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.

- *GEM will consolidate and expand its position as an internationally leading integrated long-term arctic ecosystem monitoring and research programme.*
- *GEM will maintain the continuous update and safeguard the integrity and use of the GEM long-term data series.*

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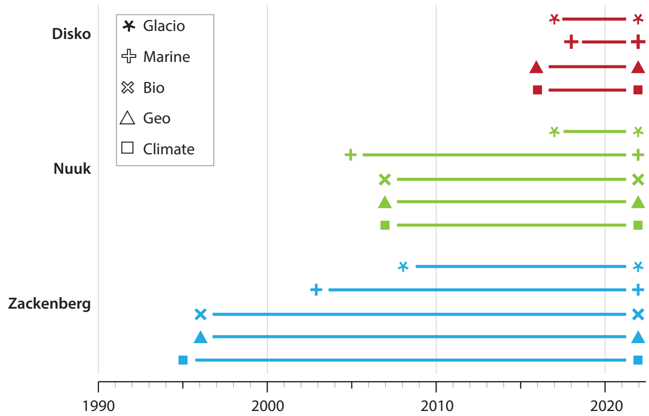


Figure 2. The GEM programme was initiated in 1995 as the Zackenberg Ecological Research Operations (ZERO). In the years 2005-2007 a new main site was established around Nuuk, and in 2016-2018 Disko area was included. All 5 Basisprogrammes are now funded at all three main sites, except for BioBasis at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

GEM
Greenland Ecosystem Monitoring

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/

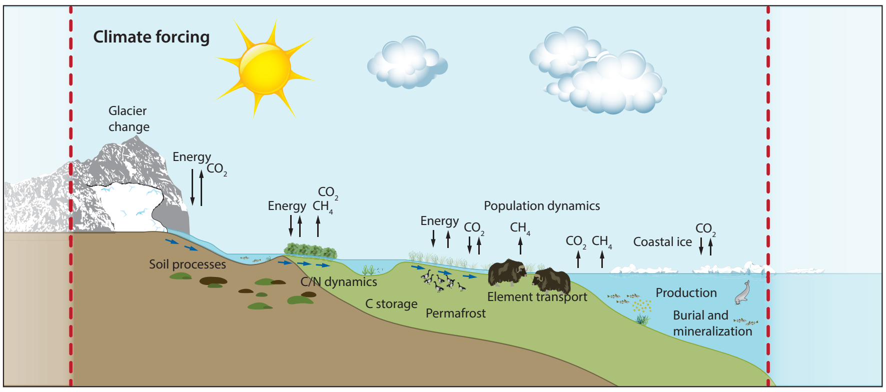


Figure 3. The GEM domain covers the glaciological, terrestrial, limnic and coastal marine compartments of the ecosystem.

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

@GreenlandEcosystemMonitoring

@GEM_Arctic

Greenland Ecosystem Monitoring

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

Arctic Station – Disko.

Zackenberg Research Station.

Kobbefjord Station.

ANNUAL REPORT

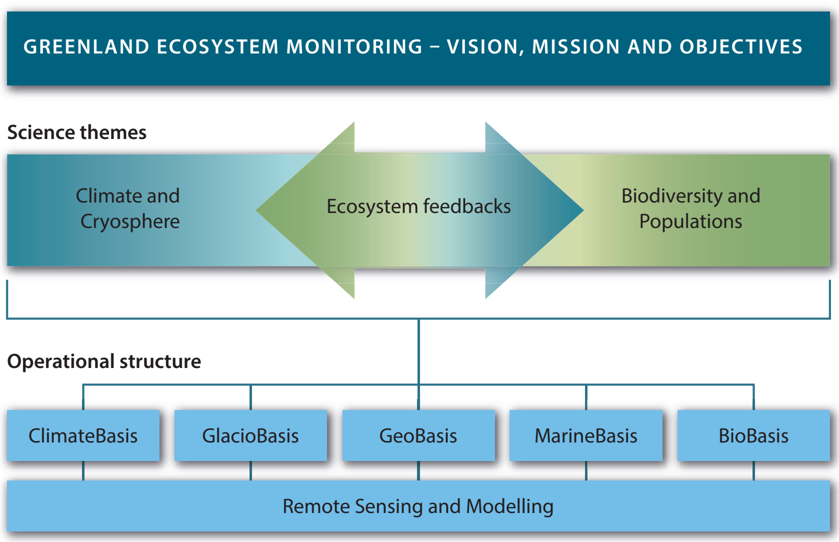
Results and achievements

In 2022 GEM entered a new 5-year strategy for 2022-2026 (strategy). Central to the new strategy is a structure focusing on three science themes under which cross-cutting projects will be conducted over the coming years.

The themes are shaped by insights from the 25 years of GEM operation and the challenges ahead as defined by a broad consensus in the scientific community. The objective is to advance integration across disciplines within GEM, and to clearly communicate and advertise the contents and relevance of GEM data for a wider scientific and stakeholder audience. The basis of the new thematic structure is a division into three fundamental themes:

- Climate and Cryosphere
- Ecosystem Feedbacks
- Biodiversity and Populations

Schematic illustration showing the overarching GEM strategy, the three GEM Science themes and the operational structure (Basisprogrammes).



With the new strategy period, GEM is approaching the conventional 30-years period of WMO Climatological Normals. This 30-year 'Climate Normal', provides an opportunity to assess gradual and abrupt ecosystem changes in relation to this standard.

The GEM strategy 2022-2026 is responding to national and international concerns about climate and ecosystem change by addressing science agendas and data needs of Arctic Council working groups (AMAP and CAFF) and UNs Intergovernmental Panel on Climate Change (IPCC).

The new subprogramme on Remote Sensing and Modelling will form a place where extrapolation and integration of GEM observational data takes place. It will enable both pan-Greenlandic extrapolations as well as projections of ecosystem change following standard IPCC scenarios. As such it will significantly add to the deliverables of GEM towards the above mentioned assessment processes.

The cross-cutting studies and methodological developments described in the Strategy are expected to evolve gradually during the coming years, but examples among the 2022 report cards include already:

- The inter-site comparison and analyses of extreme precipitation and its consequences along the west Greenland GEM sites (Sigsgaard et al.)
- The collaboration across subprogrammes on the measurements of temperatures at different scales and the introduction of citizen science in GEM with the use of an app for improved ground-truthing of vegetation maps (Jacobsen et al.)
- Directly addressing the science objectives of the theme on Ecosystem Feedbacks the report on forecasting C cycling for the GEM sites towards 2100 (López-Blanco et al.)

Torben Røjle Christensen,
Scientific leader of GEM

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2022

GEM

Greenland Ecosystem Monitoring

Solar panels in Zackenberg.
Photo: Carsten Nørgaard

Bongo net sampling.
Photo: Thomas Juul-Pedersen

ANNUAL REPORT

Visit by Minister Lea Wermelin in Kobbe-fjord.

Infrastructure, Green transition and External funding

GEM in 2022 was characterized by further infrastructure developments at all three main sites. Green transition in the operations is a central theme in all these efforts. These include a new solar panel park at Zackenberg as well as transition to solar power at Kobbefjord. Both constructions are funded by the Aage V Jensen Charity Foundation. The renovation of the Arctic Station in Disko was finalized and the station re-opened on July 1.

Arctic Station received a grant from Uddannelse og Forskningsministeriet for new monitoring equipment for MarinBasis. From the same source also instruments for radon measurements at Disko and Zackenberg was aquired to be installed during 2023. Through the EU Arctic Passion project, Arctic Station and Zackenberg received new equipment for GeoBasis.

The extreme rain and associated flooding in West Greenland 2022, as portrayed in one Report Card, had the consequence that the bridge in Kobbefjord was flushed away (see photo below of the remaining bridge in Kobbefjord). This important piece of infrastructure for the GEM program is being replaced early in 2023 as without this bridge our monitoring is severely hampered.

Outreach

There were several VIP visits in Kobbefjord in 2022. The Danish Minister of Environment, Lea Wermelin, visited Kobbefjord in late summer and got an introduction to the GEM programme. Also the Board members of the Aage V Jensen Charity Foundation heard about the monitoring work in Kobbefjord.

GEM at a glance 2022

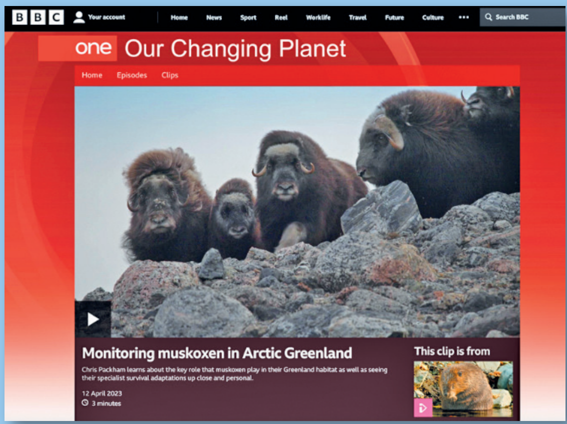
- Active Basis Programmes in 2022: 14 + remote sensing
- Scientists in the field: 69
- Scientific publications: 46
- Conference with GEM representations: 16
- Conference presentations (posters): 9 (6)
- Courses using GEM data: 15

Extreme rain has flushed away the bridge at the station in Kobbefjord in September 2022. Photo: Claus Stampe Spiles.

2022

GEM
Greenland Ecosystem Monitoring

The GEM programme in Zackenberg hosted a BBC team filming muskoxen for the program Our Changing Planet in September 2022. The lengthy program broadcasted on BBC in March 2023 portrayed the work of scientists from BioBasis Zackenberg (Aarhus University), Norwegian Polar Institute and Copenhagen Zoo capturing the animals, taking blood samples and deploying new biologgers to follow their behavior and ultimately population dynamics closer.



International collaboration

Due to the war in Ukraine the direct Arctic Council oriented activities in GEM was largely on halt in 2022. But an effort to work between the working groups AMAP and CAFF on a joint ecosystem-oriented assessment is now under way where GEM data and scientists are expected to contribute significantly. A special issue of a journal will start appearing in 2023.

During the workshop "The Future of Research Infrastructure in the Arctic" in Brussels in October 2022 there was representation of GEM and our research stations in both talks and panel discussions. GEM data has furthermore been presented at several international research conferences during 2022 such at the annual fall meeting of the American Geophysical Union in Chicago.

Education

As an offspring from GEM the UArctic BEFLUX network has been established, organizing summer schools with GEM data as basis for the research training exercises. The first of these schools were organized in Oulanka, Finland, September 2022 (https://zurl.co/VsZs).

The educational project 'Virtuel rejse i arktiske økosystemer – dyk ned i klimaforandringerne' aims to give students a better understanding of climate change and maybe inspire them to do their own research, using data from GEM. The project has been extended for one more year and runs until the end of 2024 (photo 2).

Data from GEM is also being used in a range of courses at both bachelor, master, and PhD level in the educations offered at the section for Geography at University of Copenhagen. Our integration of GEM monitoring efforts, external research projects and research-based teaching offers the students a unique access to long-term datasets of parameters closely linked to key topics of the education such as climate dynamics, interplay between terrestrial ecosystems and climate, carbon cycling, greenhouse gas dynamics etc.

GEM continues also as a central database for the courses organized in Nuuk under the Arctic Science Study Programme (ASSP). ASSP offers both marine and terrestrial oriented ecosystem study courses.

GEM database

In 2022 the GEM database experienced a record number of downloads of our datasets: 1593 downloads were delivered. This is approximately a 40% increase over 2021 and in general underlines a growing number of annual downloads since 2020 when we implemented more FAIR sharing (https://gofair.org) and open data initiatives. We now provide 412 datasets with long term monitoring data of key ecosystems elements from the GEM research stations in Disko, Nuuk and Zackenberg. 232 new users registered to use the GEM database in 2022 and a total of 1584 users are registered.

In 2022 we also started to improve our open science and collaborative efforts when it comes to code and documentation: GEM is on Github, where we progressively will add more public repositories for users and education as well as private repositories for the GEM participating institutions – https://github.com/GreenlandEcosystemMonitoring.

Photo 2: Making educational videos in Zackenberg for high schools students in Denmark and Greenland. Photo: Marie Frost Arndal.

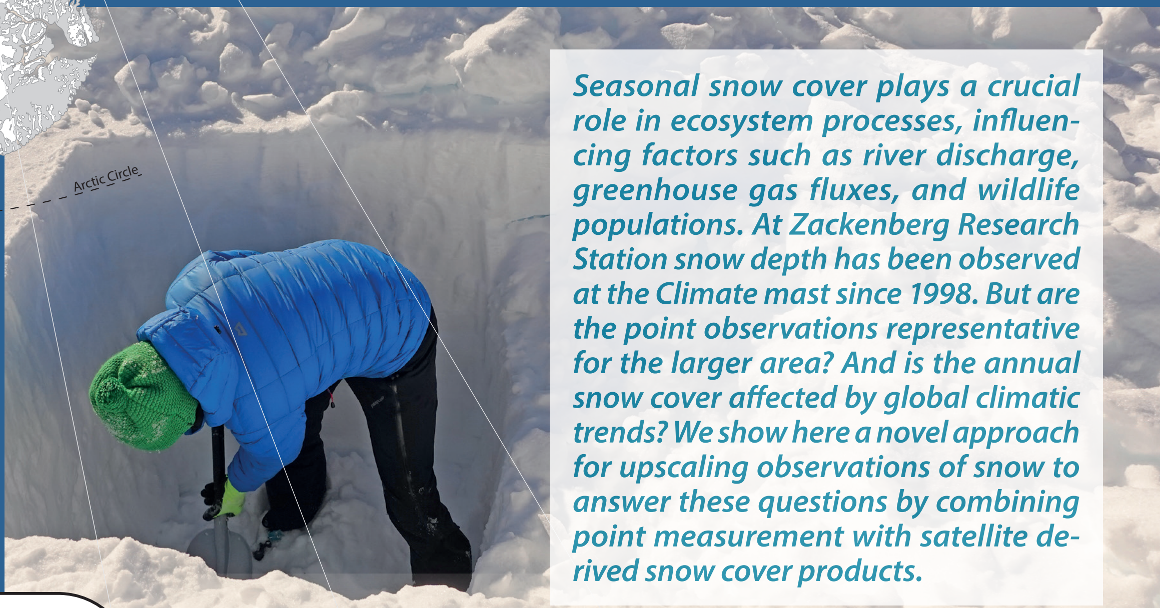

Climate
&

Cryos-phere

Photo: Thomas Juul-Pedersen.

Annual Report Card 2022

TRENDS IN THE SNOW AND SURROUNDING AREA



Seasonal snow cover plays a crucial role in ecosystem processes, influencing factors such as river discharge, greenhouse gas fluxes, and wildlife populations. At Zackenberg Research Station snow depth has been observed at the Climate mast since 1998. But are the point observations representative for the larger area? And is the annual snow cover affected by global climatic trends? We show here a novel approach for upscaling observations of snow to answer these questions by combining point measurement with satellite derived snow cover products.

Photo: Signe Hillerup Larsen

TAKE HOME MESSAGE

Using satellite derived snow cover we can map large scale snow melt dates, and by comparing it to the data from the climate mast at Zackenberg, it is now possible to upscale the observed trends in snow cover to the larger surrounding area.

Warming of the atmosphere will lead to a shorter cold period during which precipitation falls as snow. However, the amount of precipitation on land is also influenced by atmospheric flow directions and the proximity to the open ocean. As a result, the coast of East Greenland is of particular interest due to the impact of changing sea ice cover on the distance to the open ocean. Given the significant role of snow cover in the ecosystem, trends in snow cover can explain other changes observed in the ecosystem and thus is of great interest to investigate.

At the Zackenberg Research Station in NE Greenland, snow depth has been recorded since 1998 at the climate mast, providing over 20 years of data (see Fig. 1). Here, we specifically investigate the timing of snow disappearance from the ground (Fig. 1, left panel) and total snow depth (Fig. 1, right panel). Snow disappearance has occurred as early as May 28th (day 148 in 2009) and as late as July 21st (day 202 in 2018), while total snow depth on the day before melting begins ranges from below 5 cm in 2013 to over 120 cm in 2018. There are three years when snow depth is unusually low: 2009, 2013 and 2019.

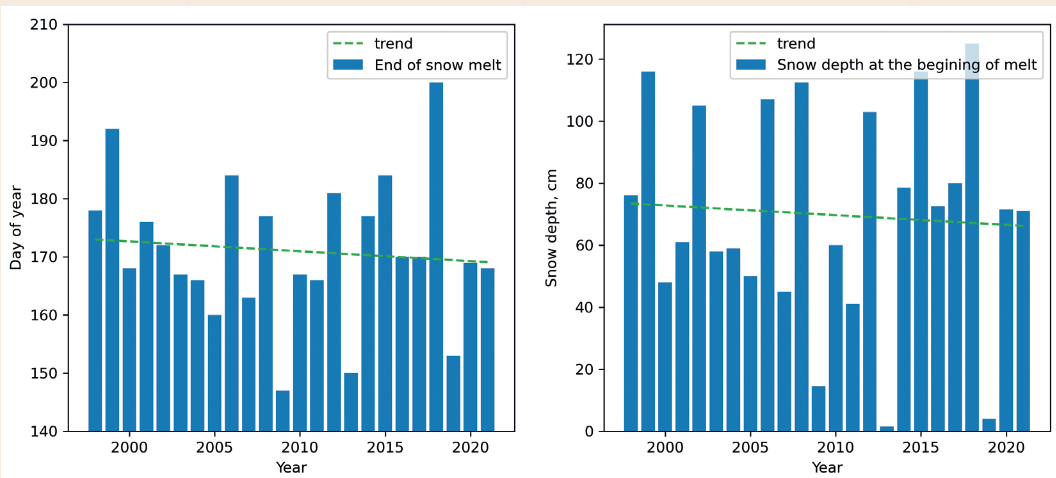


Figure 1. Left: day of year when snow disappears at the location of the climate mast in Zackenberg. Right: snow depth at the mast when the melt season starts.

Authors:

Signe Hillerup Larsen[1] & Kirsty Langley[2]

[1] Geological Survey of Denmark and Greenland, Copenhagen

[2] Asiaq, Greenland Survey, Nuuk, Greenland

Data source:

ClimateBasis data (Meterological data) and GeoBasis (Bulk density) can be accessed via G-E-M.dk. Daily global Snow Cover Fraction - snow on ground (SCFG) from MODIS (2000-2020), version 2.0 can be accessed via the ESA CCI webpage: https://climate.esa.int/en/odp/#/project/snow

COVER IN ZACKENBERG

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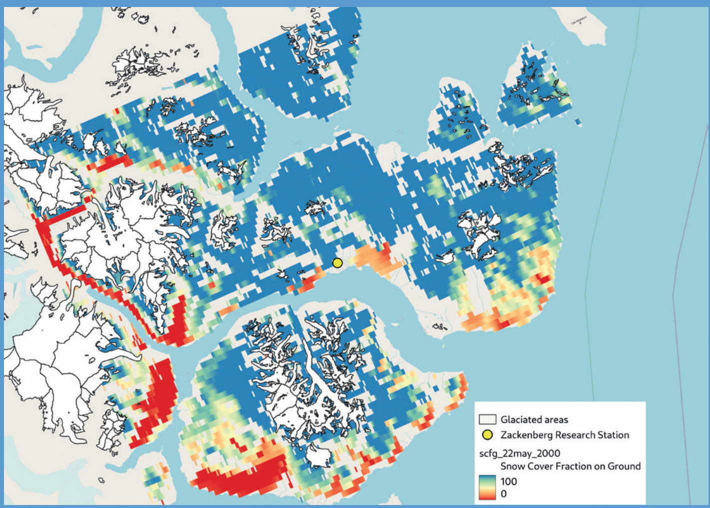


Figure 2. Example of the satellite derived snow cover fraction data product, from May 22, 2000 where blue colours are 100 % snow cover in each pixel and red is snow free pixels.

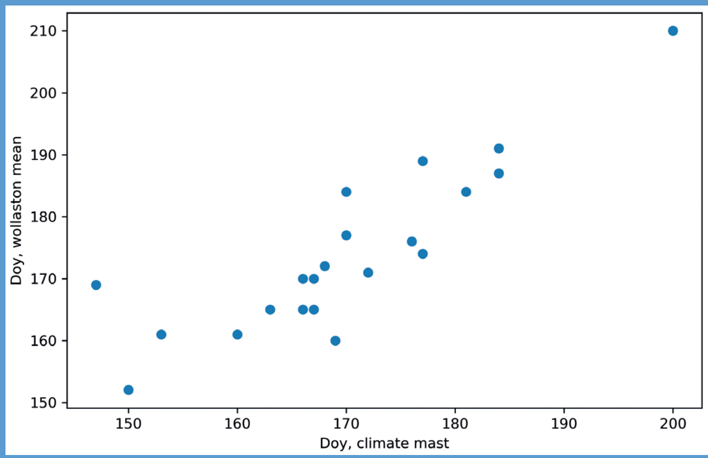


Figure 3. The day of year when snow disappears at the climate mast at Zackenberg Research Station (x-axis), compared with the average of the day of year when snow disappears from each pixel in the satellite derived snow cover product.

