Greenland Ecosystem Monitoring

ANNUAL REPORT CARDS 2019

GEM

Greenland Ecosystem Monitoring

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GREENLAND ECOSYSTEM MONITORING

ANNUAL REPORT CARDS 2019

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GEM

Greenland Ecosystem Monitoring

GEM INTRODUCTION

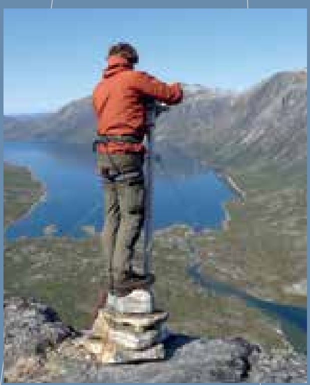

Photo: Kerstin K. Rasmussen.

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 with the aim to contribute to the programmes of the Arctic Council and improve the scientific understanding of climate and ecosystem change in the Arctic. Over the years, 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 the inhabited West Greenland, supplemented with initiatives at other locations (Figure 1 and 2).

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

The GEM organisation consists of a Steering Committee, a Secretariat, a Coordination Group and sub-programme leaders. Sub-programme leaders from the main institutions involved in GEM lead the five sub-programmes: ClimateBasis, GeoBasis, BioBasis, MarineBasis and GlacioBasis. The programme is funded by DANCEA (Danish Cooperation for Environment in the Arctic) through the Danish Ministry of Climate, Energy and Utilities and the Danish Environmental Protection Agency, and by the Government of Greenland.

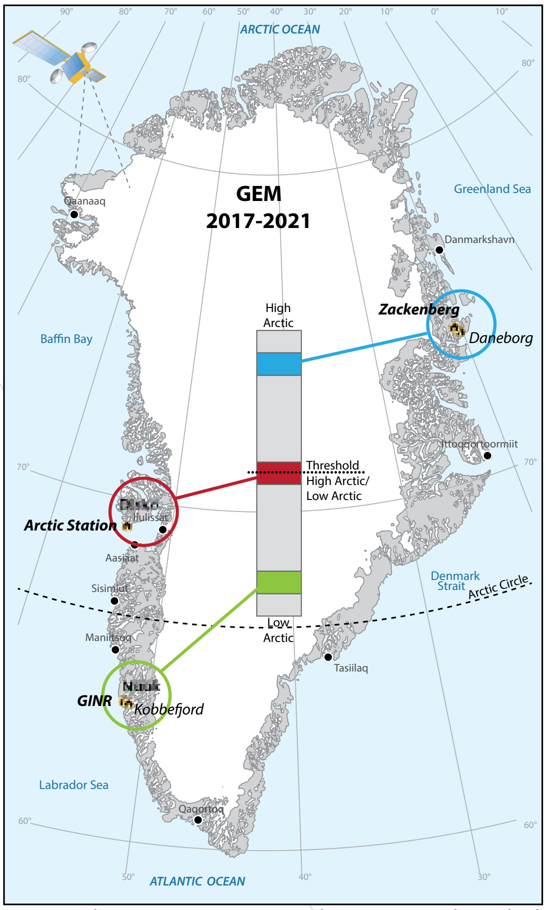

Figure 1. The GEM programme combines intensively studied ecosystems at three main sites (Disko, Nuuk and Zackenberg) with remote sensing and long-term single disciplinary sub-sites and short term research projects located along environmental and climatic gradients.

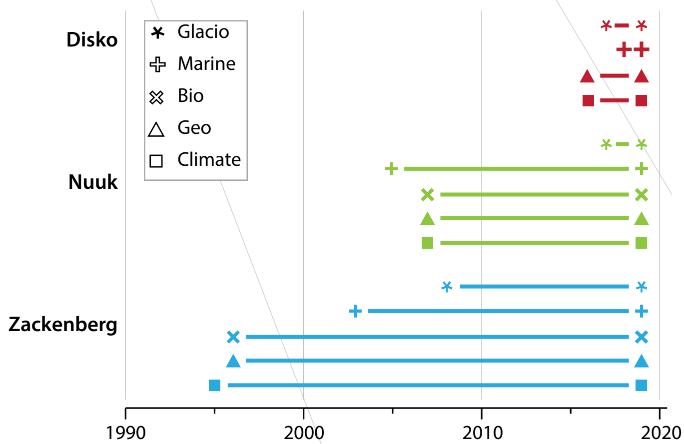

Figure 2. The GEM programme was initiated as the Zackenberg Ecological Research Station operations (ZERO). The programme developed from 1995 in Zackenberg with a gradually broader scientific scope. In the years 2005-2007 a new main site was established around Nuuk, and in 2016-2018 Disko area was included as a new main site, on the boundary between the High Arctic and low Arctic. All 5 Basisprogrammes are now funded at all 3 main sites, except for BioBasis at Disko.

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The vision of GEM

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

International cooperation

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

Education and Advice

GEM aims to play a central role in educating the next generation of scientists, with several university courses using GEM data, and associated Ph.Ds and Post Docs. GEM scientists also reach out to younger students in schools and high schools through course and information materials based on GEM knowledge and data – also in international cooperations reaching a wide Arctic audience. GEM also 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.

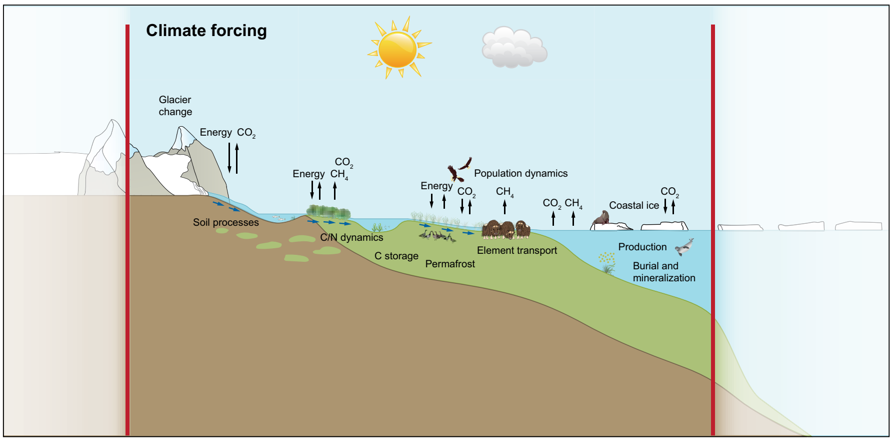


Figure 3. The GEM domain covers the glaciological, terrestrial, limnic and coastal marine compartments of the ecosystem.

Free and open access to data

GEM provides free and open access to all data collected under the programme since the start in 1995. At all three GEM sites there are data series from before GEM started operating, and being highly relevant for long-term monitoring, these have been integrated into the database. Data collection efforts have grown since the start of the programme and today includes more than 2500 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/

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. Photo: Bo Elberling.

Greenland Institute of Natural Resources (GINR), Nuuk. Photo: Carsten Egevang

Zackenberg. Photo: Henrik Spanggård Munch.

GEM ANNUAL REPORT CARDS
INTRODUCTION

Photos: Katrine Raundrup.

2019 results and achievements

In 2019 the snow depth at all three main sites were close to the long term mean. However, the annual mean temperature was higher than the 2008-2019 average at all three main sites, and especially Disko experienced record high monthly mean temperatures from May to November, compared to the period 2012-2019.