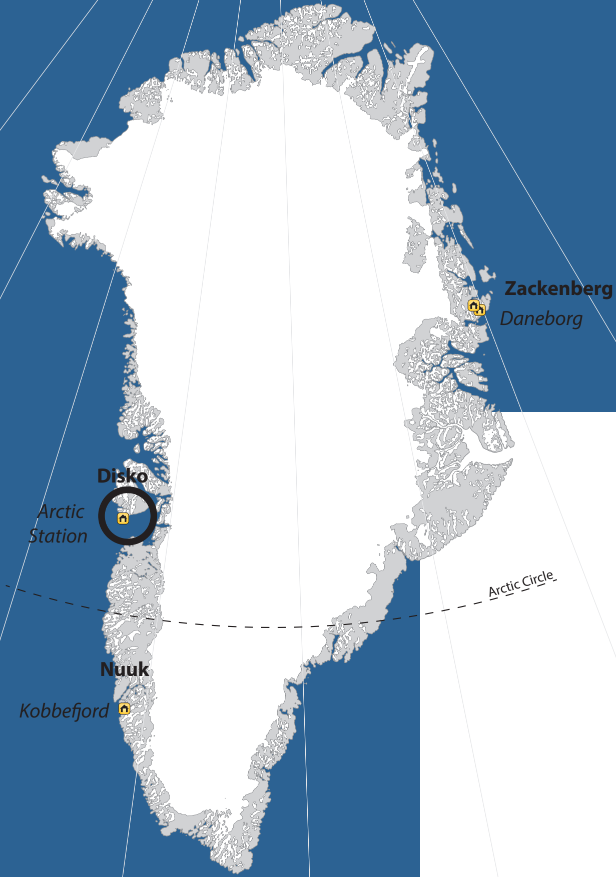
Snow cover is, however, highly heterogeneous due to factors such as wind redistribution and shadows, meaning that point observations may not be representative of larger trends in the area. To address this issue, we used a global dataset of daily snow cover maps produced for the ESA Snow Climate Change Initiative. These maps are based on daily observations from the MODIS satellite and have a 0.01 by 0.01 degree resolution (approximately 1000 by 300 m), covering the period 2000-2020. An example of a single day is shown in Figure 2 and while we cannot determine snow depth from the satellite derived dataset, we can determine when the snow disappears.

In order to combine information from the climate mast with the satellite derived snow cover we compared the average date of the end of snow for the area covering Clavering Island and Wollaston Foreland (Fig. 2) with the end of snow date at the climate mast (Fig. 3). The comparison shows that the trends observed at the climate mast are representative for the larger area. We interpret this as both snow depth and the end of snow observed at the station can be investigated as general trends in the area covering Wollaston Foreland and Clavering Island.

Both snow depth and the date when snow is completely melted away from the ground are highly variable from year to year (Fig. 1). However, there are three years with minimal snow depth: 2009, 2013, and 2019. These three years lower the average of both snow depth and date of end of snow making the overall trend pointing towards a reduction in snow cover. If we disregard the three "extreme" low years, snow depth for the remaining years in the second half of the record are on average higher than in the first half of the record pointing towards a general increase in snow over the period. On the other hand, we could speculate about the possibility of "extreme" years becoming more frequent in the future, and we do observe both the highest and the lowest snow depth in the second half of the record.

This report card demonstrates a novel method for upscaling point snow observations and provides a record of the average snow cover in the area around Zackenberg Research Station. It also shows that "extreme" low snow years are the cause of a slight decreasing trend in snow cover in the area.

Photo: Kirsty Langley



UPSCALING SNOW

THE SNOWMODEL

Snow cover serves as an indicator of climate change and is closely associated with ecosystem processes. Snow characteristics are spatially heterogeneous due to wind-induced redistribution, which further adds uncertainty to the spatial representation of other ecosystem elements. Here we aim to upscale some key snow characteristics and capture the spatial heterogeneity of snow cover by combining the observed meteorological data from GEM with SnowModel, which is in line with the GEM Strategy 2022-2026 regarding ecosystem modeling and ecological forecasting and provides essential information for subsequent simulations oriented towards ecosystem processes.

TAKE HOME MESSAGE

The snow depth, snow onset day and snow ending day exhibit notable spatial heterogeneity even within a relatively small region of approximately 21 km^2. With altitude the snow depth gradually increases, the snow onset day advances, and the snow ending day delays.

Although remote sensing observations of snow cover can represent large-scale patterns, they are still limited in the coarse spatial resolution and low accuracy in estimates of snow depths, especially in complex landscapes such as the ice-free parts of Greenland. Here, we use the southern part of Disko Island, Western Greenland (69°16'N, 53°27'W) as the study area (Fig. 1) and the SnowModel (Liston & Elder, 2006) to simulate the snow depths on 5-year time series (2016–2020), at the landscape scale (approx. 21 km^2) with a high spatial resolution (32 m) at a daily frequency.

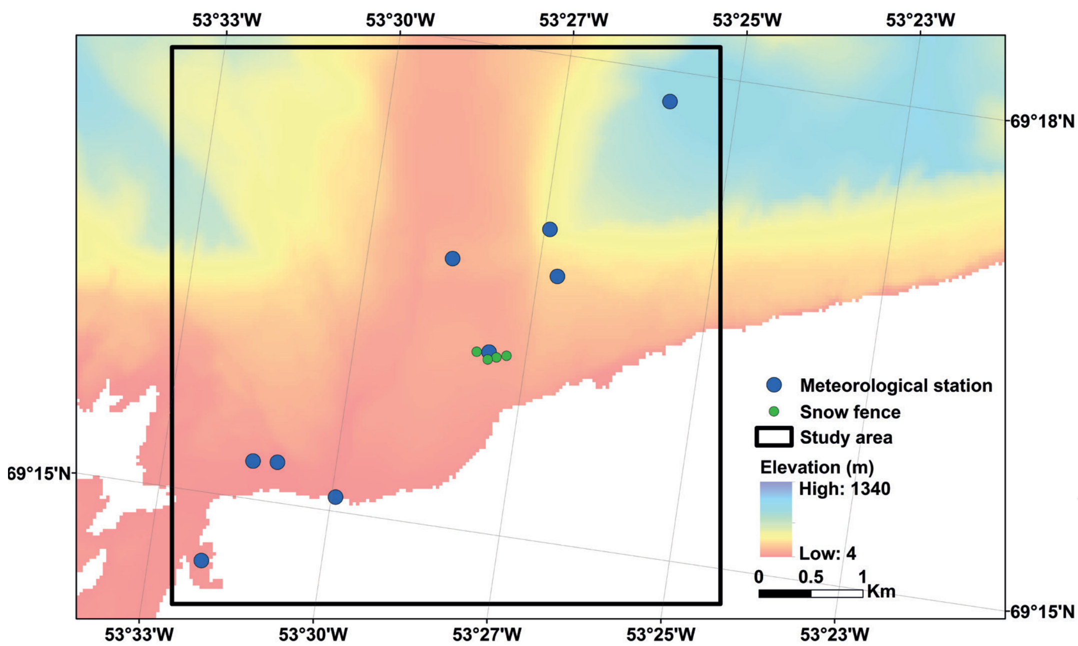


Figure 1. The spatial distribution of sites used to validate the simulated snow cover. Blue dots represent meteorological stations from Greenland Ecosystem Monitoring. Green dots represent 4 monitored snow fences. Snow depths measured across the snow fences are used to validate the simulated snow cover.

Authors:

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[1] University of Copenhagen, Department for Geosciences and Natural Resource Management

[2] Asiaq, Greenland Survey

[3] Geological Survey of Denmark and Greenland

Data source:

ClimateBasis Disko (air temperature, precipitation, wind speed and direction, relative air humidity) and GeoBasis Disko (air temperature, wind speed and direction, relative air humidity).

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

Digital elevation model data is from ArcticDEM (https://www.pgc.umn.edu/data/arcticdem/)

DYNAMICS WITH

GEM

Greenland Ecosystem Monitoring

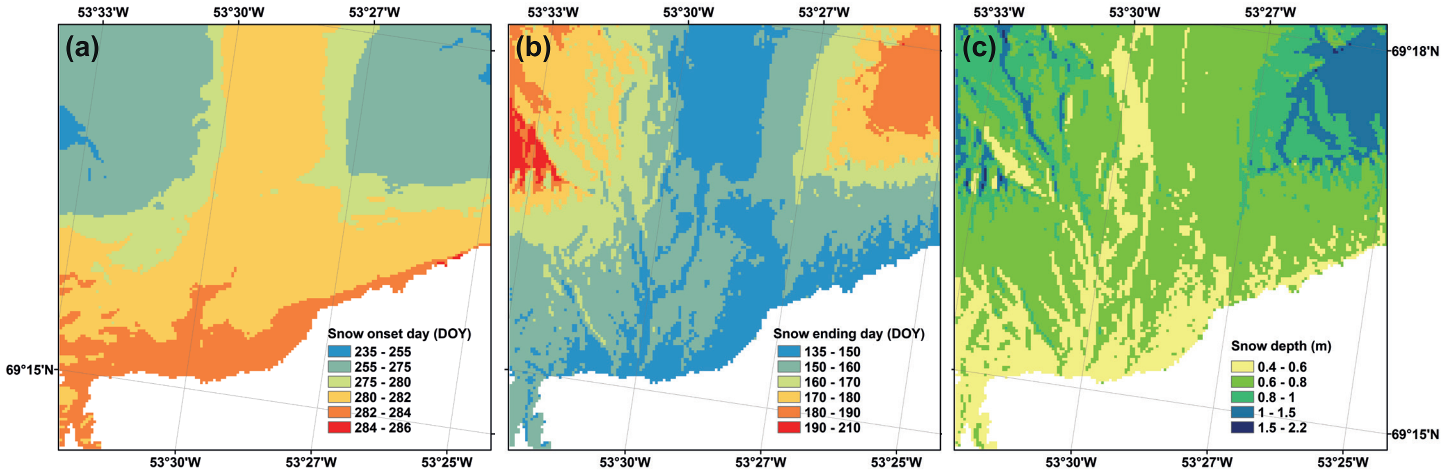


Figure 2. The spatial distribution of the annual mean (a) snow onset day, (b) snow ending day, and (c) snow depth during 2016–2020. DOY = day of the year.

SnowModel is a distributed snow-evolution model running on grid increments between 1 and 200 m and temporal increments between 10 min and 1 day (Liston & Elder, 2006). The model includes a spatial interpolation of meteorological data and simulates the mass- and energy balance, snowpack evolution, and wind-induced snow redistribution, using precipitation, wind speed and direction, air temperature, humidity, topography, and vegetation type. All meteorological data are from ClimateBasis. We use the ArcticDEM (https://www.pgc.umn.edu/data/arcticdem/) to represent topography. Using measured snow depths on snow fences as independent validation data, we found a good agreement between the observed and simulated snow depth (Pearson's R = 0.94, root mean square error = 0.12 m.). The simulated snow depths can give us the first (onset) and last (ending) day with snow, and we found no significant difference between the simulated and observed snow onset day through the study period. The mean simulated snow ending day was delayed 1.6 ±1.5 days compared to the observed dates during 2016–2020.

Figure 2 shows the spatial distribution of snow onset day, snow ending day, and snow depth separately. Generally, the snow characteristics exhibited elevational variability. As the elevation increases, the snow onset day gradually advanced, the snow ending day delayed, and the snow depth increased. On average the snow started to accumulate on the 2nd of October (±6 days) and melted away between on 9th of June (±12 days) across the modeled part of the valley (Fig. 2 and 3). The annual mean snow depth was 0.6–0.8 m. The earliest mean snow onset day and snow ending day were 25th of September and 17th of May (2018–2019), respectively. Snow depth was lowest at 0.58 m in 2019 across the study area and deepest during 2015–2016 with a mean depth of approx. 1 m.

Access to the modeled snow parameters allows for a better understanding of freshwater runoff and soil temperature insulation during winter, as well as linkages with plant phenology and potential legacy effects on gas fluxes during the growing season.

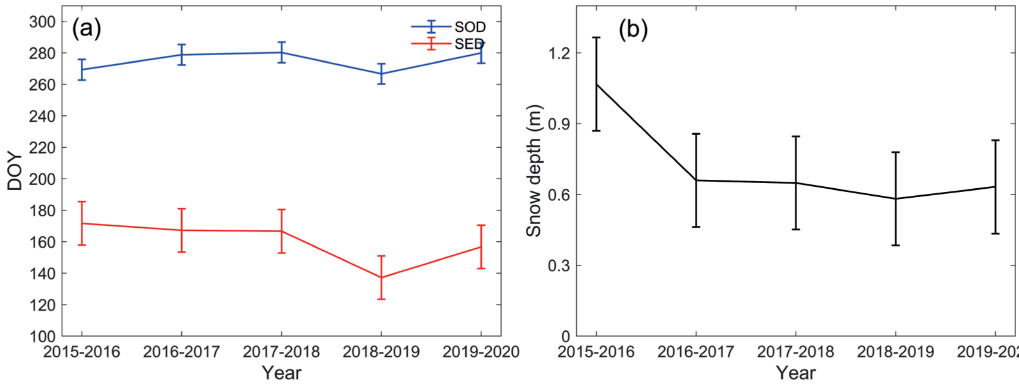


Figure 3 The changes of the mean (a) snow onset day (SOD) and snow ending day (SED) and (b) snow depth across the study area during 2016–2020. Error bars are one standard deviation of the annual means. DOY = day of the year.

References

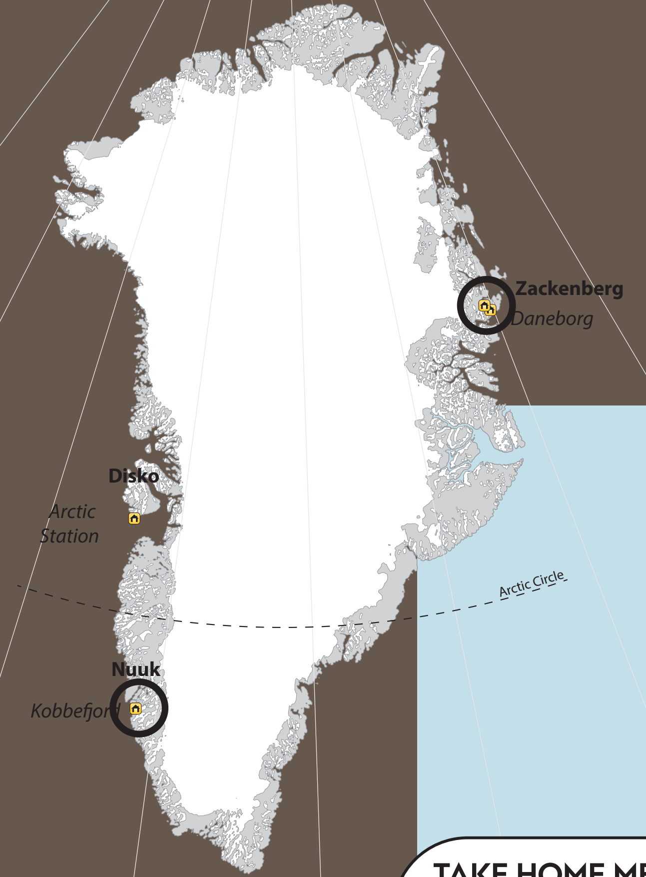
Liston, G.E. & Elder, K. (2006a). A distributed snow-evolution modeling system (SnowModel). Journal of Hydrometeorology, 7(6), 1259-1276. https://doi.org/10.1175/JHM548.1

Ecosyst
Fe

em
edbacks

Photo: Charlotte Sigsgaard

WHAT WILL THE
OF KOBBEFJORD AND



Currently, climate and ecosystem models are the only tools able to predict climate change. In a recent data-model study we integrated in-situ GEM data, an ecosystem model, and DMI regional climate projections. The results indicate a larger carbon (C) storage capacity at two of the GEM sites by 2100. The modelling framework suggests that changes in local plant traits such as foliar nitrogen will have a comparable impact on net C uptake to that of climate change.

TAKE HOME MESSAGE

Climate change and foliar nitrogen will equally control the future net carbon (C) storage in wetlands from Greenland.

Authors:

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[4] Copenhagen University, Copenhagen, Denmark

[5] Danish Meteorological Institute, Copenhagen, Denmark

[6] Asiaq, Greenland Survey, Nuuk, Greenland

Data source:

ClimateBasis data (meteorological variables), BioBasis data (NDVI), and GeoBasis data (C fluxes, C and N stocks, plant greenness, snow depth, and soil water chemistry information).

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

The continuous change in observed key indicators of climate change[1] such as the increase of temperatures and precipitation, reduction of snow cover, and permafrost thawing will have marked but uncertain consequences for the ecosystem carbon (C) sink-source functioning of the Arctic. One of the ambitions of the new *Remote Sensing and Ecosystem Modelling* GEM sub-programme is to bridge the gap between local-scale field observations and the coarse resolution modern climate simulations. Unfortunately, Greenland is typically overlooked in global modelling analyses due to its complex landscape and lack of data. To address this issue, we integrated extensive *in-situ* observations measured by the GEM programme with a state-of-the-art process-based C cycle model and high-resolution future climate projections developed by the Danish Meteorological Institute.

Our study applied a novel combination of data and models[2] to investigate how the net C uptake will change under warmer and wetter conditions across the 21st century, and to get a better understanding of the relative contribution of climate and local plant trait variability to the overall carbon sink strength. This modelling exercise focused on two climatically different tundra GEM sites, Kobbefjord and Zackenberg (Fig. 1A). Our data suggests that both sites expect temperatures to rise 5–7 °C, rainfall to increase 19–110 %, and spring snowmelt to occur 3-9 days earlier by 2100. Previous assumptions suggested that such conditions would enhance the storage capacity of terrestrial carbon and strengthen the atmospheric CO_2 sink function. Our data supports this expectation of an increase of the terrestrial carbon uptake in both sites (Fig. 2). However, our findings also reveal that, in addition to climate change, local foliar nitrogen conditions (and other key plant traits) will play a critical role in controlling future net carbon storage in these tundra ecosystems (Fig. 3). Using *in-situ* GEM data we ran a simple experiment of realistic changes in plant foliar nitrogen status and demonstrate that the potential contribution of plant N trait variations to future carbon sink strength may be as significant as that of climate. Our study highlights the need to consider both climate and local conditions in understanding the future of carbon storage in understudied and highly heterogeneous regions such as Greenland.

As significant as the modelling results are, it is clear that observations made in a handful of locations do not represent the entire range of possible outcomes for Greenland with its hugely diverse climate and ecosystems. This underlines the crucial need to continue integrating modern remote sensing and modelling techniques with the long-term monitoring efforts. This is the only reliable way to up-scale spatially and temporally in order to forecast ecosystem responses to climate change. The new GEM *Remote Sensing and Ecosystem Modelling* sub-programme is committed to advancing these much-needed efforts.

Our work demonstrates the unique synergy between monitoring data and numerical models in calibrating and validating models, reducing uncertainty, ranges and ultimately generating more reliable C cycle projections in areas like Greenland which have received less attention. By doing so, we aim to establish a strong foundation for better understanding of present and future implications of feedback mechanisms in response to climate change.

CARBON STORAGE CAPACITY

GEM
Greenland Ecosystem Monitoring

ZACKENBERG BE BY 2100?

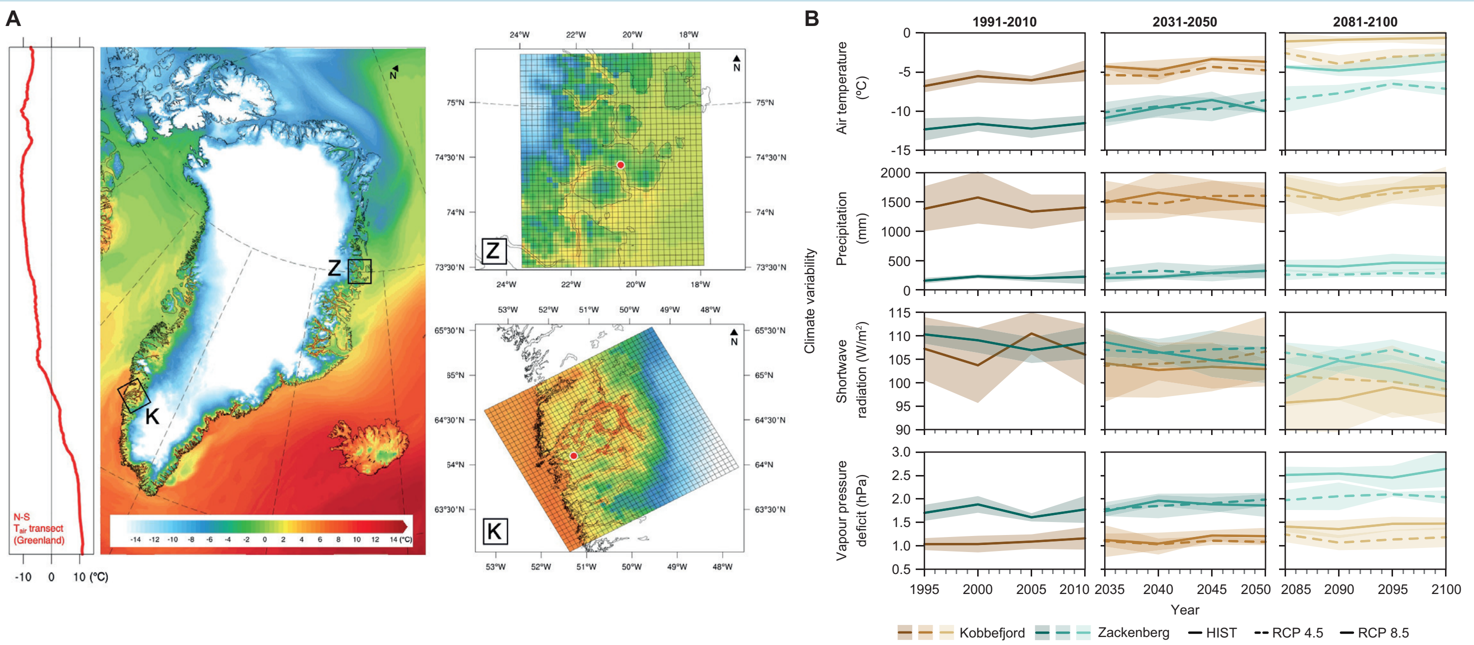


Figure 1. (A) Example of downscaled air temperature from the HIRHAM5 GCM-driven Regional Climate model (DMI) featuring Greenland on 1 August 2000 at a 5 × 5 km spatial resolution. [Z] and [K] maps zoom in on the Zackenberg and Kobbefjord areas surrounding each research station (red dots). (B) Recent past and expected future 5-year mean air temperature (°C), precipitation (mm year[1]), shortwave radiation (W m^{-2}) and vapour pressure deficit (hPa) between 1991 and 2100. The historic (HIST) runs cover the 1991-2010 period. The future scenarios follow both moderate (RCP$_{4.5}$) and highest (RCP$_{8.5}$) greenhouse gas emission scenarios based on the AR5 IPCC report.

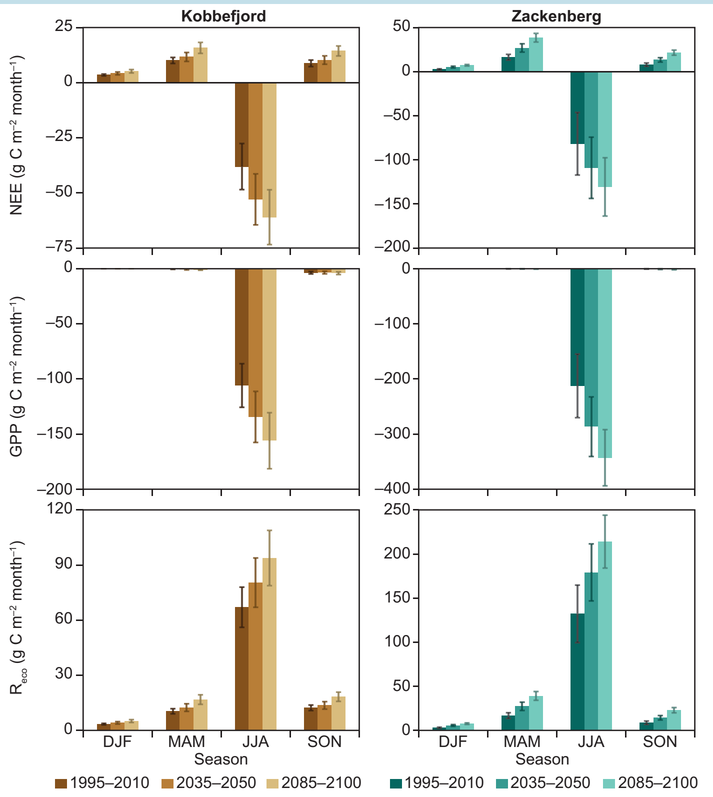
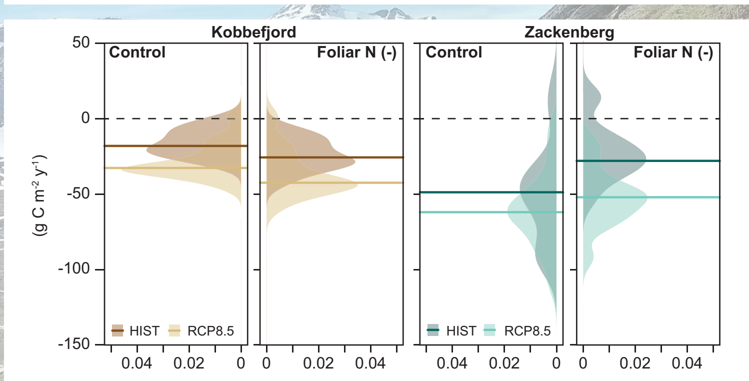


Figure 2. Projected seasonal mean and standard deviation of net ecosystem exchange (NEE) in Kobbefjord and Zackenberg during the winter (DJF), spring (MAM), summer (JJA) and autumn (SON) seasons.

Figure 3. Present and future annual mean C sink strength from Kobbefjord and Zackenberg comparing the control setups and two experimental setups including enhanced and weakened foliar N inputs from the opposite site.



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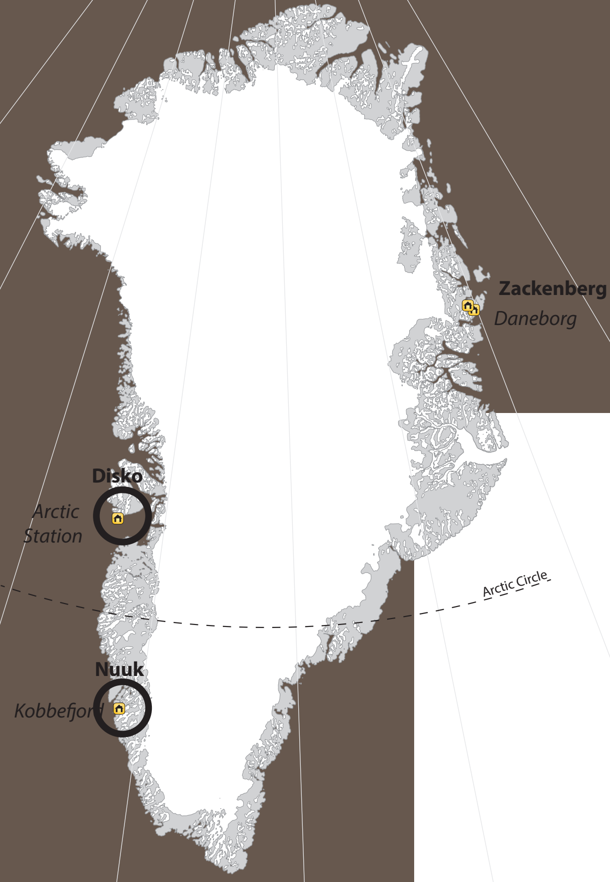
2. López-Blanco, E. et al. The future of tundra carbon storage in Greenland – Sensitivity to climate and plant trait changes. Science of The Total Environment, 2022. 846: p. 157385.



Annual Report Card 2022

THE WET SUMMER

The Greenland West coast experienced an exceptionally wet summer and autumn in 2022. This picture is clearly reflected in the continuous registrations of precipitation and river runoff carried out in collaboration between the Glacio- Climate- and Geo-Basis sub programmes. At the GEM stations in Kobbefjord and Qeqertarsuaq, record amounts of rain were measured. September stood out through high air temperatures and flood-inducing rain events. The river runoff in September was the highest recorded in the time series from both stations. The synoptic situation during this month was characterized by anomalously high sea level pressure southeast of Kap Farvel and low pressure over northeast Canada, resulting in the northward channeling of moist air in a narrow band along the west coast of Greenland.

TAKE HOME MESSAGE

Unusual amounts of rain were measured on the Greenland west coast in 2022. Heavy and intense rain were experienced for longer periods. The long-term records of climate and hydrological variables provided by the GEM programme help us to show if these types of events are becoming more frequent as most climate models predict. More rain and a potential shift in the ratio between rain and snow will have large implications for ecosystems and people in the Arctic.

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[2] Aarhus University, Roskilde, Denmark

[3] Geological Survey of Denmark and Greenland, Copenhagen

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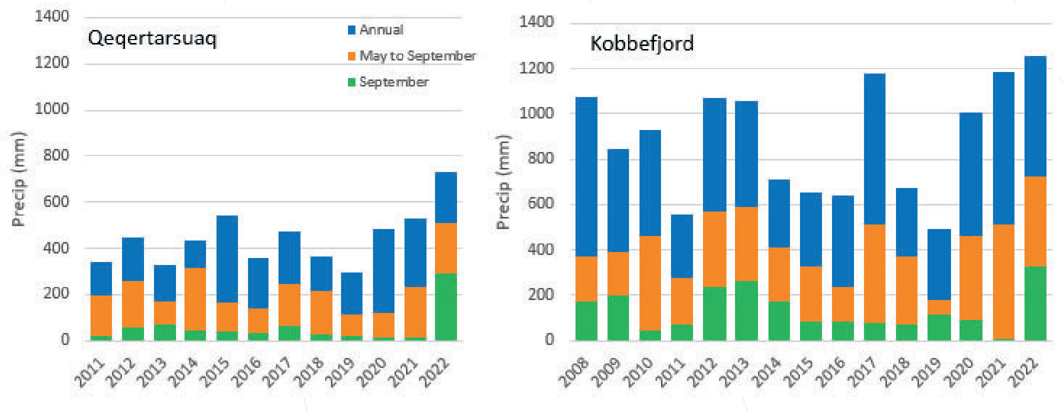
Data source:

GeoBasisDisko/Hydrology/RE-WaterDischarge_15min
https://doi.org/10.17897/C99H-DP15
ClimateBasisDisko/Precipitation
https://doi.org/10.17897/638X-3Z89
ClimateBasisNuuk/Precipitation
https://doi.org/10.17897/SXJ8-WA79
ClimateBasisNuuk/River hydrology/Discharge@river Kobbefjord
https://doi.org/10.17897/H2MR-PP28
Data can be accessed on:
www.data.g-e-m.dk

At Arctic Station in Qeqertarsuaq, a total amount of 519 mm rain was measured within the period from 1 May to 30 September 2022. This is 2.4 times the average compared to the same period for the years 1991-2021, and even above the average annual total precipitation (rain and snow) measured at this location (Fig. 1). September represents an extreme with 288 mm of recorded rainfall – 7 times the September average for the period 1991-2021, and the highest amount of rain recorded at this site for any month since 1991. Roads were flooded and the river Røde Elv reached its maximum discharge of the runoff season on 12 September after a 3 week period with several massive rain events. Usually, the discharge in September is relatively low at this site as air temperatures and therefore the amount of meltwater generated by the local ice cap gradually decrease. However, due to the high air temperatures in September 2022, meltwater production was still high, and after a wet summer the saturated soil caused much of the rain to result in overland flow ensuing a record-high river discharge for September and the highest accumulated runoff ever measured (2015-2021) (Fig. 2).

Further south, the GEM site Kobbefjord near Nuuk experienced a similarly wet summer and autumn. The total annual precipitation in Kobbefjord is, on average, about twice as high as that measured in Qeqertarsuaq (Fig. 1). Within the complete GEM record from 2008 to 2022, the station at Kobbefjord also registered the highest yearly total precipitation (1256 mm), the highest summer precipitation, and the highest September precipitation (330

Figure 1. Total annual precipitation for Qeqertarsuaq and Kobbefjord (Nuuk). In the text we refer to an even longer time series for Qeqertarsuaq (1991-2021) that only shows liquid precipitation/rain from Arctic Station. Here we show the shorter time series from comparable sensor types.



AND AUTUMN OF 2022

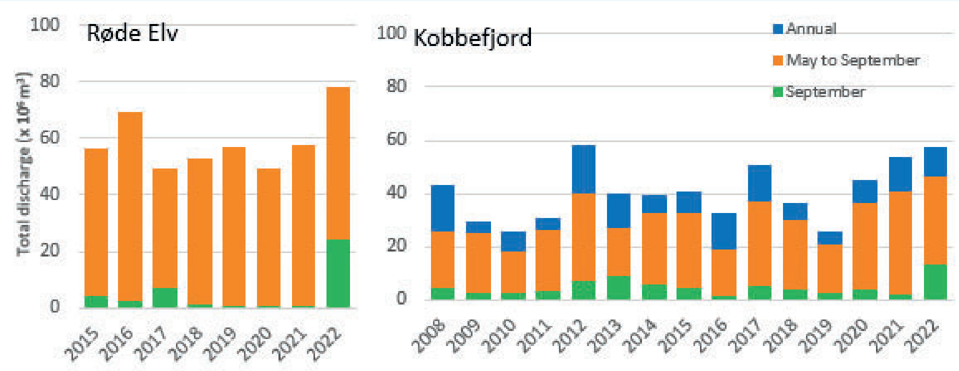


Figure 2. Total discharge from the river Røde Elv, Disko (catchment area 101 km²) and from Kobbefjord (catchment area 32 km²) with outline of September runoff (green) and summer runoff May to September (orange). From Disko the winter runoff is very limited, and data only exist for the main runoff season.

mm). In 2022, the total monthly rainfall in both June and September was roughly 2.7 times larger than the average for these months from 2008 to 2021. The air temperatures in September were not only high as in all of Greenland, but record-breaking for the GEM period (see ClimateBasis Program Description). The resulting summer discharge of the river in Kobbefjord was the highest measured (Fig. 2), and for September the monthly runoff exceeded three times the average of this month for the years 2008 to 2021. The raging river destroyed and washed away the bridge near the research station on 24 September (See photo on page 8). As was the case with Røde Elv in Qeqertarsuaq, the soils were saturated after a wet summer, which amplified the river runoff caused by the rain events (see photo below).

Precipitation in Greenland occurs primarily due to the presence of frontal cyclones and the interaction of their cloud systems with topography (Chen et al., 1997). The heavy rain events are associated with a combination of high moisture transport and uplift created by frontal activity. The water vapour content of the air registered at the GEM station Kobbefjord in September 2022 was higher compared to any previous September on record, whereas in Qeqertarsuaq, it was comparable to that of September 2010. Figure 3 shows the mean sea level air pressure anomaly for September of 2010 and 2022, together with the anomalous total atmospheric water content. The pattern shows low pressure over northern Canada and high pressure southeast of Greenland, resulting in transport of moisture-rich air northward along the west coast. Many individual cyclones passing roughly along the same path, provides the necessary atmospheric instability to convert the moist air into precipitation. Poleward moisture transport is increasing in our warming climate, bringing more precipitation to high latitudes (McCrystall et al., 2021). Studies of numerical climate projections indicate that the 21^{st} century will see fewer, but more intense cyclones (Pepler and Dowdy, 2021; Zhang and Colle, 2017) – rendering the events of September 2022 a possible glimpse into the future.

Figure 3. Total column water (shading) and mean sea level pressure anomalies (contours, labels in hPa) for the month of September, from the ERA5 reanalysis (Hersbach et al., 2023; Copernicus Climate Change Service, Climate Data Store, 2023). Anomalies are with respect to the mean 2010-2022.

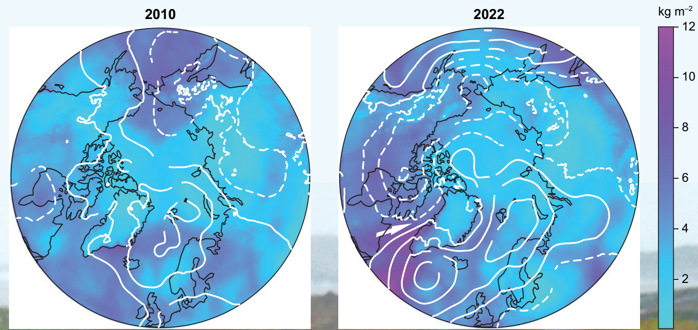


Photo: Runa Bjerre Henriksen

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MACRO TO MICRO

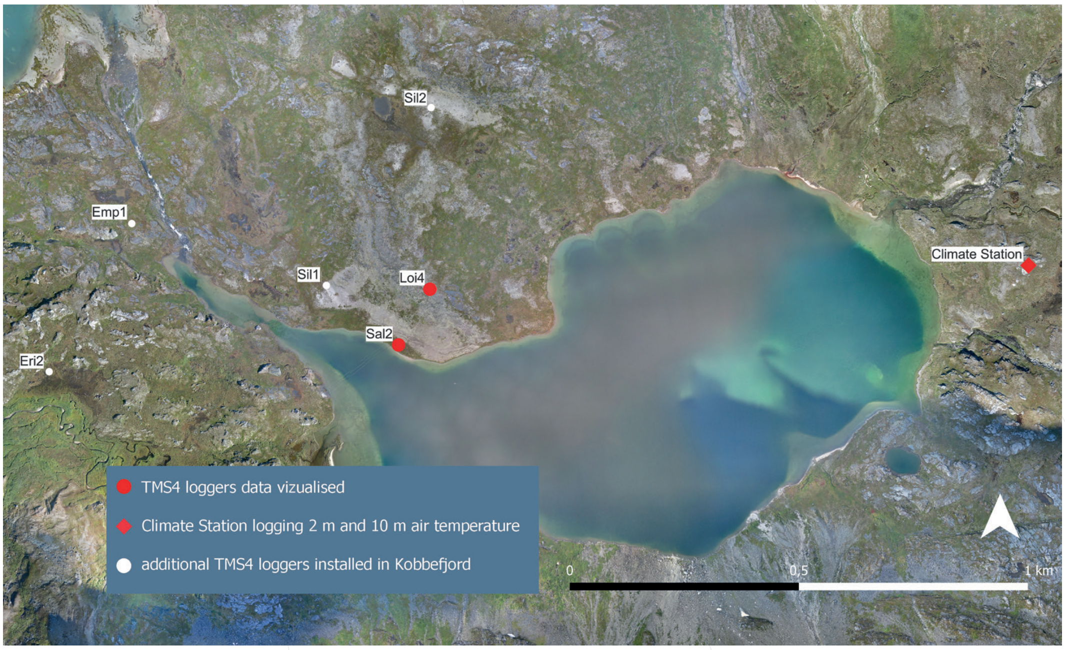
– TEMPERATURE MEASUREMENTS

Air temperature data have been collected in Kobbefjord since October 2007. In 2019 a new edition was made in the form of 5 new TMS4 data loggers. This addition to temperature measurements will enable insight to the microclimate, the coupling between air temperature (2 m and 10 m) and plots-scale measurements (–6 cm, 2 cm and 15 cm temperature as well as soil moisture) along with the monitoring of biotic variables. In 2023, 40 additional TMS4 loggers will be installed during the field season.

TAKE HOME MESSAGE

Installment of TMS4 temperature and soil moisture loggers in phenology and carbon-flux measurement plots will give much needed data on and insights to the understudied relation between microclimate and vegetation.

A number of biotic variables are measured at plot-scale in Kobbefjord. Temperature is an important abiotic variable that so far has only been measured at site-level. The addition of 45 TMS4 loggers to the Kobbefjord monitoring area will provide temperature measurements that enable understandings of the importance of microclimate for the variables being monitored including more detailed understanding of the inter-plot variability related to soil moisture and temperature.