The standardized time series, allow different drivers to be evaluated across the different GEM sites. As shown in this edition, differences in nutrient availability may in some cases overrule the impacts of differences in climate. In fjords, the primary production are different dependent on the presence of land-terminating or marine-terminating glaciers. Young Sound is among Greenland's least productive fjords due to the lack of marine terminating glaciers that bring up nutrient rich water (upwelling). In the terrestrial environment, the Zackenberg fen is more nutrient rich in comparison to Kobbefjord, with important implications for ecosystem CO_2 exchange with the atmosphere .

This edition of the reports cards also includes:

- Ecosystem dynamics pointing at significant changes in food web structure with less fatty copepods species raising concern for changing food web structures in Disko Bay with potential implications for ecosystems and fishing industry.
- Methodological developments that may shape the future of the GEM monitoring programme with automated measurements and machine learning related to plant phenology and pollination that increases observation frequency and accuracy.
- GEM data used for gradient studies, regional assessments and for validating upscaling models, in this case estimating total melt of the Greenland Ice Sheet.

GEM sites represent a unique opportunity for evaluation of remote sensing data and gridded models, which is highly relevant for the international research and operational community. From 2017 - 2018 the Remote Sensing initiative worked on gridded products of broad relevance for the GEM activities: albedo, surface temperatures, NDVI, surface wetness, transient snow lines, snow cover extent, and cloud cover products. In 2019, the Remote sensing initiative was temporarily not funded, which put a stop to developments of new remote sensing products, but will continue in 2020.

International cooperation

GEM is represented in the steering committee and leads an 'Action group' under the IASC-supported T-MOSAiC initiative (2019-2021), which together with the marine MOSAiC will study links between biotic and abiotic ecosystem components in the Arctic. The GEM secretariat presented the GEM programme at two T-MOSAIC working group meetings, during Arctic Science Summit Week in Russia, and in Canada. The GEM secretariat is active in promoting the use of GEM data in such efforts.

The GEM secretariat and scientists also promoted GEM at a number of larger conferences and meetings, including:

- Sentinel North Scientific Meeting in Quebéc, Canada
- AGU in San Francisco, USA
- 2nd Nordic ICOS Symposium, Sweden

Photo: Marie Frost Arndal.

GEM

Greenland Ecosystem Monitoring

2019

Photo: Marie Arndal.

Greenland Science Week

GEM scientists and the GEM Secretariat also played an active role in the first ever Greenland Science Week in Nuuk in early December 2019. This included presentations on the Polar Science Day and demonstrations for the public during open house at the Greenland Institute of Natural Resources and in the cultural centre Katuaq.

Recent results of the GEM programme were presented and discussed with representatives from Greenlandic ministries at a workshop entitled *"Long-term climate and ecosystem monitoring in Greenland – Recent results and discussion of relevance for decision making"*, leading to seven new synergy projects between GEM and participating ministries and institutions.

Outreach

The GEM programme is being portrayed in a 'Frozen ground cartoon', a circumArctic collaboration between scientists and artists, published throughout the Arctic. The new GEM cartoon will, in a fun way, explain science, permafrost and the importance of ecosystem monitoring, and will be distributed to all schools in Greenland.

In 2019, GEM launched a widely distributed series of portraits of active researchers in the GEM programme, called the 'GEM Scientist of the Month', which is posted on the website, and in GEM social media – see https://g-e-m.dk/news/.

GEM at a glance 2019

- Active Basis Programmes in 2019: 14
- Scientists in the field: 65 (1270 man days)
- Scientific publications: 49
- Conference with GEM representations: 24
- Conference presentations: 30 (9 posters)
- Courses using GEM data: 24

New buildings

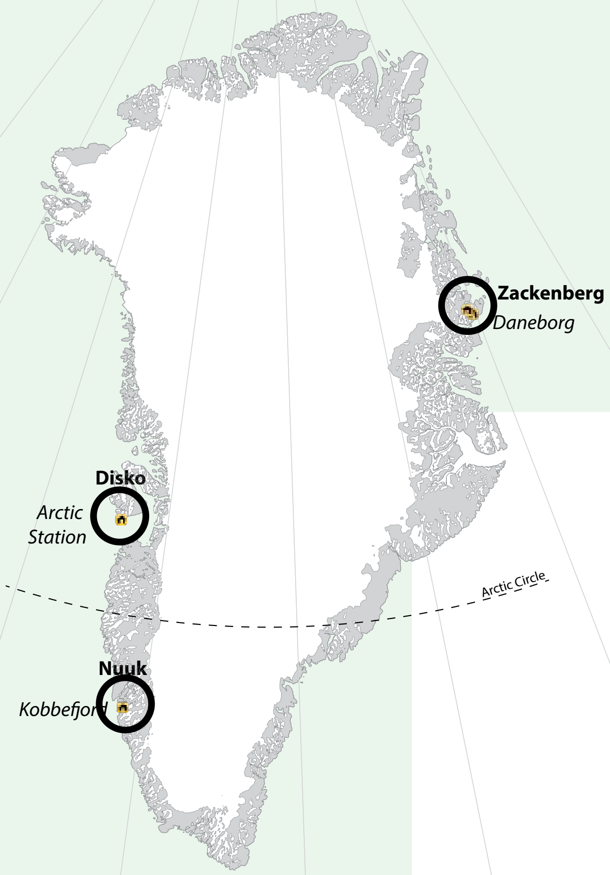
In 2019, two new buildings were added to the Kobbefjord Research Station as an important improvement of the capabilities of housing field assistants and researchers and increase of storage capacity. Solar panels were also added here to support a move towards sustainable energy solutions available for GEM operations at the Kobbefjord station. These improvements were, as much other infrastructure at both Kobbefjord and Zackenberg, constructed based on donations from the Aage V Jensen Foundation – funding which is pivotal for the continued ecosystem monitoring and research efforts in GEM.

Looking ahead

The first annual report from the monitoring programme at Zackenberg was from the year 1995 (Meltofte and Thing eds., 1996). A wider synthesis review of the programme detailing crosscutting aspects of complexity documented through the 25 years of monitoring is being prepared for submission to a journal with broad readership in 2020.

The current GEM Strategy terminates in 2021, and in parallel with the coming field seasons, GEM scientists will be working on a new strategy for the period 2022-2027. Central for this work is the five Basic programmes and the international scientific networks they are involved in, as well as a number of GEM thematic groups established around new technologies and measuring techniques, e.g. molecular tools, UAVs and remote sensing. The strategy is expected to be published in 2021.

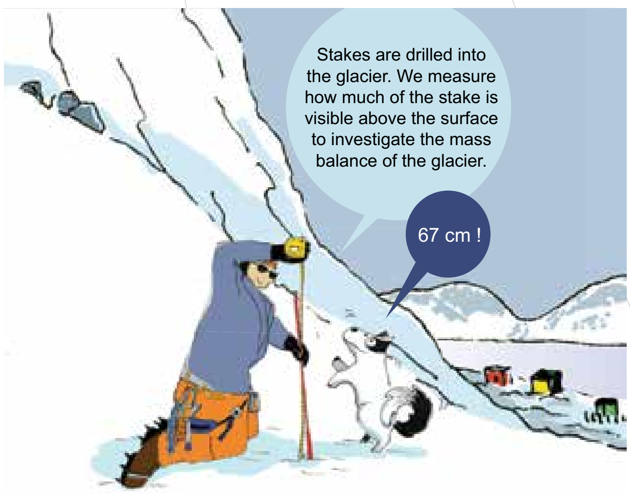
Meltofte, H. & H. Thing (eds.): Zackenberg Ecological Research Operations, 1st Annual Report, 1996. - Danish Polar Center, Ministry of Research and Information Technology



FROZEN-GROUND
GEM DATA FEATURES IN

An international scientific outreach project called 'Frozen-Ground Cartoons', aims at making permafrost science accessible and fun for children, their parents and teachers. The cartoon will soon be available in Greenlandic and Danish translations. To ensure the relevance for school children, natural science teachers, and a broad audience in Greenland, the translated versions will include four brand new pages focusing on permafrost, science and climate in Greenland based on GEM data and the activities of the GEM basis programmes.

Field work activities supporting the GEM monitoring programme.



The Sled dog, Disko, helping to measure the stakes on a glacier in Greenland.

In 2017, a series of cartoons focusing on permafrost related issues, the "Frozen-Ground Cartoons", were published. The stories of the cartoons are a result of a cooperation between international permafrost scientists and artists and aim to explain how the environment changes in permafrost areas, how the changes affect both people and animals, and how permafrost fieldwork is done. Since 2017, the original English version has been translated into several languages including Inuktitut, Swedish, German and French. Now we can add a Greenlandic and Danish version to the pile of translations.

Early in the process, we asked natural science teachers from the Greenlandic schools if they would use the translated versions of the Frozen-Ground Cartoons in their education. The answer was clear: Yes, but there is a general lack of natural science educational material focusing on Greenland, so you need to make it more relevant for the children living in Greenland!

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Data source:

GEM GeoBasis and ClimateBasis monitoring components.

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

CARTOONS

FUN FORMAT FOR BROAD AUDIENCE

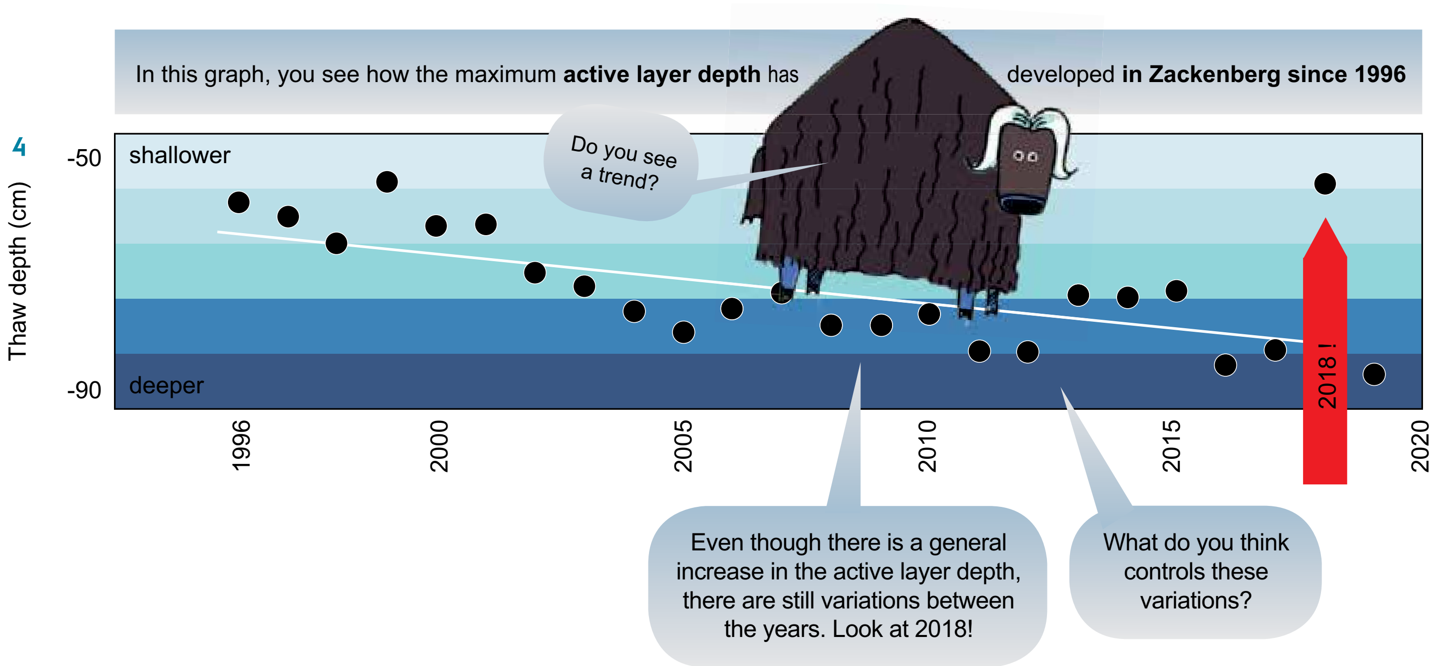
External funding from the Greenlandic government (*Tips og Lottomidler*) made it possible to add four extra pages to the original booklet focusing only on Greenland. In 2020, the new Greenlandic/Danish versions will be published online and hard-copies sent out to every school in the country.

Noémie Ross, one of the two artists working on the original version of the Frozen-Ground Cartoons, has drawn the four new pages for the Greenlandic/Danish version. She has developed three new characters, a hare, a sled dog and a muskox, each representing one of the main GEM sites. In the new cartoons, the characters help explain maps, permafrost related science in Greenland, the importance of ecosystem monitoring and scientific results in a simple and fun way. The aim of the Greenland specific cartoons is to help provide educational material of direct relevance to children in Greenland, filling a well-recognised need, and hopefully inspiring the next generation of climate scientists.

This way of communicating data and scientific results will help alter the awareness of climate change, ecosystem monitoring and not least the impact of the climate change in permafrost areas.

The Hare, Nero, watching a scientist measure the active layer depth.

The Muskox, Zero, considering the development of the maximum active layer depths in Zackenberg since 1996. Illustrations: Noémie Ross



See the full cartoon at https://frozengroundcartoon.com/

SHIFT AT THE BASE
IN DISKO BAY

Since 1992 major changes have happened in the Disko Bay. Sea ice is shrinking and thinning, the open water period is becoming longer and significant changes have happened at the base of the food web.

Disko Bay is located on the west coast of Greenland and represents a location in the transition from low Artic to high Arctic waters. Since 1992, the plankton food web in Disko Bay has been intensively studied at a monitoring site located 2 nautical miles outside the town of Qeqertarsuaq (>300 m deep). The site was recently (2018) included as a new main site in the marine component of the Greenland Ecosystem Monitoring Programme. This ensures monitoring of this important bay that supports a significant part of the Greenlandic fishery.

The Disko Bay is strongly impacted by the ongoing climate change, the sea ice cover is shrinking and thinning and the open-water period is getting longer (Figure 1). The thinner ice and the longer open-water period, that has been experienced in the area, increase irradiance of the surface water. This leads to an earlier phytoplankton spring bloom and increased annual primary production, though, increased stratification caused by warming and ice-melt may limit production.