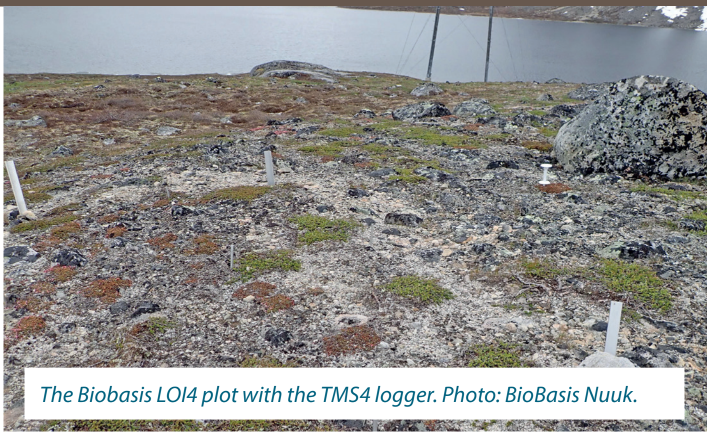
Authors:
Ida Bomholt Dyrholm Jacobsen[1], Katrine Raundrup[1] & Kirsty Langley[2]
[1] Greenland Institute of Natural Resources
[2] Asiaq

Data source:
ClimateBasis and BioBasis
Data can be accessed on:
www.data.g-e-m.dk
https://doi.org/10.17897/PGN3-7597

FROM 200 CM TO 2 CM

The monitoring within GEM of e.g., NDVI and reproductive phenology of plants is done on different species and hence in very different habitats. With the addition of TMS4 loggers we will be able to quantify these differences in terms of temperature and soil moisture. The comparison of plots dominated by *Salix glauca* (Northern willow; Sal2), *Loiseleuria procumbens* (Trailing azalea; Loi4) and 2 m air temperature data clearly visualizes the differences between two very different habitats. The Sal2 plot is dominated by up to 40 cm tall shrubs of *Salix glauca* and *Betula nana*. It is located near the shore of Badesø (Fig. 1) at ca. 25 m asl. It is clear from the stable temperatures just below 0°C that this plot is snowcovered during winter and spring (Fig. 2).

The Loi4 plot has this inconspicuous prostrate species as the only vegetation. The plot is located highly exposed at 58 m asl on a rocky and sandy surface. It is evident from the temperature data that the microclimate of this plot reflects the air temperature to a larger degree compared to the Sal2 plot (Fig. 3). The plot is fairly wind exposed and snow only settles for shorter periods of time.



The Biobasis LOI4 plot with the TMS4 logger. Photo: BioBasis Nuuk.

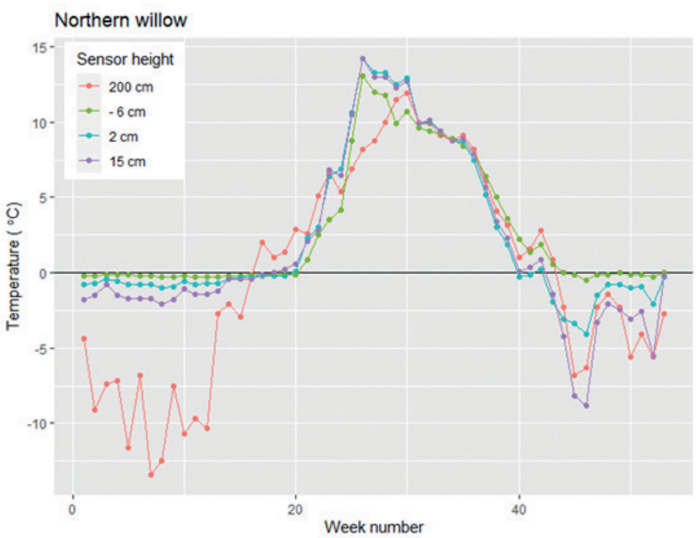


Figure 2. Temperature measurements (°C) at 200 cm, 6 cm below the soil surface, as well as at 2 and 15 cm above ground in Northern willow (Salix glauca) dominated plot. The data presented are weekly averages from 2020 to 2022.

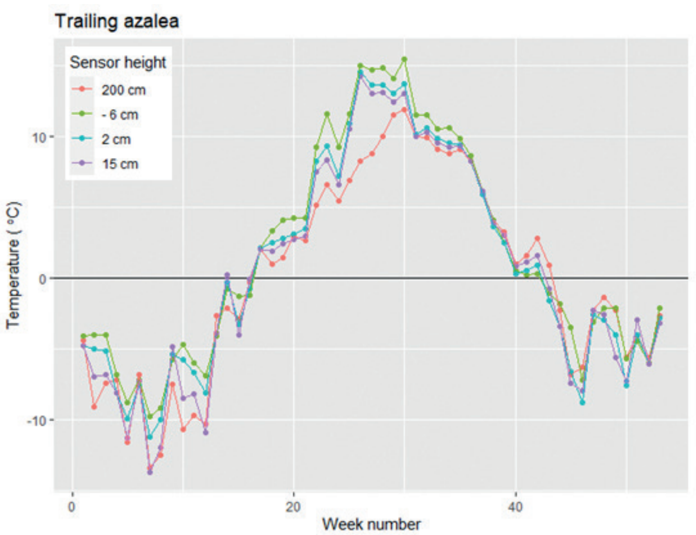


Figure 3. Temperature measurements (°C) at 200 cm, 6 cm below the soil surface, as well as at 2 and 15 cm above ground in Loiseleuria procumbens dominated plot. The data presented are weekly averages from 2020 to 2022.

Additional loggers have been acquired and will be installed during the field season of 2023. These loggers will enable the exploration of the relationship between macro and micro temperatures both at a larger scale within the research area but particularly in relation to the importance of microclimatic temperatures and soil moistures for carbon fluxes. The loggers will be installed in several of the carbon flux measurement plots and will enable detailed insights to the microclimate relating to the vegetation in the individual plots. This includes setting up the TMS4 loggers in plots where treatments have been applied (passive heating using open-top chambers (OTC's) and shading using hessian tents).

It is well known that comparing microclimate measurements from loggers may result in a multitude of variables depending on parameters such as aspect, elevation, slope, vegetation height, wind, humidity, surface roughness, as well as the soil/surface type of the location of the logger (Maclean et al., 2021). Setting up the new loggers will shed light on some of the variability of the microclimates in Kobbefjord.

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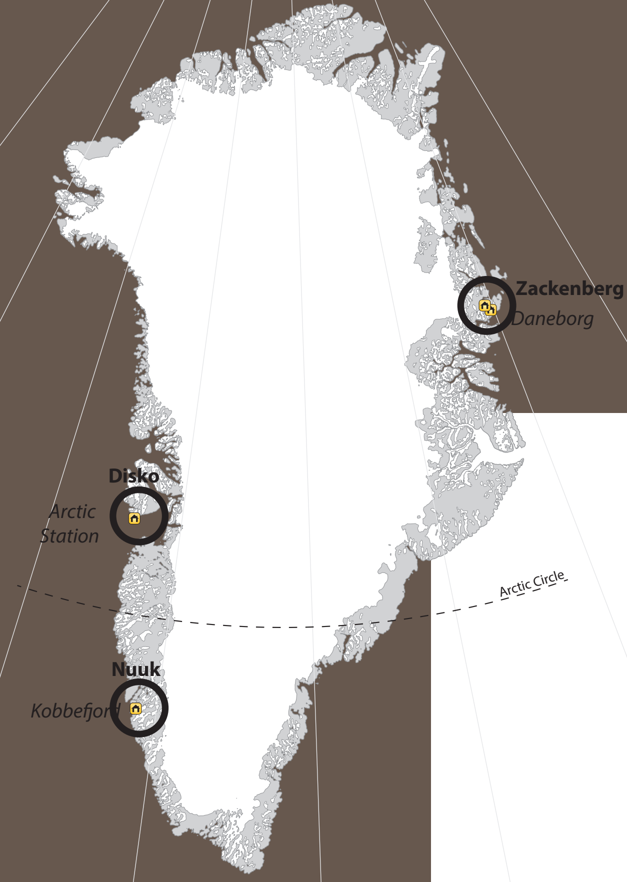

COMPARING FLUXES

In 2022 GEM could celebrate the first year when all four GEM eddy co-variance stations were fully operational according to ICOS standards. We present some of the data acquired, processed, and quality controlled using common procedures, making future site intercomparison studies more reliable. For the first time, we also present wintertime fluxes from high-arctic Zackenberg, the northernmost station in ICOS and GEM portfolios.

TAKE HOME MESSAGE

By standardizing the flux instrument setup, data processing, and quality control across all GEM sites and bringing it in line with flux community standards sites we have strengthened the visibility and value of the GEM flux datasets. This makes direct site intercomparison studies more reliable and opens new studies of the controls of carbon balance along climate gradients and different ecosystems.

The carbon balance of arctic ecosystems is vulnerable to changes in climate and other environmental factors. Because fluxes in the Artic are often small, studies uncovering the effects of changes in different ecosystems and potential climate feedback heavily rely on the quality and comparability of the data.

Eddy covariance (EC) systems at GEM stations at Nuuk, Disko and Zackenberg have over the past years gone through a process of getting in line with the standards of the Integrated Carbon Observation System, ICOS. ICOS is a European-wide greenhouse gas research infrastructure established with the purpose of providing the highest quality flux data for free use to the scientific community and beyond.

In the autumn of 2022, two eddy covariance stations at Zackenberg obtained ICOS approval as so-called Class-2 labelled, which certifies that the station is operated according to strict protocols. This brought the number of GEM eddy covariance stations with ICOS certifications up to four. In 2021, Disko Østerlien and Nuuk Fen stations got the ICOS label as Associated Stations. In 2022 Zackenberg Heath was approved as an Associated Station, whereas Zackenberg Fen was granted the higher Class 2 label which means that the station team is obliged to strictly follow extensive ICOS protocols regarding instrumentation and setup, along with extensive campaigns of ancillary

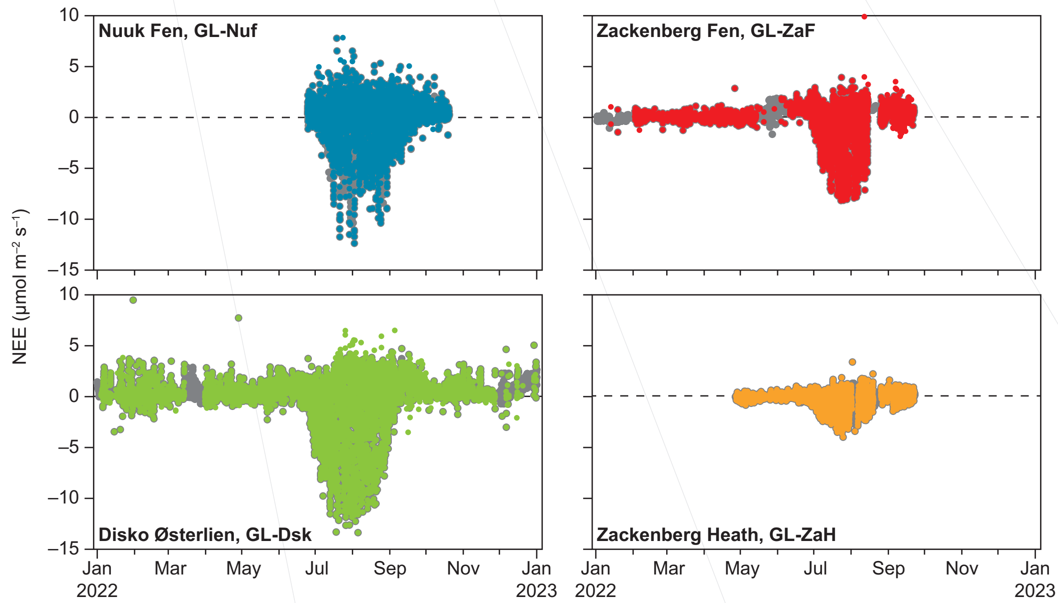

Figure 1. Half-hourly fluxes of CO_2. Coloured dots are original quality-controlled data, and grey dots are gap-filled data.

Authors:

Rasmus Jensen[1,2], Marcin Jackowicz-Korczynski[1], Thomas Friborg[2] & GeoBasis teams at the three sites.

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Data source:

C fluxes from GeoBasis.

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

ACROSS SITES

vegetation measurements to monitor C stock in soil and vegetation. Station teams from Disko, Nuuk and Zackenberg collaborate closely to make sure all ICOS-GEM stations are similar with respect to instrumentation, setup, and not least data processing with the aim of producing the highest quality data for the GEM database.

Following the ICOS processing procedure, we calculated half-hourly CO_2 fluxes from all four sites. The data were carefully quality controlled, and those acquired under non-ideal conditions for measuring the turbulent fluxes were flagged. Data gaps were filled utilizing standard flux community gap-filling routines, to yield continuous datasets for CO_2 balance estimation.

In Figure 1, the half-hourly net ecosystem exchange (NEE) is depicted for the stations. For all four stations, the data covers the main part of the productive summer season of the ecosystems. The wet ecosystems at Nuuk Fen and Zackenberg Fen, along with the semi-wet heath ecosystem at Disko Østerlien showed similar amplitudes of the fluxes over the season, whereas the dry heath at Zackenberg showed markedly lower fluxes throughout the growing season.

The two stations with winter flux measurements showed different patterns and magnitudes for fluxes during the winter period. The site at Disko Østerlien has for major parts of the winter period limited or no snow cover and showed episodes of positive fluxes (i.e., indicate emission of CO_2 from the ecosystem to the atmosphere). The Zackenberg Fen site, which was snow-covered until June, showed smaller fluxes of CO_2 during the winter period.

Figure 2 shows gap-filled and accumulated C budgets for the growing season. Here we have defined the onset of the growing season after three consecutive days of daily net uptake of CO_2, and the end of the growing season is three days before the fluxes turn into net daily sources of CO_2. The timing of the onset and termination of the productive period and the effectiveness (steepness) of the respective ecosystem determines the net accumulation of carbon in the different ecosystems. Stations with sustained and deep snow cover throughout the winter period (Nuuk and Zackenberg) result in the late end of the snow melt season and hence a delayed growing season with carbon uptake. The two northernmost stations in Zack-

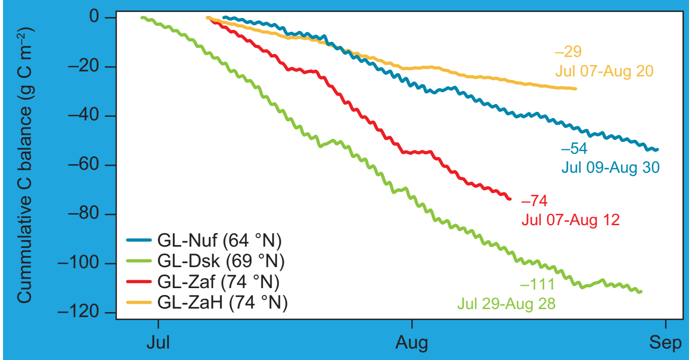
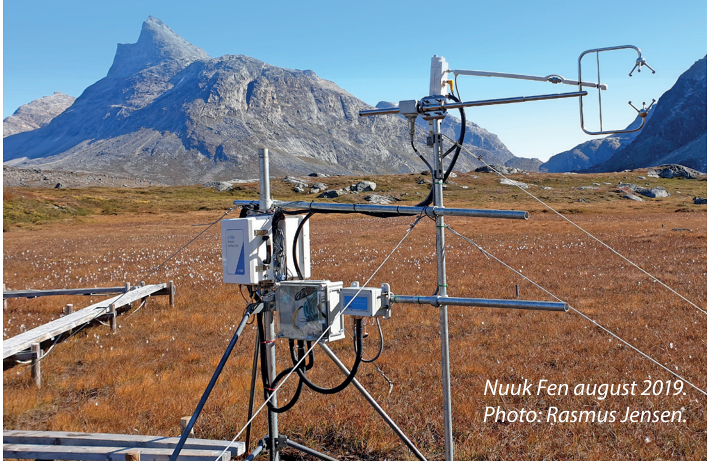


Figure 2. Cumulative C balance for the productive growing season. The annotations at the end of each line give the cumulative C balance and the carbon uptake period for the respective station. Negative balances depict that the ecosystems are sinks for atmospheric CO_2.

enberg experienced an early transition into the dormant period in late summer when it starts to get cold. As we have good faith in the measured data because of the ICOS certification, we can say that the sites in Disko (GL-Dsk) and Zackenberg fen (GL-ZaF) to a large extent act in the same way when it comes to CO_2 uptake during the growing season. The difference in the seasonal uptake in 2022 can mainly be attributed to the length of the season, which in turn is controlled by differences in snow conditions and photoperiod.

Operating eddy covariance flux systems is a challenging task in the Arctic. The environment is harsh, and the stations are not accessible for extended periods of the year. Furthermore, the EC systems require a steady power supply for high-frequency data acquisition, which makes wintertime operations challenging. The dataset from Disko Østerlien stands out with very high data coverage. Only minor periods of instrument failure and power cuts due to construction work at the Arctic Station occurred. The high data coverage is secured by the availability of line power, internet access and year-round manning of the station. However, with a robust off-grid power system it has been shown at Zackenberg Fen that it is possible to operate the systems under the harshest conditions during winter. This was done during the winter of 2021/2022 (data not shown).

All data can be found in the GEM database under GeoBasis for the three sites and in the ICOS database https://www.icos-cp.eu/ which is known as the Carbo Portal.



*Nuuk Fen august 2019.
Photo: Rasmus Jensen.*

*Zackenberg Fen June 2022.
Photo: Rasmus Jensen.*

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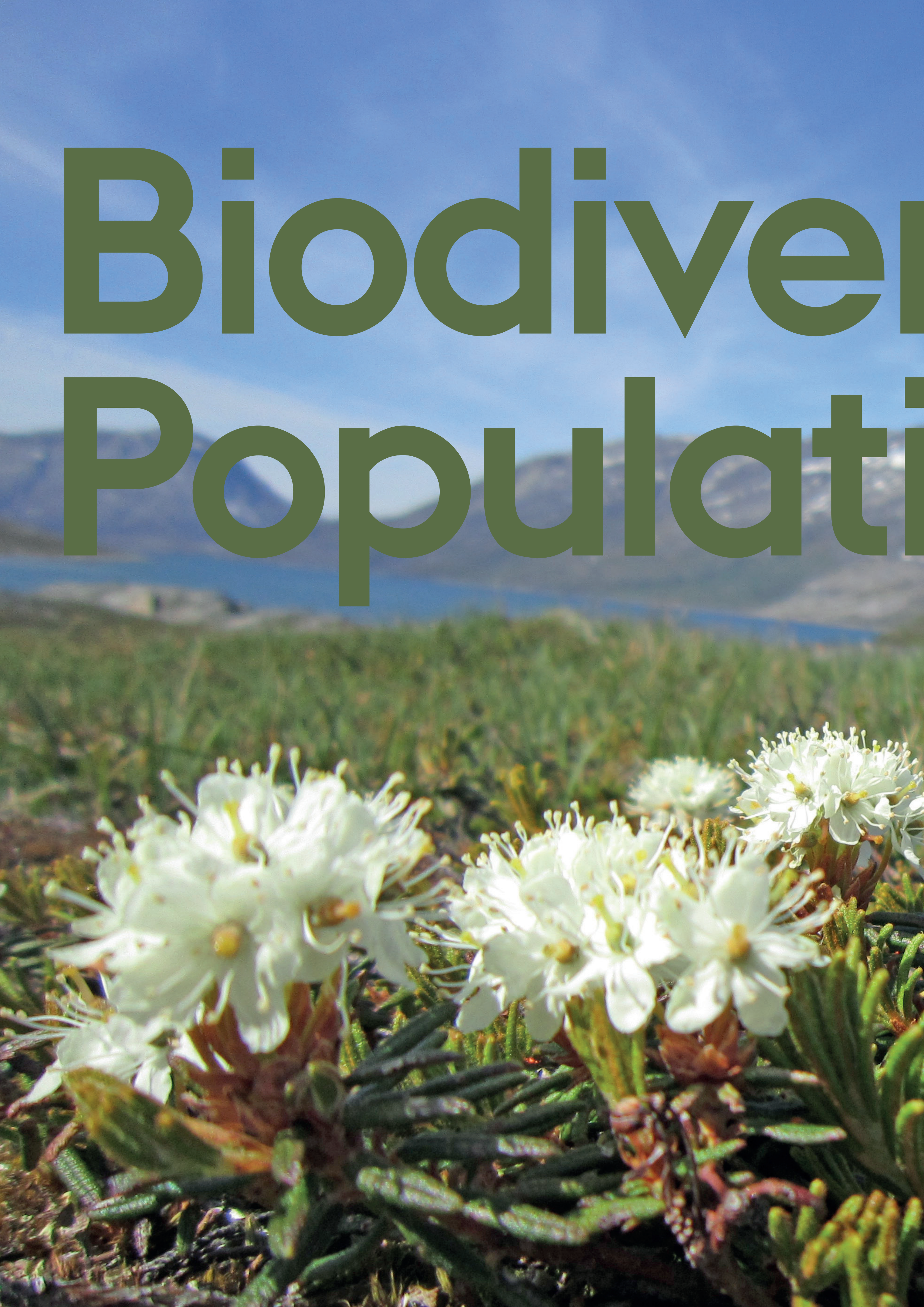

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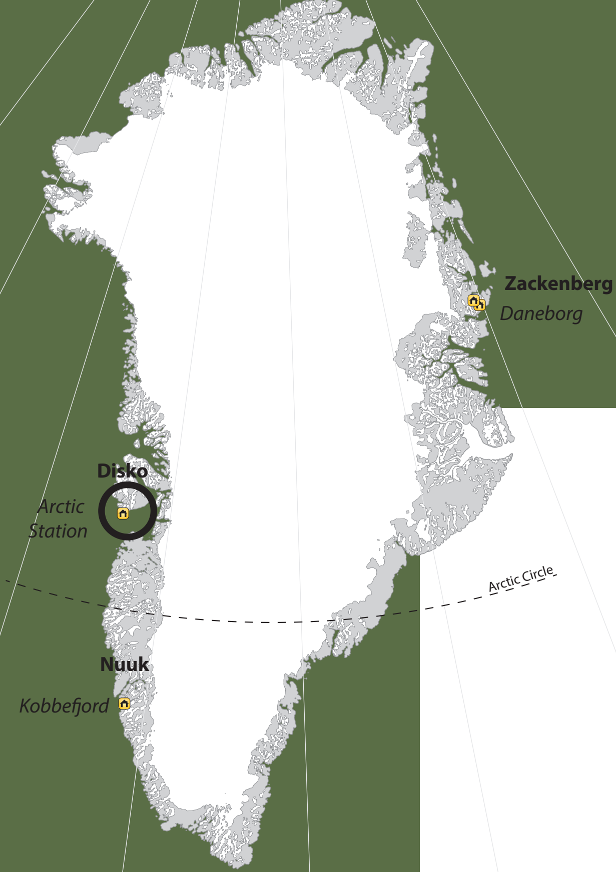

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TRACING MACROALGAE USING ENVIRONMENTAL DNA

Macroalgae are the main marine primary producer along Greenland's coast and an important subject of the GEM activities because they are sensitive to climate change and support key ecosystem functions including habitat provision and carbon flows. Boreal macroalgae are expanding northward due to warming and loss of sea-ice that opens up new habitats for colonization. Tracing macroalgae in marine sediments by environmental DNA (eDNA) could potentially supplement traditional methods for assessing macroalgal biodiversity, migration patterns and trends. Such tracing is possible as macroalgae shed vegetative tissues and spores making them detectable through DNA analyses of the ambient environment.