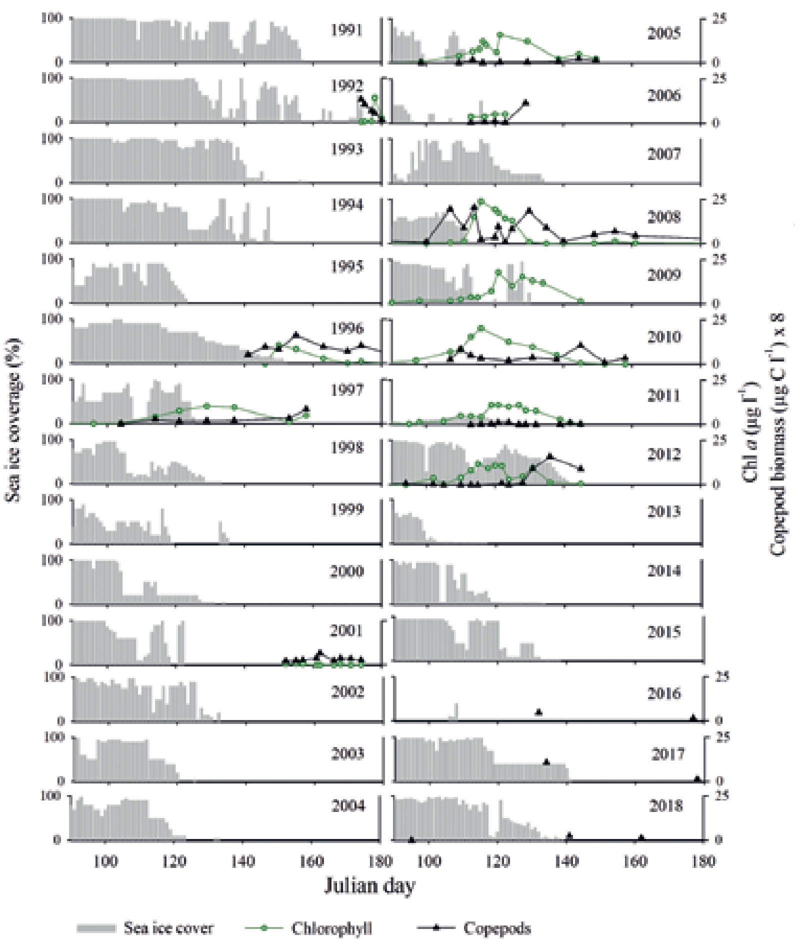


Figure 1. Sea ice cover, Chlorophyll a, and total copepod biomass in the upper 50 m in Disko Bay (except in 2016-2018 where zooplankton were collected at 0–100 m). (Møller & Nielsen 2019).

Authors:

Eva Friis Møller[1], Per Juel Hansen[2] & Torkel Gissel Nielsen[3]

[1]Aarhus University
[2]University of Copenhagen
[3]DTU Aqua

Data source:

MarinBasis Disko.

OF THE PELAGIC FOOD WEB

In general, few biological time series exist that allow evaluation of the climate impact on the biological system compared with the well-documented changes in the physical environment. Therefore, the inclusion of Disko Bay in the Greenland Monitoring Programme is important and unique, because it continues a nearly 30 year long time series on the structure of the pelagic food web.

In the Arctic and sub-Arctic ecosystems, the zooplankton genus *Calanus* forms the key link between the primary producers and higher trophic levels in the marine food web. Therefore, understanding the response of the *Calanus* community to a changing climate is crucial to predict the function of the Arctic ecosystem in a warmer future. Three *Calanus* species coexist in the Disko Bay: *Calanus finmarchicus, Calanus glacialis* and *Calanus hyperboreus* (Figure 2). *Calanus finmarchicus* is primarily associated with North Atlantic waters, while the latter two species are considered Arctic species. Although the three species have the same general life cycle and morphology, they exhibit important differences, particularly in size and phenology. *C. hyperboreus* reaches a prosome length of 7 mm, *C. glacialis* 4.6 mm, and *C. finmarchicus* only 3.2 mm. All species store large amounts of lipids, and these lipid reserves are used to fuel hibernation at depth and the following trophic levels of the food web. The different phenologies of the species means that the females achieve their maximum lipid contents at different times of the year.

We focused our analyses on *Calanus* data from May and June, the period with the most complete data coverage as well as the most equally distributed data in the early and late part of the period (Møller & Nielsen 2019). *Calanus* totally dominate the copepod biomass with an average of 96% of the copepod biomass in May/June, with females accounting for ~ 46%. The period with 100% sea ice cover during early spring in Disko Bay decreased from 1991 to 2018 (Figure 1). The biomass of female *C. hyperboreus* and *C. glacialis* were significantly, and positively, correlated with sea ice cover. *C. finmarchicus* female biomass was, on the other hand positively correlated with fraction of Atlantic water entering the bay. From the early sampling period until now, there has been an increase in the relative contribution of *C. finmarchicus* female biomass to the total *Calanus* female biomass. *C. finmarchicus* constituted on average, 64% of the biomass in 2005–2018 compared with 39% in 1992–2001 (Figure 3). The total *Calanus* biomass and production have not changed significantly, but because of the species shift, the average *Calanus* is now 34% smaller and the the lipid content of the average *Calanus females* (Figure 3) during spring and summer is only half of that two decades ago. The documented shift in the quality of Arctic marine secondary production will likely have a vital impact for *Calanus* predators including fish, sea birds, and marine mammals, bowhead whales in particular.

Figure 2. The three coexisting Calanus *from the Disko bay, are very similar morphological but different size and phenology. Photo: Russ R Hopcroftt.*

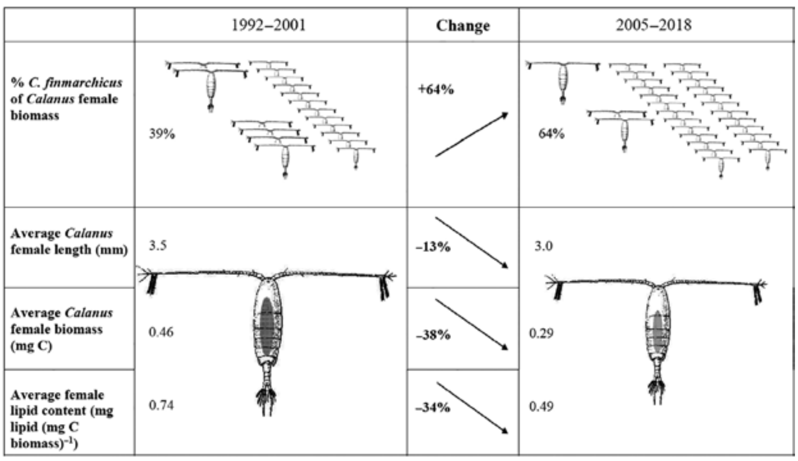
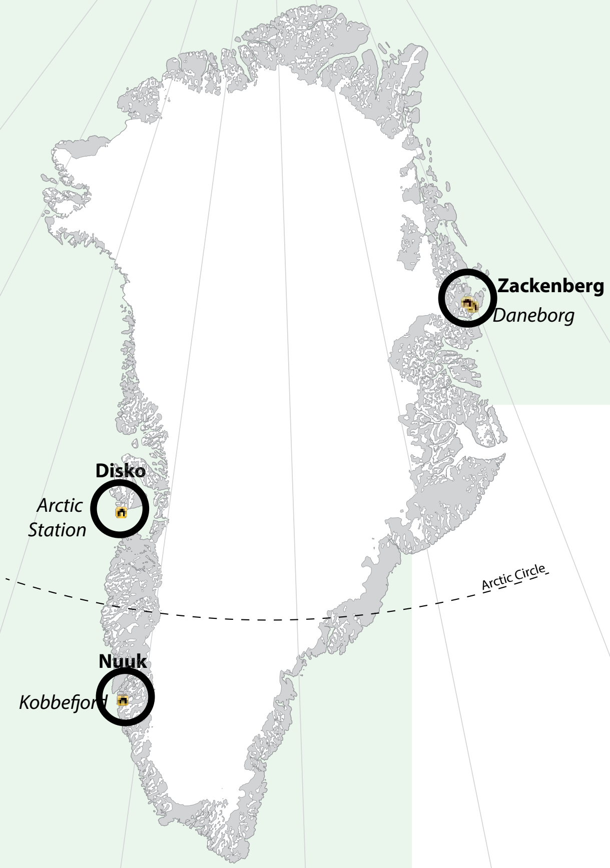