TAKE HOME MESSAGE

We compared an eDNA based method with a traditional method for surveying local biodiversity of macroalgae. Overall, our results point at good potentials of macroalgal eDNA fingerprints to supplement traditional monitoring. The eDNA based method can also be applied on dated sediment cores, enabling analyses of previous biodiversity patterns and effects of environmental change.

Macroalgae, especially brown algae (Fig. 1), provide key ecosystem functions, e.g., as habitats for other marine species, and also export part of their primary production beyond the habitat where it may support secondary producers or carbon sequestration in sinks in the sediment and the deep sea (Krause-Jensen et al. 2016). Knowledge on expansion or retreat of macroalgal taxa, e.g., monitoring of biodiversity, is important for understanding how these key ecosystems and their functions respond to climate change.

While studying carbon sources in Greenlandic sediments, we documented DNA from a range of macroalgal taxa using sedimentary eDNA analyses (Ørberg et al. in review), and we became curious to understand how well sedimentary eDNA reflects local communities of macroalgae. If proven efficient, eDNA-based surveys could supplement current monitoring, providing a less-labor intensive method to monitor macroalgal biodiversity compared to traditional methods.

Figure 1. Dense intertidal macroalgal vegetation in Kobbefjord, SW Greenland, mainly brown algae Fucus vesiculosus and Ascophyllum nodosum. Photo: Scott Bennett.

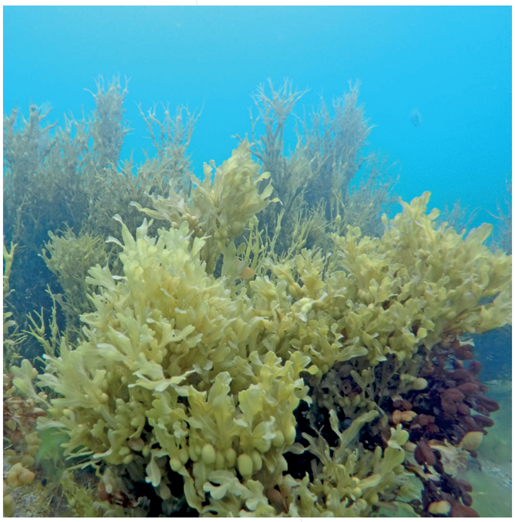
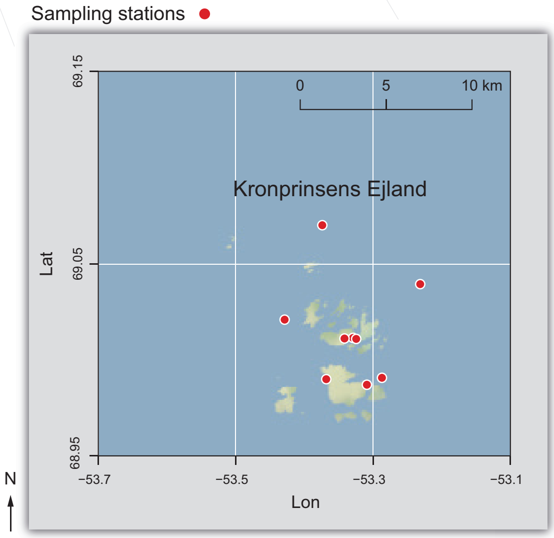


Figure 2. Surface sediment sampling stations at Kronprinsens Ejland, Disko Bay. From Ørberg et al. in review.



Authors:

Ørberg, S.[1,2], Duarte, C.[2,3], Geraldi, N.[3], Sejr, M.[1,2], Wegeberg, S.[2,4], Hansen, J.[4] & Krause-Jensen, D.[1,2]

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IN ARCTIC SEDIMENTS

We compared an eDNA based method (Fig. 3) with a traditional method for surveying local biodiversity of macroalgae at Kronprinsens Ejland. For this, eDNA sequences from eight surface sediment samples collected alongside GEM monitoring in 2016 (Fig. 2) were compared with species richness and coverage surveyed by divers in nearby macroalgal habitats.

Macroalgal biodiversity reflected in sedimentary eDNA

Surface sediment eDNA largely reflected nearby macroalgal community composition obtained from diver surveys (Fig. 4). The most abundant taxa observed by divers (coverage and species richness) were also the most abundant (sequences) in sedimentary eDNA (Fig. 4a).

Using sedimentary eDNA, we documented eight out of the 14 macroalgal orders observed in nearby communities plus three orders that were not observed by divers (Fig. 4b), including Hapalidales that includes many cryptic species not easily visible to divers. Hence, the method shows good potential. The differences may partly reflect the limitations in sediment sampling of this small case study and an incomplete sequence reference DNA database.

Limitations of sedimentary eDNA for biodiversity assessments

The eDNA method applied here only resolves by order, hence it is mainly considered a supplement to current monitoring activities.

The sequence reference database is not complete and if species are not represented in this, they will not be identified based on the eDNA-based survey. However, the database has recently been enriched with macroalgal species relevant for Greenland (Ørberg et al. 2021).

Some macroalgal taxa, e.g., Corallinales, which represent encrusted red algae, may not be readily exported and traceable in sediment beyond the habitat (Fig. 3a). For such taxa, eDNA from water samples may be a better option, but sediments have the strength of better preserving eDNA and the possibility to provide insight into the past through analyses of dated sediment cores, which can then potentially be used as historic archives of change in macroalgal communities over time.

The eDNA sampling was originally directed at documenting carbon sources in the sediment and not at assessing overall biodiversity. Increasing the sampling effort will likely increase the number of taxa detected by sedimentary eDNA.

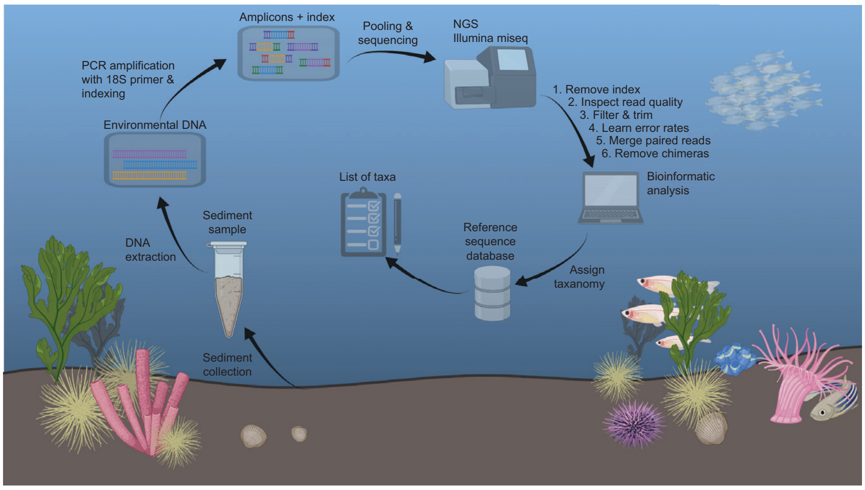

Figure 3. Schematic overview of environmental DNA analysis of marine sediment using metabarcoding. From Ørberg et al. in review.

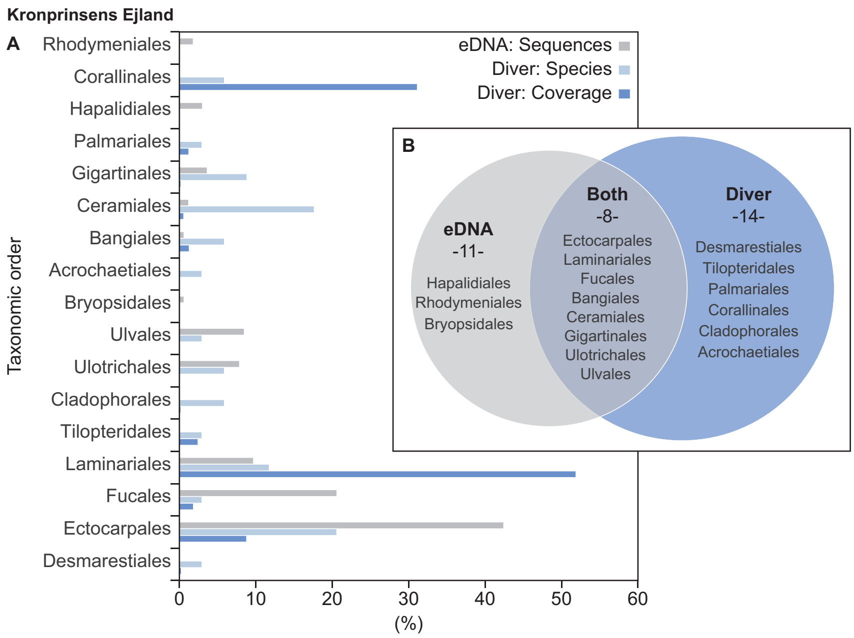

Figure 4. Macroalgal orders detected with sedimentary eDNA and by divers at Kronprinsens Ejland, Disko bay. A) Barplot showing percent sequences, species and coverage of each taxa. B) Venn-diagram displaying the overlap of taxa detected by each method. From Ørberg et al. in review.

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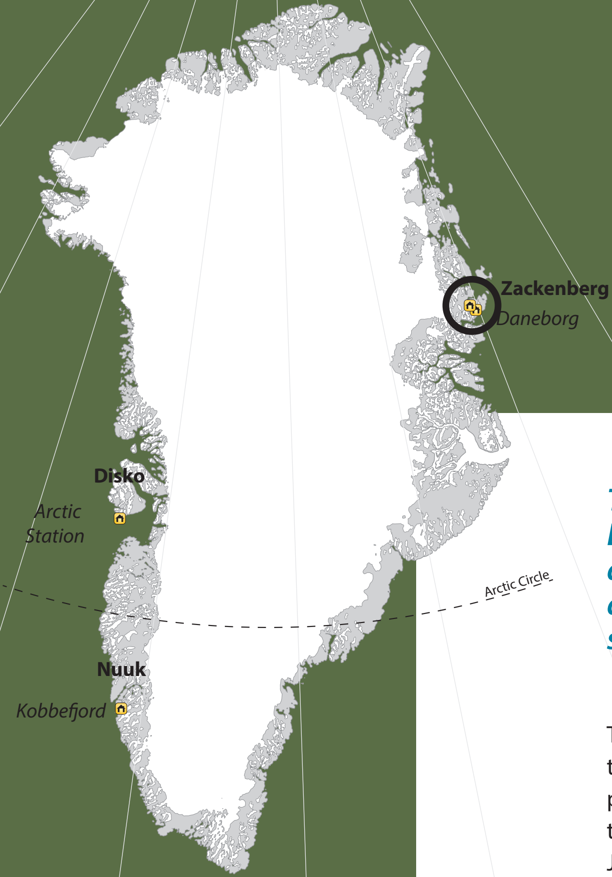

Annual Report Card 2022

LAKE PHYTOPLANKTON

TO EARLY ICE MELT

The phytoplankton communities of clear, nutrient-poor arctic lakes like Langemandssø and Sommerfuglesø in the Zackenberg valley include a variety of micro-algae groups. The phytoplankton and zooplankton are active before the ice disappears completely and a longer ice free season will result in a longer growing season.

TAKE HOME MESSAGE

The number of phytoplankton taxa increased during the monitored period, and phytoplankton biomass showed an overall increase with length of the ice-free season. The biodiversity parameter seems more sensitive to extreme events than long term subtle warming.

The long ice-covered period implies that water temperature and irradiance peak during the open water period that typically lasts from the beginning of July to the end of September. The ice thickness reaches 1.5 to 2 m by the end of the winter and has on top a layer of snow. Thus, the amount of light that can enter the water column is limited. However, phytoplankton and zooplankton are, in fact, active before the ice will disappear by late June or early July. Water temperature will start to increase during spring (April-May), and as soon as the snow on the lake ice melts, more and more light can penetrate through the ice and into the water column. Still, phytoplankton production is low, and the accumulation of biomass is little due to a short summer season with "full" light and due to low nutrient levels. These conditions may change by direct and indirect effects of climate warming. Most obviously, a lengthening of the ice-free season will lead to a longer growing season (more light) and more runoff from the catchment (more nutrients).

The most common phytoplankton are Diatoms, dinoflagellates, chrysophytes, and green algae. Diatoms are represented by species such as *Tabellaria flocculosa* (Fig. 2A) and chrysophytes by e.g., *Dinobryon hilliardii* (Fig. 2B). Dinoflagellates are represented by, for instance, *Gymnodinium* spp. (Fig. 2C) and *Peridinium* spp., while *Euastrum anatum* (Fig. 2D) and *Elaktothrix genevensis* (Fig. 2E) are present among the chlorophytes.

In this study, we have examined the possible climate-induced changes in lake phytoplankton communities over 23 years using the monitoring data from two Arctic lakes; Langemandssø and Sommerfuglesø as well as climate data. Interestingly, no major changes were found in the phytoplankton communities in the lakes, despite an increase in annual air temperature in the Zackenberg valley. However, a lengthening of the ice-free season resulted in a greater number of spices and an increase in diatom biomass of which led to an increased total phytoplankton biomass (Fig. 3 A and B). Nutrient levels, air temperature, and zooplankton biomass were also found to have an impact on phytoplankton community structure. Cyanobacteria biomass did not change in response to abiotic variables, likely due to their ability to fix nitrogen. Diatom biomass increased due to increased ion input, while chrysophyte, dia-

Figure 1. Langemandssø (left) and Sommerfuglesø (right) in August 2020. Photo: Kirsten S. Christoffersen.

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Data source:

BioBasis Zackenberg (Phytoplankton, Zooplankton and Water chemistry).

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

COMMUNITIES RESPOND

Figure 2. Examples of phytoplankton species from Sommerfuglesø and Langemandssø. Photo: Trine W. Perlt.

tom, and dinoflagellate biomass all responded positively to air temperature. Extreme weather events, such as heavy snowfall, can have a large, short-term impact on phytoplankton community composition. Our results suggest that phytoplankton biomass in High Arctic lakes will increase with a warming climate, with air temperature, length of the ice-free season, light availability, and nutrient levels as the most important predictors. Long-term monitoring programs and collaboration across regions and institutes are essential for understanding the effects of climate change on Arctic lake ecosystems.

More information about Arctic lakes

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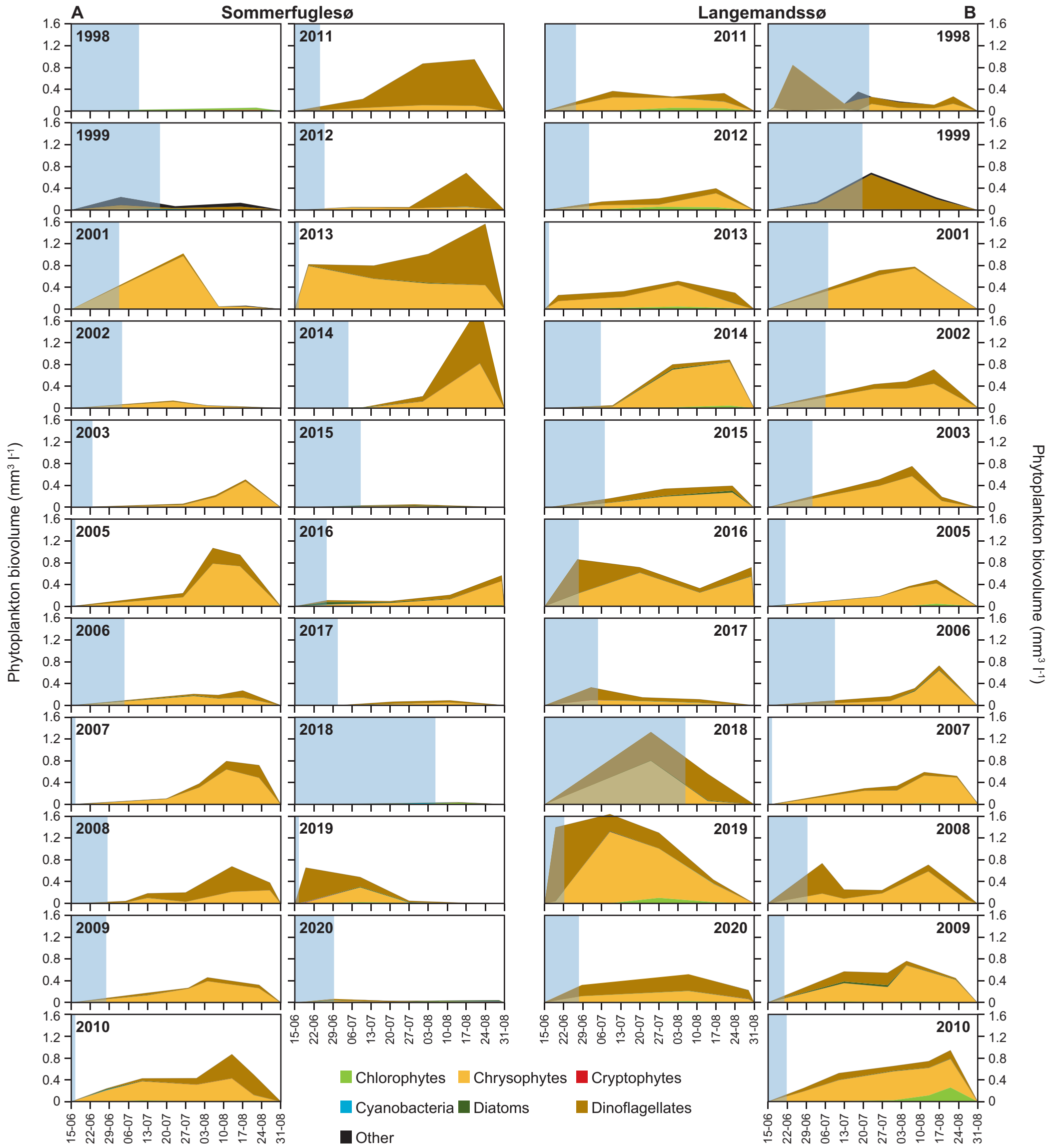
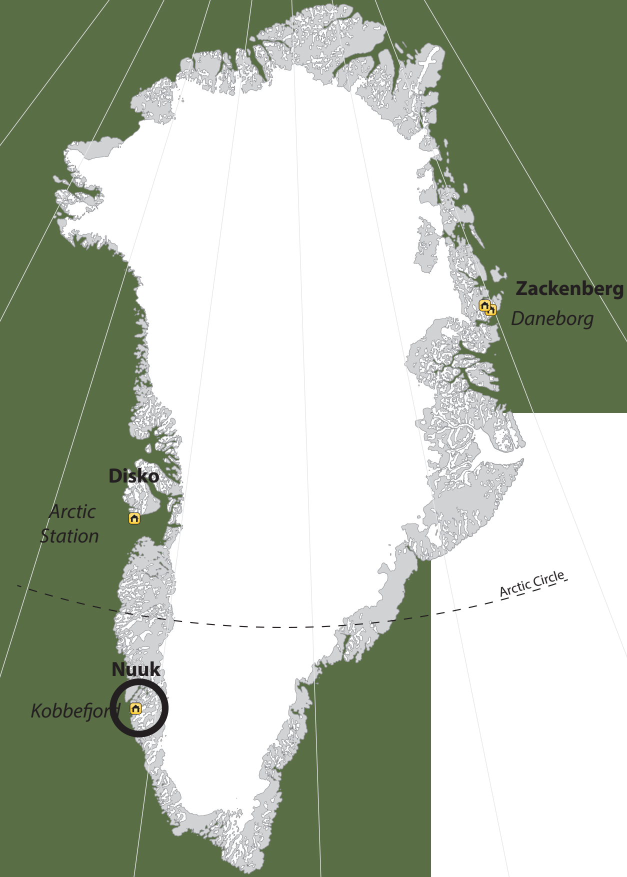


Figure 3. A). Summer phytoplankton biovolume (mm³ l⁻¹) in Langemandssø. Color codes represent the various phytoplankton groups. The blue box represent melting of the ice cover. The right side of the box indicate the date for 50% ice cover.). Summer phytoplankton biovolume (mm³ l⁻¹) in Sommerfuglesø. Color codes represent the various phytoplankton groups. The blue box represent melting of the ice cover. The right side of the box indicate the date for 50% ice cover.



MONITORING MARINE NUUP KANGERLUA WITH

Ocean color remote sensing can provide estimates of marine phytoplankton biomass and community composition which can supplement ship-based measurements and extend temporal and regional coverage. As part of the GEM Remote Sensing Initiative, in this pilot study we show the potential of using data from high-resolution satellite imagery from the European Space Agency's Sentinel-3 (ESA-S3) to track changes of phytoplankton dynamics in Nuup Kangerlua.

TAKE HOME MESSAGE

Satellite data can retrieve a great amount of information, allowing to capture more details on the spatial and temporal evolution of phytoplankton communities in the Greenlandic fjords, which is often not possible through *in situ* water sampling.

The MarineBasis Nuuk Monitoring Programme in Nuup Kangerlua has performed monthly sampling of hydrography, water chemistry and phytoplankton communities, production, and biomass, for over 15 years. Results indicate that events with warm and low salinity surface water in Nuup Kangerlua have triggered a decrease in phytoplankton species diversity, although no trend has been observed with respect to phytoplankton biomass (Vonnahme et al., 2022). Monthly sampling may not capture changes in phytoplankton communities occurring at shorter time windows. Likewise, the sampling location is limited to a single station which may not cover the patchy spatial distribution of phytoplankton. For that reason, satellite imagery can be an effective and valuable supplementary tool for monitoring phytoplankton, providing high spatial and temporal resolution.

Satellite ocean color provide estimates of the concentration of Chlorophyll *a* (Chol *a*; a proxy for phytoplankton biomass), detritus and dissolved organic matter (Gonçalves-Araujo et al., 2022). For instance, satellite-based detections of Chl *a* have revealed the presence of an secondary phytoplankton bloom in open waters close to Nuup Kangerlua (Zhao et al., 2022). Since 2016, the European Space Agency's Sentinel-3 (ESA-S3) satellite has been collecting global daily Ocean Colour data at 300m resolution, which enables monitoring of small environments, such as Nuup Kangerlua (Fig. 1). In this study, we investigate the performance of ESA-Chl *a* estimates (2016-2022)

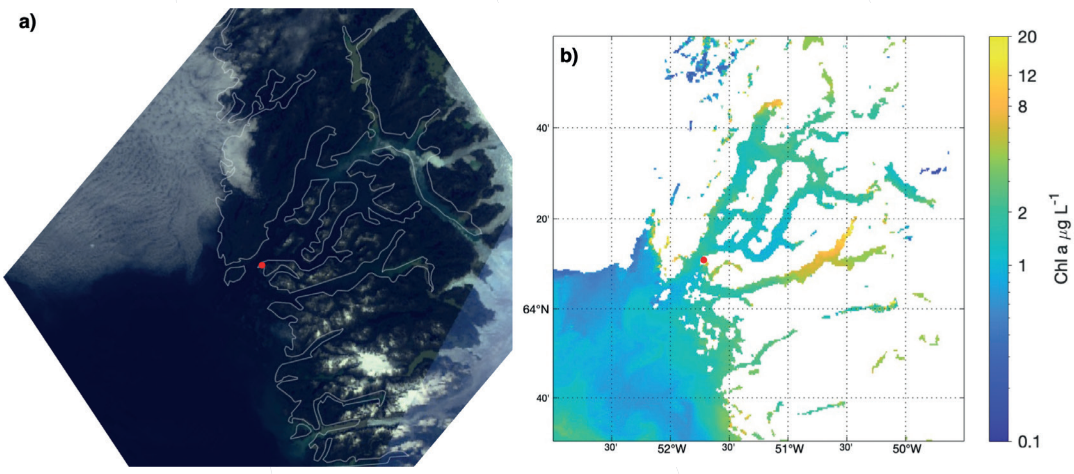


Figure 1. a) True color ESA-S3 scene for Nuup Kangerlua on 29 July 2021. b) Chl a concentration (μg L⁻¹) provided by The European Service for Ocean Colour (GlobColour) for the same date as (a). In both panels, the red dot indicates the location of Nuuk.

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Data source:

MarineBasis Nuuk data (*in situ* Chlorophyll a).

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

GEM
Greenland Ecosystem Monitoring

PHYTOPLANKTON IN SATELLITE REMOTE SENSING

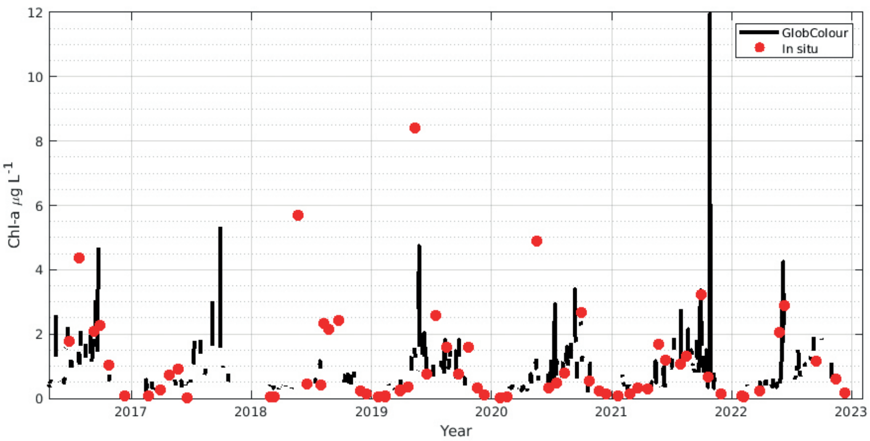

Figure 2. Time series (Apr 2016 to Dec 2022) of Chl-a concentrations (µg L-1) obtained in situ through the MarineBasis Nuuk Monitoring Programme (red dots) and GlobColour retrievals (black line). The data shows high seasonal and interannual variability in Chl-a, with no apparent trend (as observed also for the in situ data (Vonnahme et al., 2022)), however this is will be further investigated in the project.

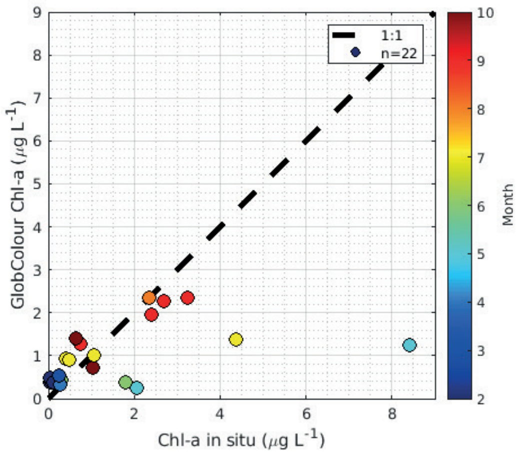

Figure 3. In situ Chl a measurements versus GlobColour Chl a estimates for the exact same date and location (within 300 m distance). Color bar represents the month of the year when the in situ sample was collected.

in relation to *in situ* data collected in Nuup Kangerlua as part of the MarineBasis Nuuk Monitoring Programme.

The GlobColour Chl *a* estimates for the *in situ* sampling station (within 300 m) generate a significantly higher data frequency compared to the monthly *in situ* water sampling from the MarineBasis Nuuk programme (Fig. 2). Additionally, GlobColour data showed a more detailed seasonal pattern along with additional peaks in Chl *a* outside of the *in situ* sampling dates. However, since ocean color sensors depend on the reflected sunlight there is a lack of data during the winter months and cloudy periods (i.e., discontinued lines in Fig. 2).

The cloud-coverage can partially be rectified by expanding the target area by averaging near pixels or by employing interpolation techniques. Additionally, particles in the water, for example silt discharged from land influence the light reflected by the ocean's surface. Moreover, part of the phytoplankton production in Arctic coastal ecosystems occurs at depths which are not visible to satellites. Altogether these interfering processes underline the importance of comparative studies of *in situ* and remote sensing data.

Overall, the GlobColour estimates were in agreement and showed a significant correlation with the *in situ* measurements, with a few exceptions (Fig. 2 and 3). Two cases were, however, identified to challenge the GlobColour performance: a) during spring, when *in situ* measurements report the highest Chl *a* values that are underestimated by GlobColour; and b) during late-summer and autumn, when Chl *a* values are low but with an overestimation by GlobColour. Underestimation in spring is likely due to the reduced availability of data (i.e., cloud cover) and high phytoplankton concentrations reducing the detectable depth to less than the depth where phytoplankton thrives (i.e., photic zone). On the other hand, the overestimation observed later in the year is attributed to the presence of glacier flour (silt), which interacts with light at the same wavelengths as phytoplankton pigments (e.g., Chl *a*), thus leading to an overestimation of Chl *a* biomass.

This is a first application of high-resolution satellite imagery (ESA-S3 GlobColour) to monitor surface phytoplankton dynamics in Nuup Kangerlua, which was conducted as part of the GEM Remote Sensing Initiative, and results are encouraging. Moreover, this study underlines the importance of maintaining *in situ* measurements (as currently done by the MarineBasis Nuuk programme) to continuously validate satellite-based products and provide ecosystem parameters necessary for providing the answers to satellite-based observations.

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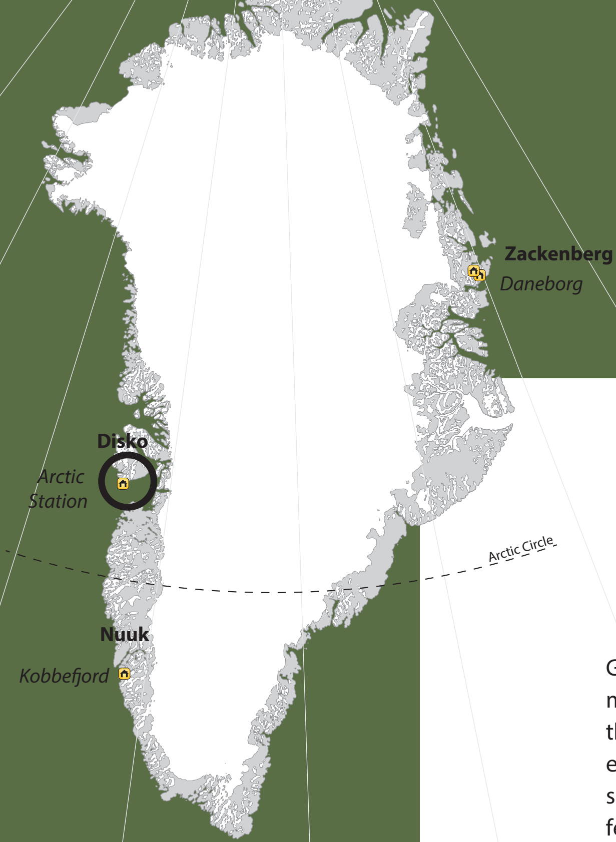
Photo: Thomas Juul-Pedersen.

SEASONAL SUCCESSION OF THE
– IMPLICATIONS OF CLIMATE CHANGE



The GEM Marine monitoring programme explores the seasonal distribution of phototrophic and heterotrophic plankton organisms, allowing for documentation of climate driven changes in the food web structure.

TAKE HOME MESSAGE

The food chain in Disko Bay is far more complex than the standard textbook example. After the spring bloom the plankton community is dominated by unicellular grazers and smaller copepod species as opposed to the *Calanus* dominated spring bloom community as a driver of the carbon vertical flux and remineralization in surface waters respectively.

Greenland's economy is highly dependent on marine resources. Fishing accounts for more than 95% of Greenland's exports income. The early planktonic life stages of the targeted shrimp, crab and fish species are pelagic and feed on the planktonic food web. Changes in the plankton community structure and production will therefore potentially impact the recruitment to the stocks and thereby fishery. Disko Bay is one of the most productive areas on the Greenland west coast and the GEM MarineBasis programme in Disko monitors the seasonality of the plankton, thereby documenting impacts of climate change on the pelagic food web.

Arctic marine food webs are considered to be characterized by a short grazing chain, i.e., dominated by large autotrophic diatoms (silicified algae) that via large copepods support the fish larvae. However, the marine food web in the Arctic is far more diverse. It consists of:

- Entirely photoautotrophs (A) that carry out photosynthesis using their own chloroplasts
- Constitutive mixotrophs (CMs), which are organisms with their own chloroplasts, that also can eat
- Non-constitutive mixotrophs (NCMs), which are organisms that lack chloroplasts of their own, utilizing chloroplasts from their algal prey
- Heterotrophs, which rely entirely on prey for growth

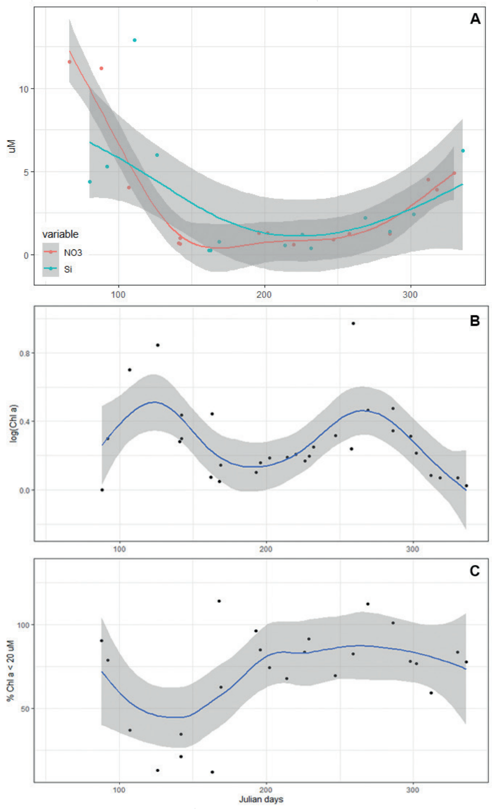


Figure 1. The seasonal variation off Qeqertarsuaq, Disko Bay based on data from 2018-2022. A. Nitrate and silicate (µM), B: Total Chlorophyll a (µg Chla L[-1]) and C: Percentage of Chlorophyll a < 20 µm. Solid lines reflect the overall temporal trends based on locally weighted regressions and the shaded areas their associated 95% confidence intervals.

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Data source:

MarineBasis Disko.

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

PLANKTONIC FOOD WEB IN DISKO BAY

GEM
Greenland Ecosystem Monitoring

During winter, nutrient concentrations (nitrate and silicate) are high due to mixing of the water column and the primary production is low. The community of primary producers are dominated by small bacterivorous CM mixotrophs, while the autotrophs (diatoms) contribute a small percentage (Figs. 1 and 2); i.e., the fraction of Chl *a* less than 20 µm dominates. As the day length and irradiance increase during spring, the autotrophs (diatoms) bloom and become the dominant primary producers. They deplete the photic zone for nitrate and silicate from April to June (day 100-160). During summer, June to August (day 160-240), the biomass of primary producers is low and dominated by small cells (Chl *a* fraction less than 20 µm, Fig.1). Summer to early autumn, the mixotrophs prevail, and the large CMs (dinoflagellates) and NCMs (mainly ciliates) have their main occurrence (Fig. 2).

The entire heterotrophic protozooplankton (ciliates and heterotrophic dinoflagellates) make up for a biomass, which is comparable to the copepods (Fig 2). Due to their faster growth rates, they have a greater impact on the primary producers than copepods, but they are often ignored in Arctic food webs (Levinsen and Nielsen 2002). The heterotrophic protozoans can exploit small as well as larger primary producers. The copepod biomass is dominated by the large *Calanus* copepods during spring – early summer, while *Calanus* developmental stages and smaller copepod species (*Oithona*, *Microsetella* and *Pseudocalanus*) dominate during autumn and winter.

How will global warming impact the pelagic food web? The sea ice cover has been decreasing in Disko Bay for the past 25 years, indicating warming of the atmosphere in the area. Yet, long-term data from Arctic Station, which dates back almost 100 years, do not yet reveal significant changes in salinity or temperature in the upper 100 m of the water column (Hansen et al 2012; Fig, 3), probably because the heat is trapped in the large water masses in the area. The longer open water periods will increase the primary production, since the sunlight penetrates into the water column earlier, and consequently the spring bloom develop earlier. We also expect that the importance of the mixotrophs in Disko Bay will increase in the future since the period with low nutrient concentrations will increase.

The situation is, however, different at depths. Increases in temperature by 1–1.5 °C at 200-300 m depth have been evident since 1997 (Hansen et al., 2012; Fig. 3). However, it is also clear that we now observe significant year-to-year fluctuations. This may especially impact the *Calanus* dominated copepod community, which overwinters at these depths. If more Atlantic water enters the Disko Bay a larger fraction of Atlantic *Calanus* species with lower lipid content, may replace Arctic *Calanus* species with a higher lipid content. This lower lipid content may potentially impact the growth and recruitment of fish and shrimp/crap larvae that are of paramount importance for the Greenlandic economy.

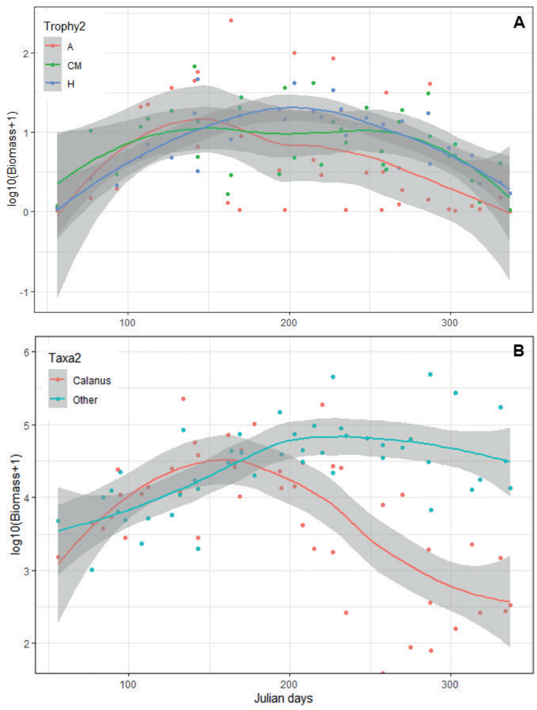

Figure 2. The seasonal succession of biomass (µgC L⁻¹) of planktonic organisms off Qeqertarsuaq, Disko Bay. A: Autotrophic (A), constitutive mixotrophic (CM) and heterotrophic (H) protists, B: Biomass of large copepods (Calanus spp.) and other small copepods (Oithona, Microsetella, and Pseudocalanus). Solid lines reflect the overall temporal trends based on locally weighted regressions and the shaded areas their associated 95% confidence intervals.