Figure 3. Changes in community composition of the female part of the Calanus *population between the early and late sampling period and the effects of community change on the average size and lipid content of the female* Calanus *community (Møller & Nielsen 2019).*

Møller, E.F. & T.G. Nielsen (2019). Borealization of Arctic zooplankton – smaller and less fat zooplankton species in Disko Bay, Western Greenland. Limnology and Oceanography 9999: p. 1-14.



Annual Report Card 2019

STATUS AND TRENDS
OF ARCTIC TERRESTRIAL

Keeping track of the changing Arctic and its inhabitants is challenging. However, recent efforts to merge on-going and future monitoring across the circum-Arctic region into a common framework now allow us to report the status and trends of key components of Arctic terrestrial biodiversity. Greenland Ecosystem Monitoring has made a significant contribution to this effort led by the Circumpolar Biodiversity Monitoring Program (CBMP), a programme under the Arctic Council working group Conservation of Arctic Flora and Fauna (CAFF).

One of the major challenges faced by scientists and ultimately decision-makers is that of keeping track of the changing distribution and abundances of plants and animals across the globe. While much efforts is being put into understanding the complex dynamics of nature, the lack of long-term monitoring data, particularly in remote regions like the Arctic, hampers the detection of trends and thus hampers our ability to take adequate actions to mitigate biodiversity loss (Christensen et al. 2020). The Arctic Council has recommended that adaptive long-term ecosystem and biodiversity monitoring efforts should be increased and focused to address key knowledge gaps in order to better inform development and implementation of conservation and management strategies for the Arctic (CAFF 2013).

Monitoring and research in the Arctic region has a long tradition, and has yielded much insight into the dynamics of tundra ecosystems. However, until now these efforts have been conducted more or less independently, and thus more or less uncoordinated. In response, the Arctic Council working group Conservation of Arctic Flora and Fauna (CAFF) established the Circumpolar Biodiversity Monitoring Programme (CBMP), as an umbrella for all these initiatives to maximize the knowledge-gain and thus impact of current (and future) monitoring efforts in the Arctic region. The monitoring protocols developed by CBMP are therefore based on all available knowledge and monitoring experience from within the circum-Arctic region (Christensen et al. 2013; Christensen et al. 2020). As long time series are invaluable when it comes to reporting the status and trends of species or species groups, the CBMP protocols use both harmonizing and standardizing of monitoring efforts to obtain the most coherent overview of Arctic biodiversity: Harmonizing information across methodologies to obtain comparable information from existing monitoring, and standardizing of new monitoring initiatives to align protocols in the best possible way.

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Data source:

GEM BioBasis.

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

BIODIVERSITY

The CBMP monitoring protocols build on conceptual models, where the major inter-linkages in the trophic system, importance to local communities and the likely drivers of change in the ecosystem are identified based on all available information, from research and expert knowledge to traditional knowledge. Based on main research and management questions the programme set out to answer, these conceptual models are then used to select the key species or species groups for monitoring. These key species and species groups are termed Focal Ecosystem Components (FECs). Each FEC has a number of attributes attached, each of which are important for the evaluation of the status and trend of the FEC (e.g. abundance, distribution etc.). Attached to each attribute is a number of parameters, whose methodology may vary between monitoring programmes. Hence, the attribute "Abundance", a key measure of status and trends, may be evaluated based on various data related to abundance, such as actual densities, numbers or indices (Christensen et al. 2020).

The extensive programme and long term commitment by Greenland Ecosystem Monitoring within Arctic biodiversity monitoring was reflected in a marked imprint of GEM on the first Arctic Biodiversity Assessment published in 2013 (CAFF 2013), which also laid the foundation for the rapid development of CBMP. GEM has been instrumental for the development of the monitoring protocols within CBMP, and researchers from GEM have been actively involved throughout the process of scoping and developing the CBMP Terrestrial Monitoring Plan (Christensen et al. 2013), the newly published special issue in journal Ambio (Taylor et al. 2020; Christensen et al. 2020) providing a comprehensive overview of Arctic biodiversity for the upcoming "State of the Arctic Terrestrial Biodiversity Report," the first CAFF report on the status and trends of Arctic terrestrial biodiversity.

The involvement of GEM in CBMP is thus good example of how the work conducted within GEM on behalf of the Kingdom of Denmark facilitates the "knowledge chain" from the collection of coherent field data, to regional-scale biodiversity assessments, to the global biodiversity assessments conducted by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and thus ultimately to the decision-maker level.

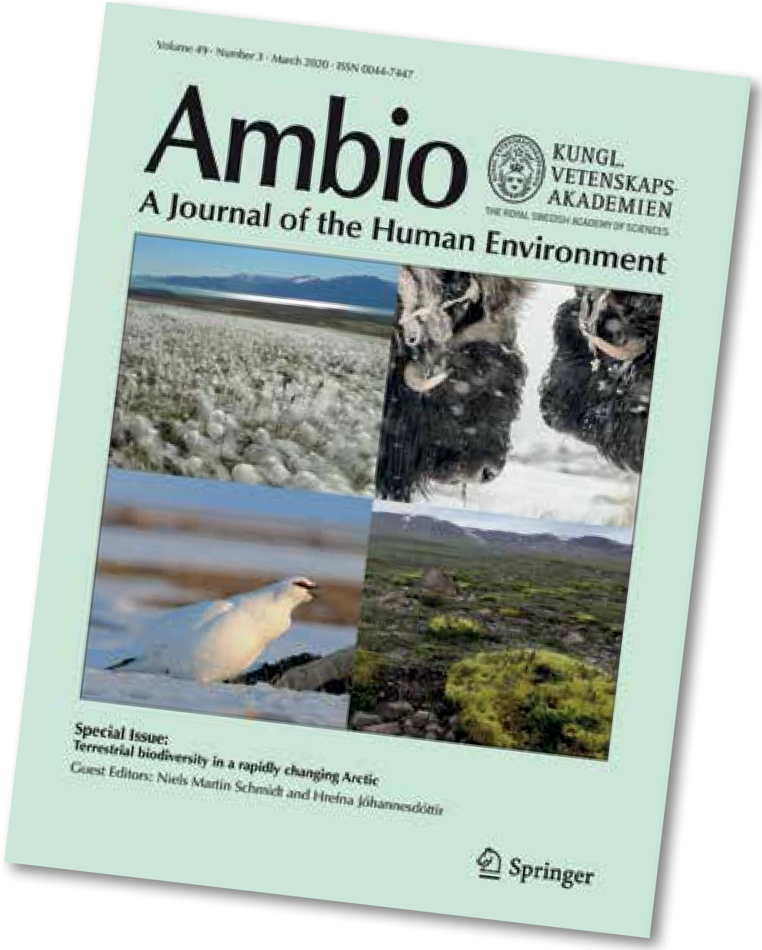

Figure 1. The cover of the CBMP terrestrial special issue in journal Ambio 2020.