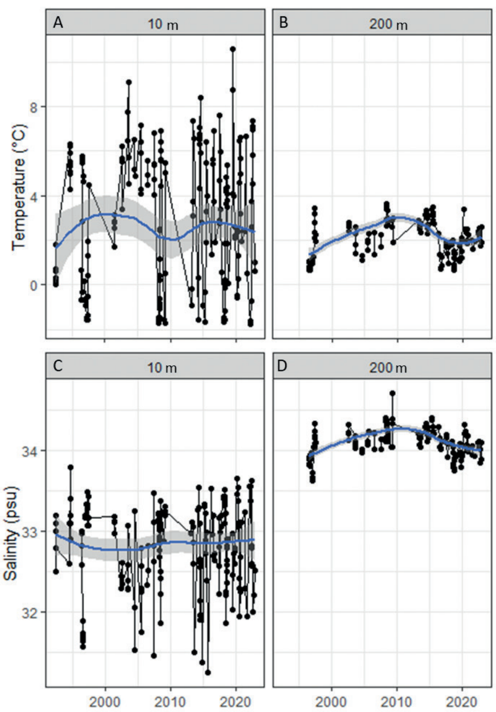

Figure 3. Temperature and salinity at 10 and 200 m off Qeqertarsuaq, Disko Bay during the period 1992-2022; data from the years 2010-2012 were omitted due to lack of summer values. Solid lines reflect the overall temporal trends based on locally weighted regressions and the shaded areas their associated 95% confidence intervals.

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VEG(M)APP: ENHANCING GROUND TRUTHING DATA

To improve vegetation mapping in Kobbefjord, 264 ground reference data (GRD) points have been collected. The sampling included testing a smartphone app for collection of the GRD points. Our testing indicates that while the app has potential for effective GRD collection there is room for optimization, and collected data cannot be used without considerable processing. None the less, the data collection efforts have yielded a refined vegetation map for Kobbefjord though future evaluation and processing will enhance the output even further.

TAKE HOME MESSAGE

A simple smartphone app can be an efficient tool for ground truthing vegetation data and hence ensure better coupling between remote sensing and *in-situ* environment.

Great advances have happened within vegetation mapping in the Arctic during the past decades (Karami et al., 2018; Rudd et al., 2021; Walker et al., 2018). However, there is still a long way to go and the need for high resolution, accurate and ground truthed vegetation mapping persists. Highly accurate maps are crucial for e.g., detection of vegetation changes with implications for research such as modelling and remote sensing as well as with applications for management and conservation.

Our contributions to more accurate vegetation mapping of the Kobbefjord area include the use of a smartphone app based on the ArcGIS platform (Fig. 1) and subsequent analysis and classification of the data in Google Earth Engine (GEE). While the app shows great potential for effective and convenient data collection, attention should be paid to how much and what data needs to be collected. The convenience of the app data collection emphasizes important questions such as how much data is necessary to collect, how to ensure representativeness, what vegetation classes/types to apply and whether this is in fact the best data to collect.

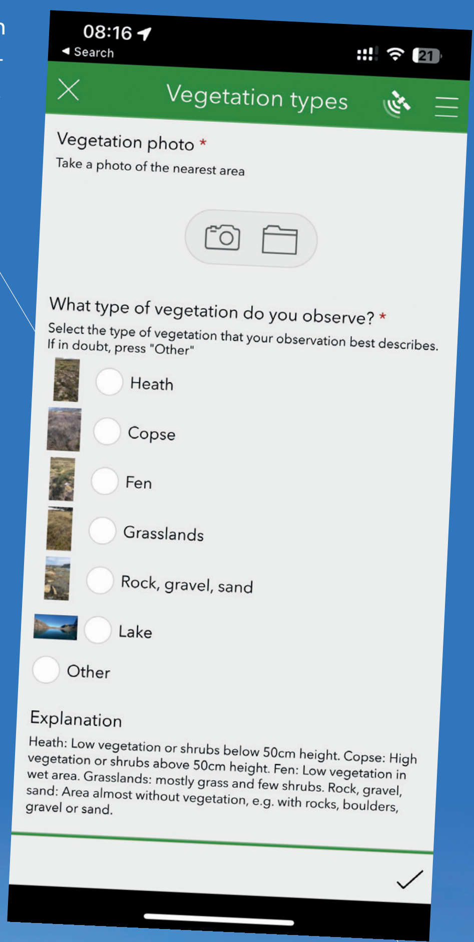

Figure 1. Screen shot of the Survey123 smartphone app highlighting the simple setup that can be used by both researchers and as a tool for citizen science.

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[2] Aarhus University, Denmark

Data source:

GEM BioBasis Vegetation Monitoring component in Kobbefjorden, West Greenland.

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

VEGETATION MAPPING USING
FROM A SIMPLE SMARTPHONE APP

GEM
Greenland Ecosystem Monitoring

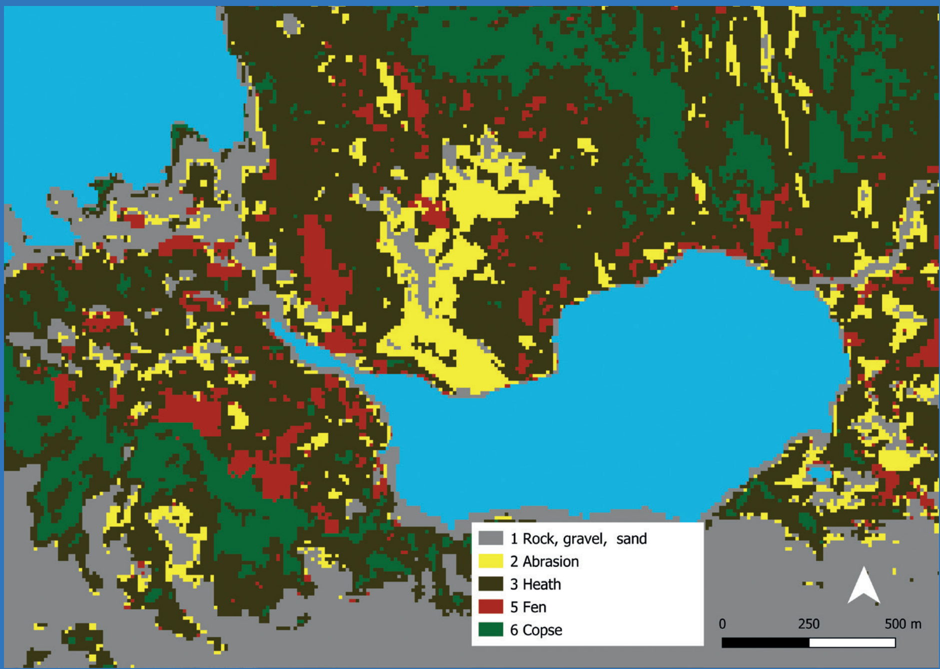

Figure 2. Vegetation map from Kobbefjord updated using the GRD points collected in part by the smartphone app.

Out of the 264 GRD points collected by researchers only 114 were used in the improved vegetation mapping (Fig. 2), which had an overall accuracy (OA) of 89 %. The initial GEE analysis including all GRD points revealed a lower OA (74 %) and review of the data showed a low degree of representativeness of some data points. Subsequently the data was manually processed, including removing overlapping GRD point and adding additional 94 points by visual interpretation of a high resolution orthophoto to ensure equal representation of all the vegetation types. This was only possible with reference to the GRD and resulted in omitting 150 of the original GRD points and made it very evident that GRD needs to be representative in terms of both homogeneity of the sampled location and equally distributed between in each vegetation type.

The future of vegetation mapping in Kobbefjord should include additional collections of unbiased characteristics such as vegetation height, indicator plants species and exploration of data assimilation classification, as well as considerations of how to evaluate the quality and accuracy of vegetation maps in general. The ArcGIS Survey123 app provides a convenient, easily adjustable, and publicly available platform for collection of any georeferenced data we decide on. The latter meaning that it also holds potential to be deployed as a citizen science tool where people can contribute to the collection of data and mapping of vegetation.

References

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Photo: Ida Bomholt Dyrholm Jacobsen, Kobbefjord, 64.142175, -51.368847 (292 m gps altitude)

PROGR
DESCR

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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.

Annual Report Card 2022

GEM CLIMATEBASIS

The ClimateBasis programme monitors climate and hydrology in Zackenberg, Kobbefjord and Disko and is run by Asiaq - Greenland Survey. The collected data build base-line information on climate variability and trends for all the other sub-programmes within GEM and serve as a trustworthy foundation for adaptation strategies for the Greenlandic society. The stations are embedded in Asiaq's extensive climate and hydrology monitoring network. Furthermore, the runoff data is delivered to the World Hydrological Cycle Observing System (WHYCOS) and the Global Runoff Data Centre (GRDC) networks. Atmospheric parameters are collected redundantly at each location on two separated masts with individual energy supplies in order to be able to treat data gaps and sensor biases consistently. Hydrometric parameters are monitored on various automated stations. Emphasis is placed on the establishment of reliable stage-discharge relations, a challenging task since their temporal stability depends on the 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 2022 was very close to the longer-term mean (2008-2022) at all three GEM sites (–0.2°C, +0.3°C and –0.3°C difference at Kobbefjord, Disko and Zackenberg, respectively). While the summer months were relatively cool, the temperatures during the rest of the year were highly variable and exhibited frequent month-to-month whiplash; only at Disko, arguably the most maritime of the three locations, were the swings less pronounced. This indicates that frequent incursions of warm southerly air alternated with cold air from the north.

Monitored parameter groups

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

Discharge measurements using diluted salt in Kobbefjord. Photo: Asiaq.

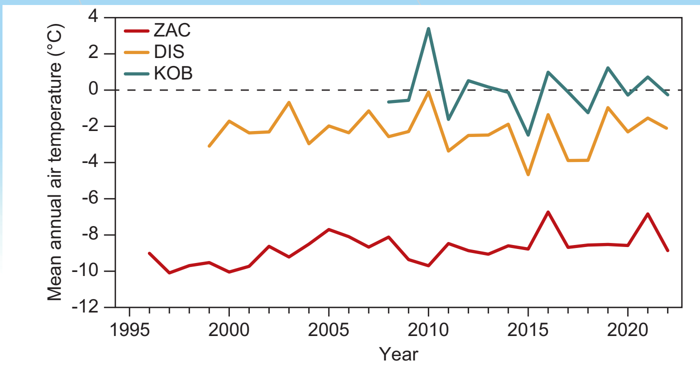

Figure 1. Mean annual air temperature at the three GEM sites Zackenberg (ZAC), Disko (DIS) and Kobbefjord (KOB).

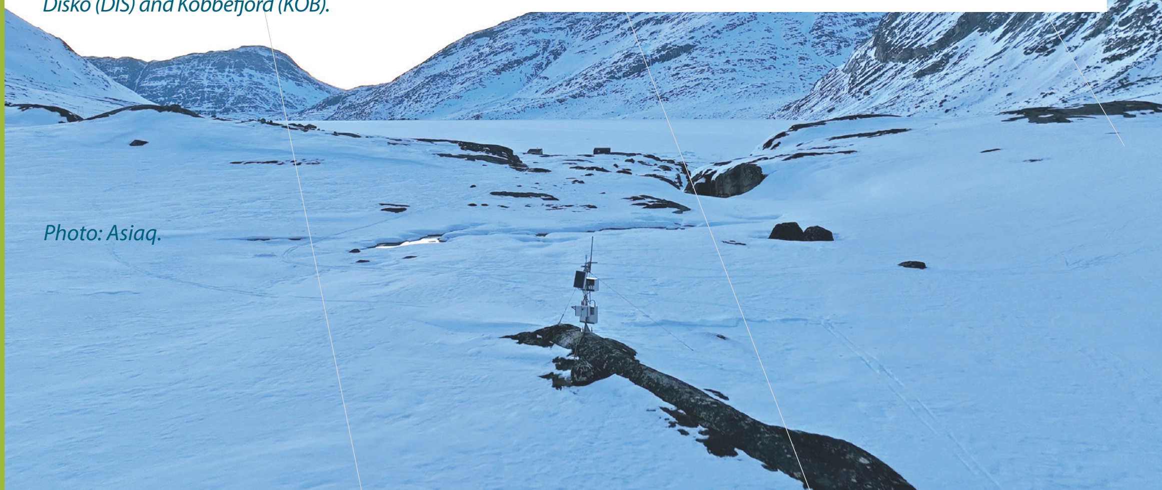

Photo: Asiaq.

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Disko:
Asiaq – Greenland Survey, manager: Arno Hammann, ach@asiaq.gl

Contributing authors:
Arno Hammann, Kirsty Langley

PROGRAMME DESCRIPTION

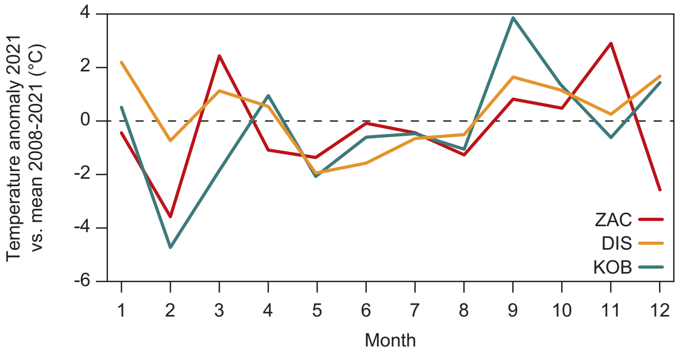


Figure 2. Monthly air temperature anomaly for 2022 compared to the common reference period 2008-2022 for Zackenberg (ZAC), Disko (DIS) and Kobbefjord (KOB). A triangle marks a month whose mean temperature has been more extreme than those of the corresponding month in any other year from 2008-2021. The upward pointing triangle indicates that the month has been the warmest in this period, and the downward pointing triangle indicates that the month has been the coldest in this period.

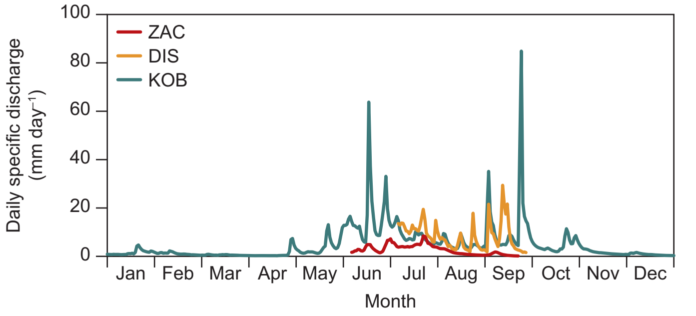


Figure 3. Specific daily discharge for 2022 for Zackenberg (ZAC), Disko (DIS) and Kobbefjord (KOB).

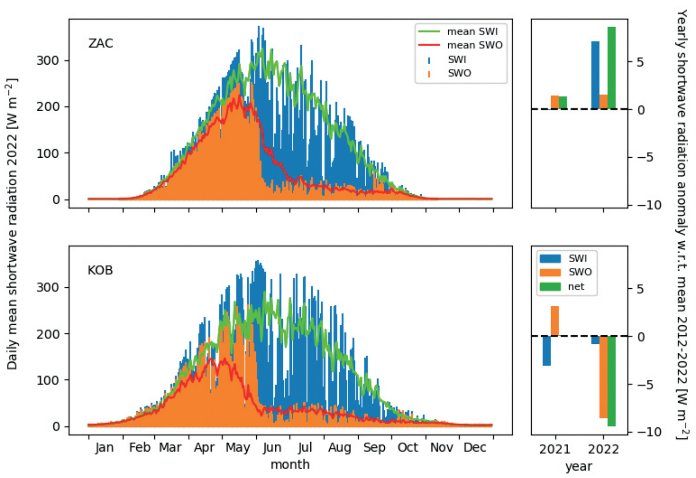


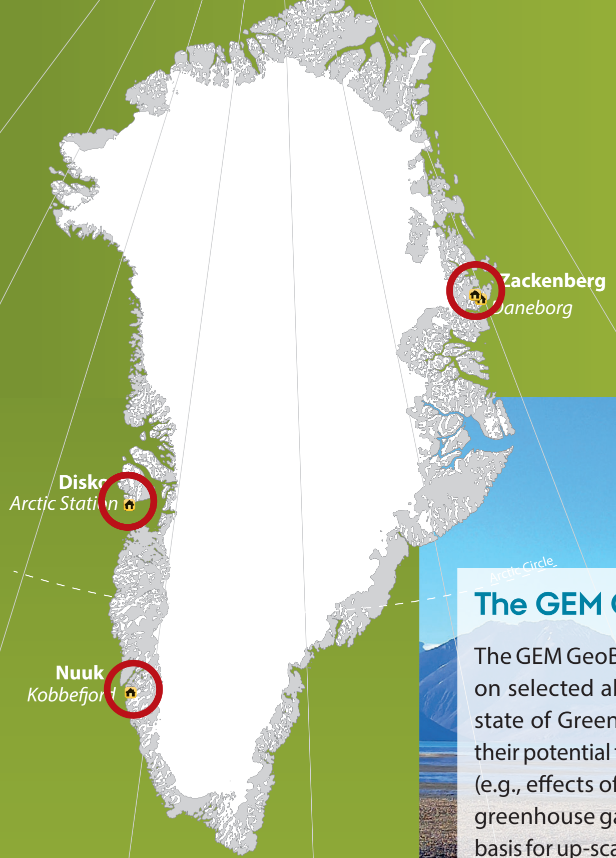
Figure 4. Main plots: Daily mean shortwave incoming radiation (SWI) and shortwave outgoing radiation (SWO) in 2022 with their respective daily means for the period 2012 to 2022 (SWI mean and SWO mean) for Zackenberg (ZAC) and Kobbefjord (KOB). Bar plots (right columns) show yearly mean anomalies for 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.

The Kobbefjord record saw two monthly mean records broken: The coldest August was followed by the warmest September. While the previous coldest August occurred in 2018 and was only about 0.2°C warmer than August 2022, September 2022 was warmer by nearly 1.3°C than the previous record, which occurred in 2010. The warm air in September also brought large precipitation events along the West Coast (see the report card on precipitation events). At Kobbefjord, the ensuing peak discharge from Badesø resulted in the destruction of the foot bridge near the research station, which was first noticed on 24.09.

The autumn of 2022 was exceptionally wet on Greenland's West Coast, as can be seen in the discharge data from Kobbefjord and Disko. In a number of locations, floods, landscape changes and infrastructure damage occurred as a result. For more details see report card "The wet summer and autumn of 2022" on page 20.

The incoming shortwave radiation tells the same story as monthly temperatures and river discharge: cloudiness associated with the intrusion of moist air leads to many periods of reduced incoming solar radiation and high general variability of the record. Nonetheless, Zackenberg received a very slightly higher amount of net radiation in 2022 compared to the previous year. Net radiation is the difference between incoming and outgoing radiation – the latter primarily a result of the reflection of sunlight by the soil and vegetation and, in particular, the snow in winter. Because the snow cover lasted comparatively long in Kobbefjord, the net radiation receipt there was lower in 2022 due to larger amounts of reflected radiation.

Climate station in Kobbefjord.
Photo Asiaq.



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GEM GEOBASIS

The GEM GeoBasis Programme

The GEM GeoBasis monitoring programme focuses on selected abiotic characteristics describing the state of Greenlandic terrestrial environments and their potential feedback effects in a changing climate (e.g., effects of permafrost thaw, energy fluxes and greenhouse gases). Monitored plot data provides a basis for up-scaling to a landscape level and improvements of ecosystem models to be able to quantify interactions in relation to the atmosphere and also the adjacent marine environment. The GeoBasis 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.

Coastline monitoring with drone in Zackenberg. Photo: Daniel Alexander Rudd.

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Monitored parameters

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

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

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

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

Automatic weather station (AWS2) in September 2022. Photo: Lars Rasmussen.