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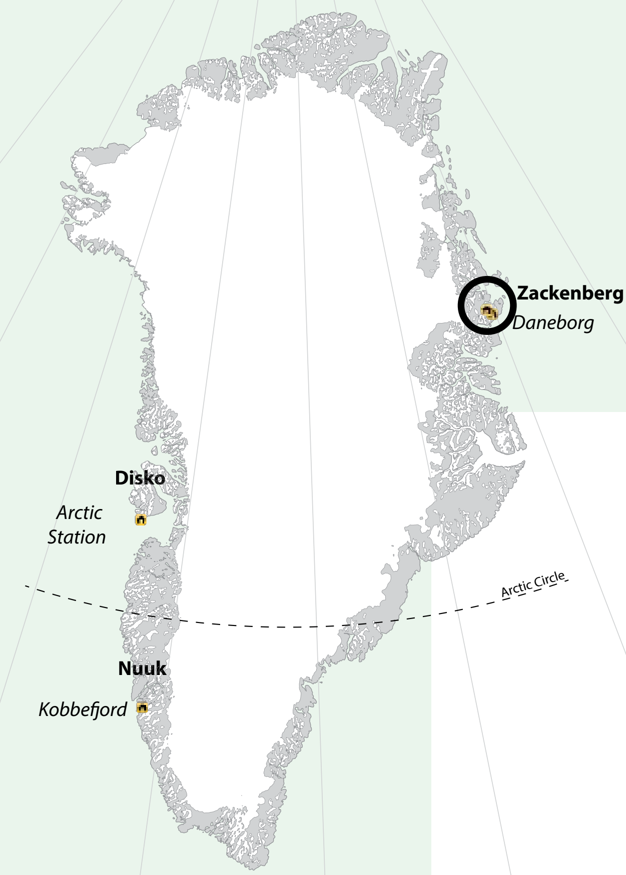
Taylor, J.J. et al. (2020). Arctic terrestrial biodiversity status and trends: A synopsis of science supporting the CBMP State of Arctic Terrestrial Biodiversity Report. Ambio 49: 833-847.



ICE CAP–WIDE
FROM RADAR AND

Snow accounts for virtually all the mass gains of a glacier, and topography has a strong effect on where and how much snow accumulates. Within the same region, higher elevations tend to receive more snow and near-surface wind redistributes it across the landscape. Every year GlacioBasis measures the depth of the snowpack along several snow scooter transects using ground penetrating radar. However, these transects are limited to the southeastern region of the A.P. Olsen ice cap. We trained a machine learning algorithm to overcome that limitation and produce a spatially distributed snow depth estimate for the whole ice cap.

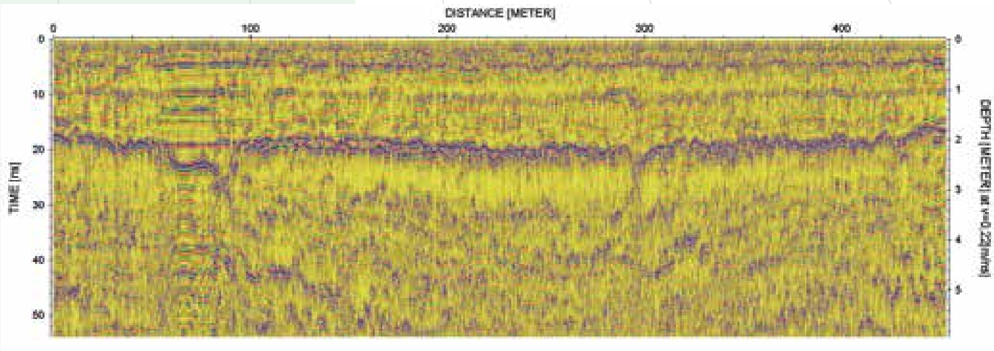


Figure 1. Processed radar data showing a strong reflector undulating at a depth of around 2 m in this image and representing the bottom of the snowpack on the glacier. The top surface of the snowpack appears exactly horizontal because the antenna is fixed on a sled and very close to the snow surface.

Several methods exist to measure snow depth in the field. The simplest ones only provide information at a single point, either using an avalanche probe or by pinging the surface with ultrasounds from a reference height above it and timing the echo. This second technique is used year-round to follow the evolution of the snowpack over time at the GlacioBasis automatic weather stations (three on A.P Olsen ice cap in Zackenberg, two on Chamberlin glacier on Disko and one on Qasigiannguit glacier close to Nuuk).

Ground penetrating radar makes it possible to rapidly measure quasi-continuous snow depth along transects by towing the transmitting and receiving antennas with a snow scooter and timing the radio echoes received from the bottom of the snowpack (Fig. 1). During the 12 years since GlacioBasis started at Zackenberg, it has become clear that the spatial variability of snow depth is large, with major annual differences not only in the overall amount of snow but also on where it accumulates. Wind plays a major role by eroding the snowpack on upwind slopes and convex parts of the topography while filling hollows and downwind areas. Near-surface wind is controlled by topography and mesoscale weather during and after snowfalls, which explains annually varying spatial patterns of snow depth.

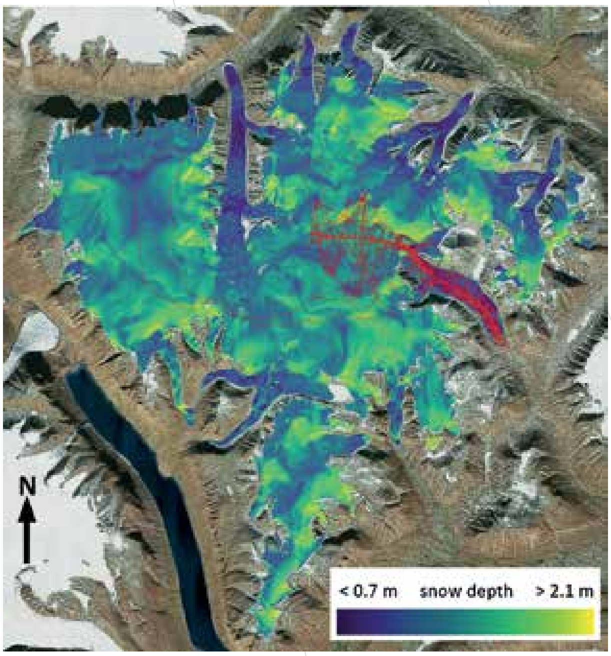


Figure 2. Average snow depth from the 2008-2018 grids produced by training the random decision forest using the snow radar transects measured in the field (red lines) and then estimating snow depth everywhere else based on terrain parameters extracted from a digital elevation model.