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

PROGRAMME DESCRIPTION

Greenland Ecosystem Monitoring

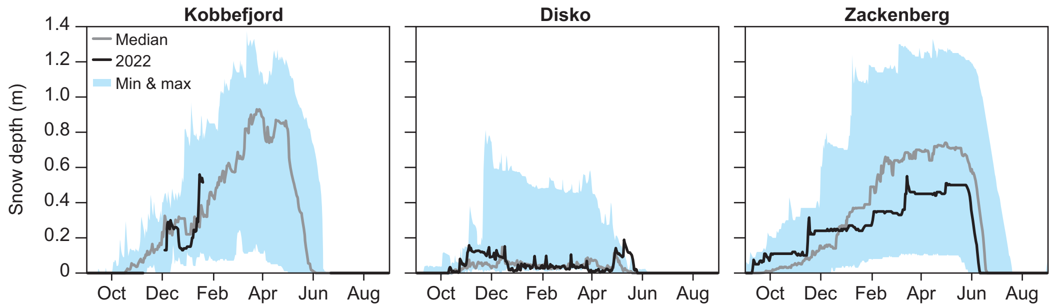

Figure 1. Daily snow depth measurements in 2022 (black lines) compared to min and max for the historical record (shaded area) and the median (grey line). Snow is a key parameter in Arctic ecosystem functioning. Several different monitoring methods are put in place to get information on spatial distribution and temporal patterns in snow cover, across the three GEM sites. Methods include time-lapse photography, transect surveys, snow density measurements and, as shown here, long-term point-based monitoring of snow depth. Data used in the figure: Kobbefjord: 2008-2022, Disko: 2012-2022 and Zackenberg: 1997-2022.

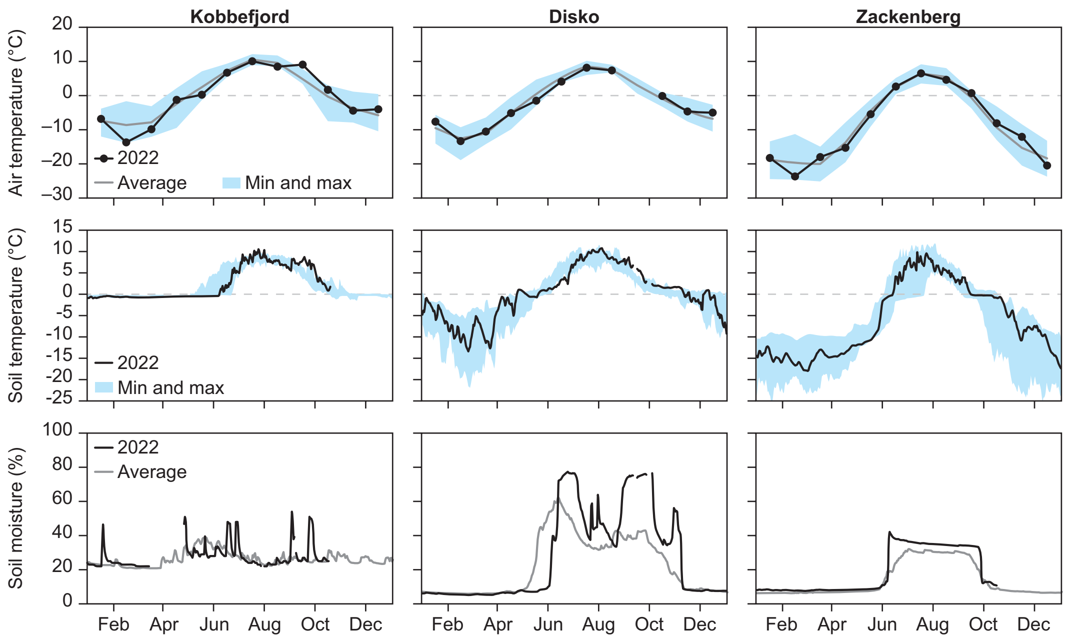

Figure 2. Mean monthly air temperature across sites (top panel) in 2022 compared to average (grey line) and minimum, and maximum (shaded area) in historical data. Heath soil temperatures in 10 cm (middle panel) in 2022 compared with minimum and maximum (shaded area) and soil moisture within the top 10 cm, shown together with long-term average (grey line). Soil temperature and soil moisture content are important parameters for plant growth, phenology, permafrost, energy fluxes and carbon exchange. Soil temperature and soil moisture are measured under several different vegetation communities and in a wide range of depths, as part of the GeoBasis programme. Data used in the figure: Air temperature: Kobbefjord: 2008-2022, Disko: 2012-2022 and Zackenberg: 1996-2022. Soil temperature: Kobbefjord: 2012-2022, Disko: 2012-2022 and Zackenberg: 1996-2022. Soil moisture: Kobbefjord: 2013-2022, Disko: 2012-2022 and Zackenberg: 2005-2022.

In Zackenberg, the end of winter snow depth was in the low end compared to previous years, and the timing of snow melt quite early (Fig. 1). This is in contrast to Kobbefjord and Disko on the West coast of Greenland, where snow melt was late in 2022. It is common to see the snow depth decrease due to rain or Føhn events during winter in both Kobbefjord and Disko, whereas in Zackenberg the snow builds up steadily over the winter. The late snowmelt also caused late soil thaw compared to earlier years in both Kobbefjord and Disko (Fig. 2) and several rain events including some major ones in June and September kept the soils very wet with saturated conditions throughout long periods (Fig. 2). The autumn was very warm with mean temperatures in September close to or above earlier registrations at all three sites (Fig. 2).

In Zackenberg, the mean maximum thaw depth of the 110 grid nodes in ZEROCALM-1 reached 86 cm (Fig. 3).

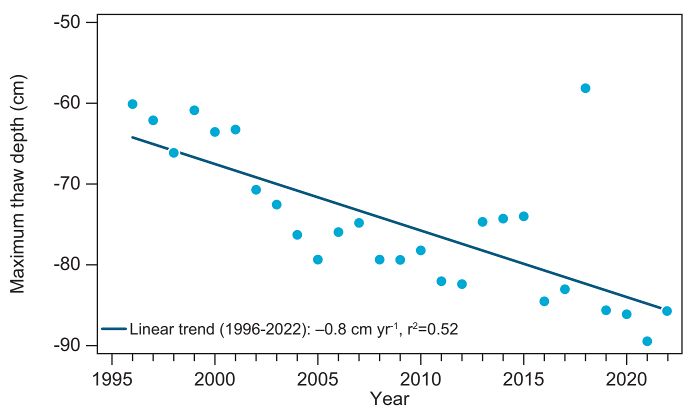

Figure 3. Long-term trend in annual maximum soil thaw depth in Zackenberg Circumpolar Active Layer Monitoring grid #1 (ZEROCALM-1). Soil thaw and active layer depth are studied under different vegetation types. Monitoring methods include manual probing, as the one shown here, and borehole temperature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

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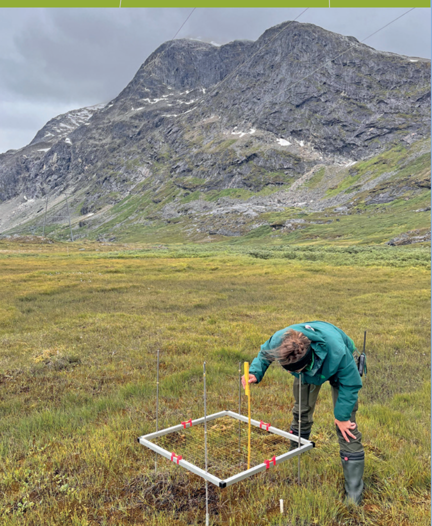
GEM BIOBASIS

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



Monitored parameters

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

Arthropods and microarthropods
- Abundance
- Emergence phenology
- Herbivory rates

Birds
- Abundance
- Reproductive phenology
- Reproduction and predation rates

Mammals
- Abundance
- Spatial distribution
- Reproduction and predation rates

Lake flora and fauna
- Phytoplankton abundance and diversity
- Zooplankton abundance and diversity
- Fish stocks

General
- Tissue sampling
- Plot-scale abiotic parameters

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PROGRAMME DESCRIPTION

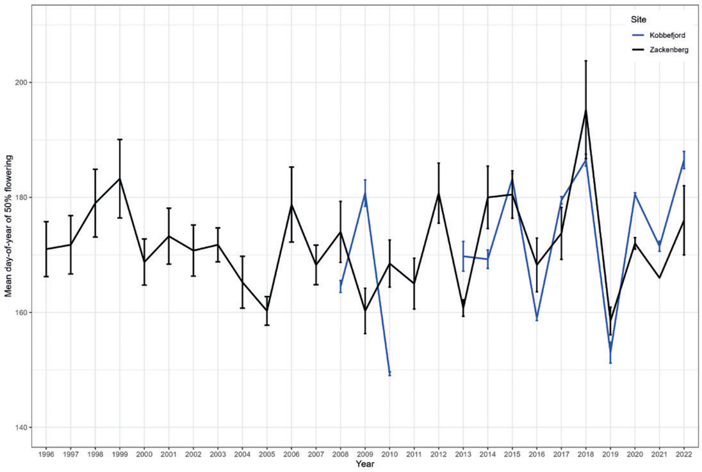

Figure 1. Day of 50% flowering is indicative of the effect of climate variability on the timing of flowering. The timing of plant growth and flowering is important for e.g. insects and herbivorous animals.The graph shows inter-annual variation in mean Salix flowering phenology in selected permanent plots in Kobbefjord and Zackenberg 1996-2022. Note that no flowering was observed in Kobbefjord in the years 2011 and 2012 due to insect outbreak, and due to the covid-19-induced late arrival to Zackenberg in 2020 and 2021, two out of four plots in 2020 and three out of four in 2021 had reached 50% flowering prior to arrival.

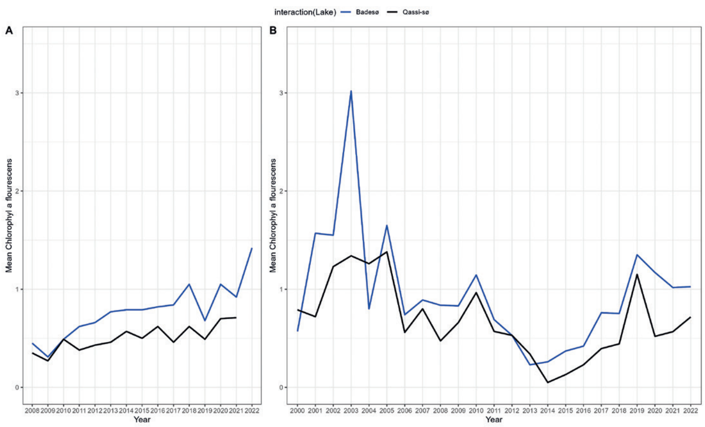

Figure 2. Chlorophyll fluorescence is a measure of productivity in the limnic ecosystem. The graphs show inter-annual variation in chlorophyll fluorescence in lakes at Kobbefjord and Zackenberg 1996-2022. Blue lines indicate lakes with fish, black lines lakes without fish. Note that due to the late onset of the 2020 season at Zackenberg dictated by the covid-situation, only one measurement was conducted in July. In 2022, one lake could not be sampled due to logistical constraints.

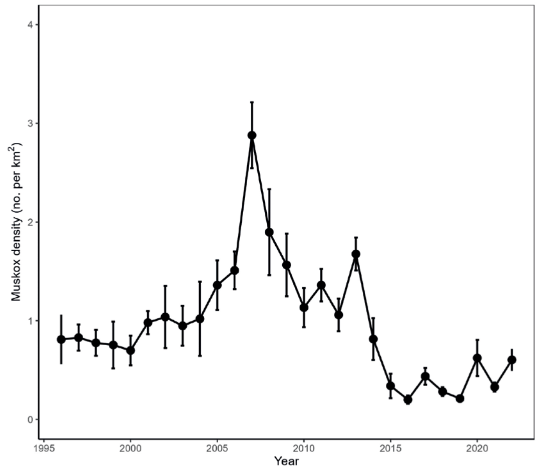

Figure 3. Inter-annual variation in muskox population dynamics (July and August) at Zackenberg 1996-2022.

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GEM MARINEBASIS


Photo: Mie Winding.

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

Monitored parameters:

- Sea Ice and Snow Conditions
- CTD Measurement
- *p*CO_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

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Photo: Mie Winding.

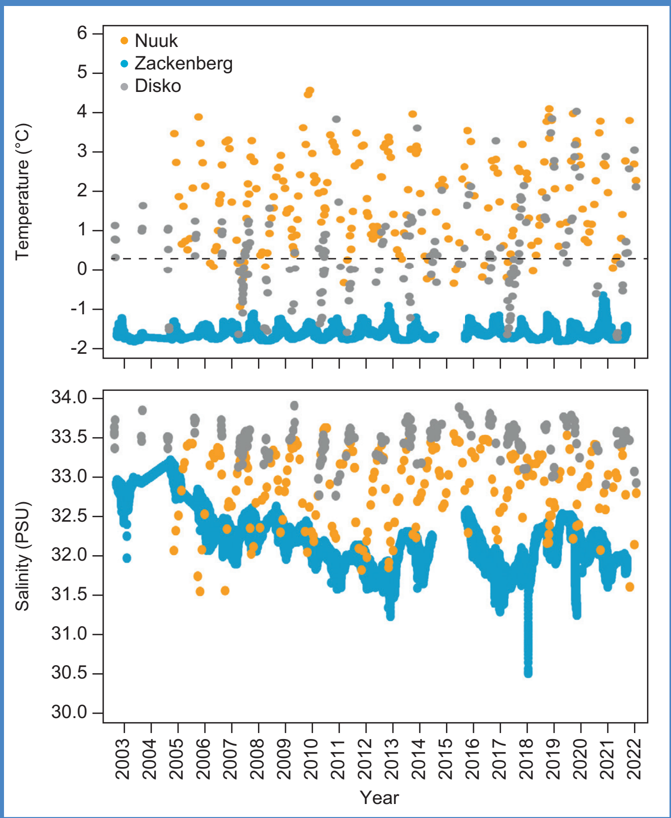

Figure 1. Water temperature and salinity at the permanent monitoring stations in Nuuk, Disko and Zackenberg. The time series from Nuuk and Disko represents one depth (63 m) selected from a monthly profile covering the entire water column. The time series from Zackenberg represents an autonomous mooring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

Photo: Mie Winding.

Photo: Mie Winding.

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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.

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)

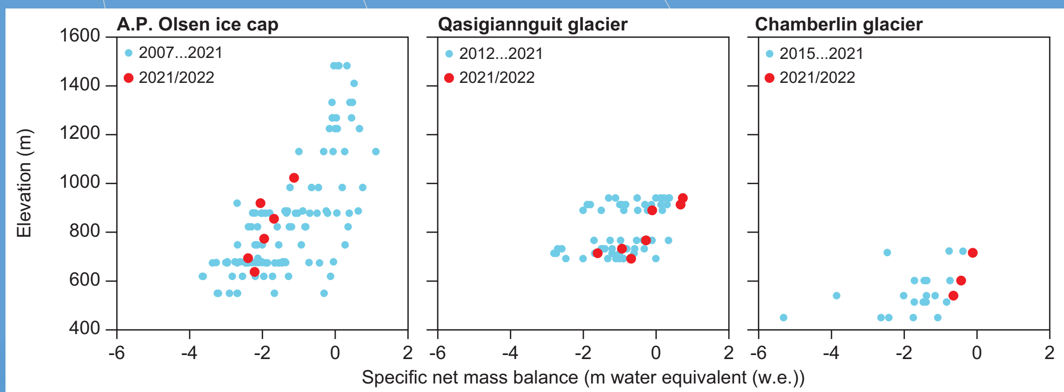

Figure 1. Glacier surface mass balance vs. elevation at the stakes on A.P. Olsen ice cap (Zackenberg, 14 stakes), Qasigiannguit glacier (Kobbefjord, 9 stakes) and Chamberlin Glacier (Disko, 7 stakes).

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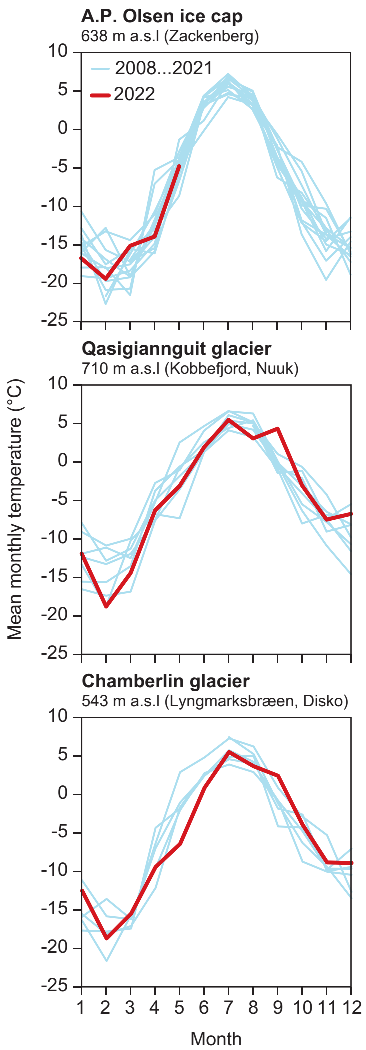


Figure 2. Mean monthly air temperatures from automatic weather stations in the ablation zone of the monitored glaciers at the three GEM sites in 2022 (red) vs. earlier years (gray).

GlacioBasis monitors three glaciers: Qassinguit Sermiaq at the Kobbefjord, Nuuk site, Chamberlin glacier at the Disko site and A.P. Olsen Ice cap at the Zackenberg site. At Chamberlin glacier the 2022 melt season was colder than average during spring and early summer leading to a late start of the melt season and late disappearance of the deeper than average snowpack, resulting in lower total ice melt compared to other years. Both at Qassinguit Sermiaq and Chamberlin glacier the autumn was unusually warm. The total ice melt at A.P. Olsen ice cap was close to average in 2022.

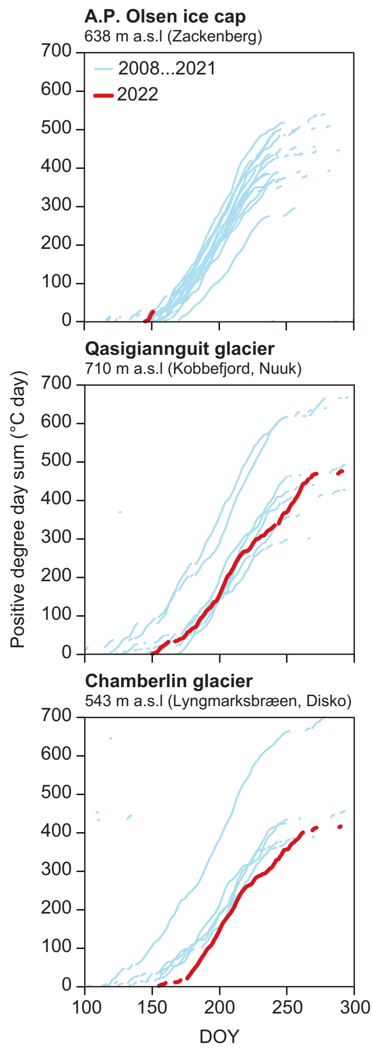


Figure 3. Positive degree day (PDD) sums, indicating melting conditions, from GlacioBasis automatic weather stations in the ablation zone of the monitored glaciers at the three GEM sites in 2022 (red) vs. earlier years (gray). Gaps visible in the curves indicate sub-freezing daily mean temperatures.

Greenland Ecosystem Monitoring

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

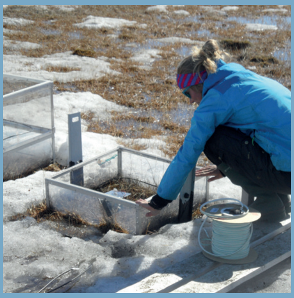
www.g-e-m.dk

ClimateBasis Programme

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

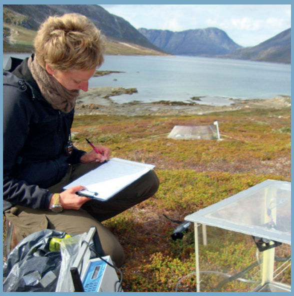
GeoBasis Programme

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



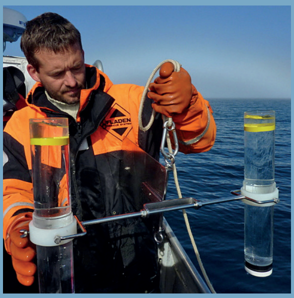
BioBasis Programme

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



MarineBasis Programme

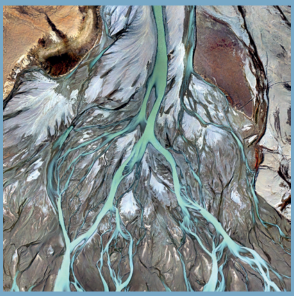
The GEM MarineBasis Programme studies key physical, chemical and biological parameters in marine environments.



GlacioBasis Programme

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

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.



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ASIAQ

GEUS

Grønlands Naturinstitut
Pinngortitaleriffik · Greenland Institute of Natural Resources

DTU Technical University of Denmark

UNIVERSITY OF COPENHAGEN