Authors:

Michele Citterio[1] & Daniel Binder[1,2]

[1]GEUS, Copenhagen
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Data source:

GEM GlacioBasis Zackenberg, snow cover and snow depth_radar

Machine learning data not yet available in GEM database

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

SNOW DEPTHS
MACHINE LEARNING

Modelling the physics of near surface wind at the required level of detail is difficult and requires more *in situ* measurements than can be produced within a reasonable budget. However, simpler empirical techniques exist to account for snow redistribution by wind (Winstral et al., 2002) and estimate snow depth everywhere on the glacier. The overall approach is to rank the importance of quantitative terrain-based parameters that can be derived from a digital elevation model (DEM) and estimate their quantitative relation to observed snow depths along the radar transects. The main challenges when implementing this conceptual approach are the large number of candidate parameters among which we want to find the most important ones, the need to avoid overfitting to the training dataset which in our case is mostly measured along a single glacier outlet of the ice cap, and limiting computing time and memory requirements to practical limits. 'Random decision forest' (Breiman, 2001, Geurts et al., 2006) is a method of ensemble machine learning that allows finding the most important variables in the regression between topography parameters and observed snow depth, while reducing overfitting by averaging multiple decision trees trained on varying samples of the training dataset. Open source software libraries are available (Pedregosa et al., 2011) implementing the core of the random decision forest algorithm. In 2019, GlacioBasis developed a processing toolchain automating part of the processing and produced annual grids (2008-2018) of snow depth at 20×20 m resolution over the entire 292 km^2 of the A.P. Olsen ice cap and 33 km^2 of the nearest ice masses surrounding it (Fig. 2). These grids will be freely available through the GEM database.

We found that the terrain parameters which explain most of the observed snow depths variability are elevation, slope, roughness and curvature, as derived directional products such as hillshade can account for the dominant direction of mesoscale wind. However, more specific directional snow redistribution parameters exist (e.g. Winstral et al., 2002; Lindsay and Rothwell, 2008) and are currently being evaluated. The cross-validation of the model is very satisfactory (Fig. 3), especially considering that the largest errors are overestimation of snow depth in the lower elevations (Fig. 4). We know that the low observed snow in the lower part of the glacier outlet, where we do most of the fieldwork, is a local feature which may not be representative of other parts of the ice cap. This shows the robustness of the method to overfitting, as a large part of our radar measurements come from this part of the ice cap. The main limitation of this machine learning approach is that it cannot be directly applied in the years (2009, and 2013) when it was not possible to carry out the radar campaign due to poor snow conditions. Furthermore, decision trees cannot extrapolate beyond the snow depth range of the training dataset. The layout of the GlacioBasis radar transects will be optimized to mitigate the latter limitation. This work improves the GlacioBasis monitoring and modelling of the glacier mass balance, and by providing snow depth over the entire ice cap it strengthens our contribution to the global observation of snow and glaciers, two of the four cryosphere ECV (Essential Climate Variable) in GCOS (Global Climate Observing System).

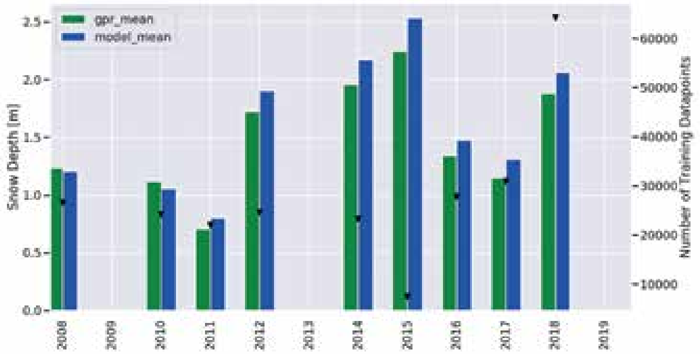

Figure 3. Mean measured and modelled snow depths plotted for all years when it has been possible to carry out snow radar in the field. The number of samples in the training dataset is shown as black triangles.

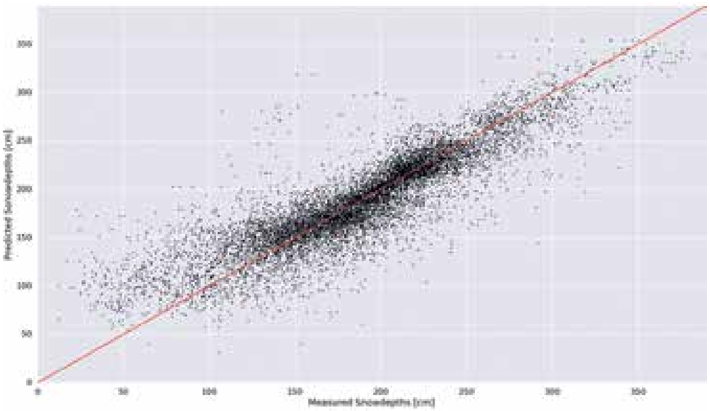

Figure 4. Comparison of year 2014 modelled snow depth vs. measurements using a validation dataset distinct from the algorithm training dataset.

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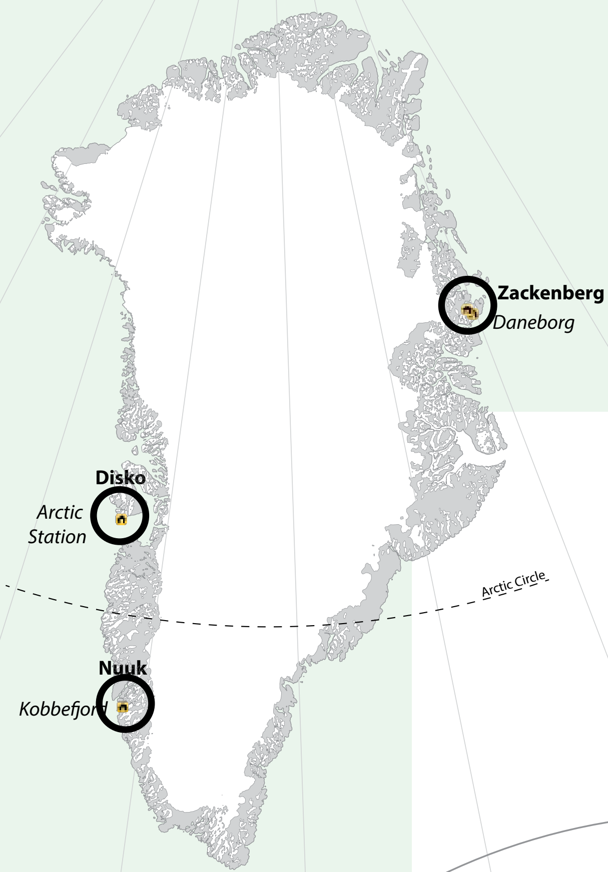
SCALING-UP THROUGH



Research and monitoring conducted in remote areas such as the Arctic are prone to difficulties in getting a sufficient spatial coverage. While Greenland Ecosystem Monitoring has developed mechanistic models for some key ecosystem parameters, not everything can be scaled up using this approach. Here, studies across environmental gradients offer an appealing alternative.

A former colleague and expert in spatial modelling once said that one should never trust a pretty map. While this word of caution likely is rooted in the acknowledgment of the uncertainties in input data and the resulting models, it also points to the tendency for people to be fascinated by the visually appealing colorful maps. Depending of research question and the data available, scaling up initiatives may indeed provide highly accurate predictive maps. However, in remote areas such as the Arctic, the vast geographical areas and limited on-ground information may hamper this approach, particularly for many biological parameters.

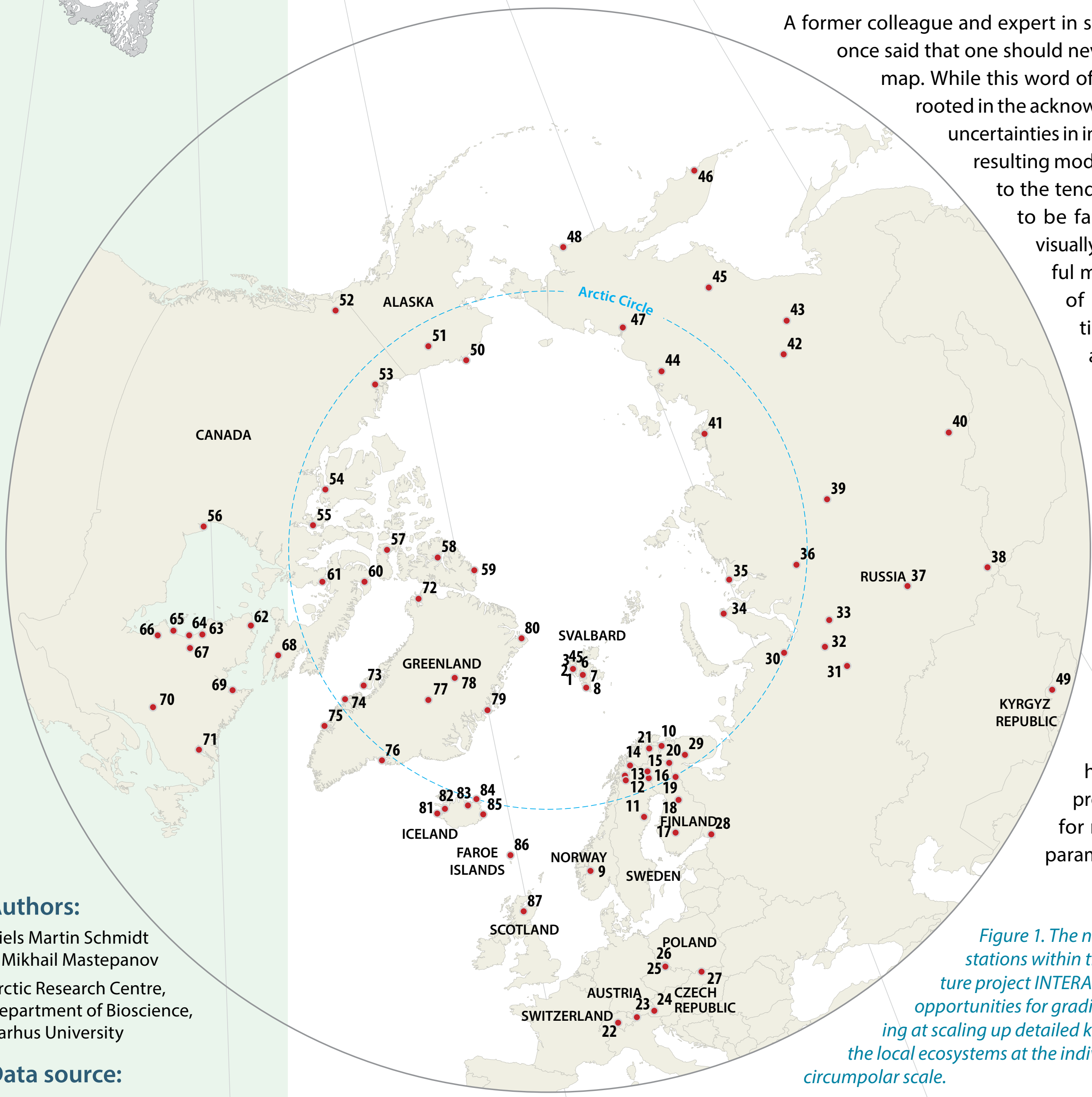


Figure 1. The network of Arctic stations within the EU infrastructure project INTERACT offers great opportunities for gradient studies aiming at scaling up detailed knowledge about the local ecosystems at the individual sites to the circumpolar scale.

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Data source:

GEM BioBasis and GEM GeoBasis.

INTERNATIONAL COLLABORATION

Greenland Ecosystem Monitoring has implemented a number of mechanistic models that allow us to scale up some of the core terrestrial parameters where sufficient data are available. Hence, a spatially and temporally explicit snow model has been developed for the Zackenberg region (Pedersen et al. 2018) and a spatially explicit vegetation model for the Zackenberg valley (Stewart et al. 2018). Such models rely heavily on field data but also remotely sensed data, such as satellite data. Our on-going development of our monitoring by use of drones also assist in bridging the gap between ground data and satellite data. However, for other parameters, especially biotic parameters, where local conditions appear highly influential and at the same time are hard to quantify remotely, studies across environmental gradients constitutes a complementary approach to up-scaling, also offering insight into large-scale patterns, albeit with less spatial information, but with a (potentially) higher degree of certainty for each data point.

The latter is particular true when field protocols have been aligned across sites. Greenland Ecosystem Monitoring has a long tradition of being involved in international collaborative projects and syntheses, specifically aiming at understanding large-scale geographical patterns by examining responses across gradients. Examples showing the potential for unravelling key patterns and processes of the Arctic ecosystems include vegetation responses to environmental change (Elmendorf et al. 2012), factors shaping predator-prey communities (Legagneux et al. 2014), quantifications of invertebrate herbivory (Barrio et al. 2017), storage, landscape distribution and burial history of soil organic matter (Palmtag et al. 2015), analysis of wetlands climate footprint (Petrescu et al. 2015).

Participating in international programs, scientific syntheses and assessments remain a corner stone in the monitoring conducted within Greenland Ecosystem Monitoring. Not only does it put our long-term data and findings in a broader, often circumpolar perspective, it also facilitates the flow of information from the field, onto scientific articles to international syntheses and assessments and ultimately informing decision-making at the end-user level.

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Annual Report Card 2019

YOUNG SOUND: THE LEAST PRODUCTIVE

The Greenland Ice Sheet is meting rapidly due to climate change. Glacial retreat and freshwater associated with Ice Sheet melting affects fjord production in a variety of ways. Young Sound is among Greenland's least productive fjords and may serve as a model of how fjords will respond to future climate change.

Glacial fjords are often described as productive environments that are important for local fisheries. Meltwater that is channelled underneath marine-terminating glaciers is less dense and buoyant and rises to the surface at the glacier front bringing up deep waters from below that are replete with nutrients. These nutrients allow for prolonged phytoplankton blooms throughout summer which allows for efficient trophic transfer.

However, as glaciers retreat, this important mechanism, mixing nutrients into the upper water column, will be lost. Additionally, freshwater run-off from the Ice Sheet stratifies the water column, dampening other external mixing mechanisms, and introduces suspend sediment and glacial flour that cloud the surface ocean and limit light availability for phytoplankton.

Photo: Johnna Holding.

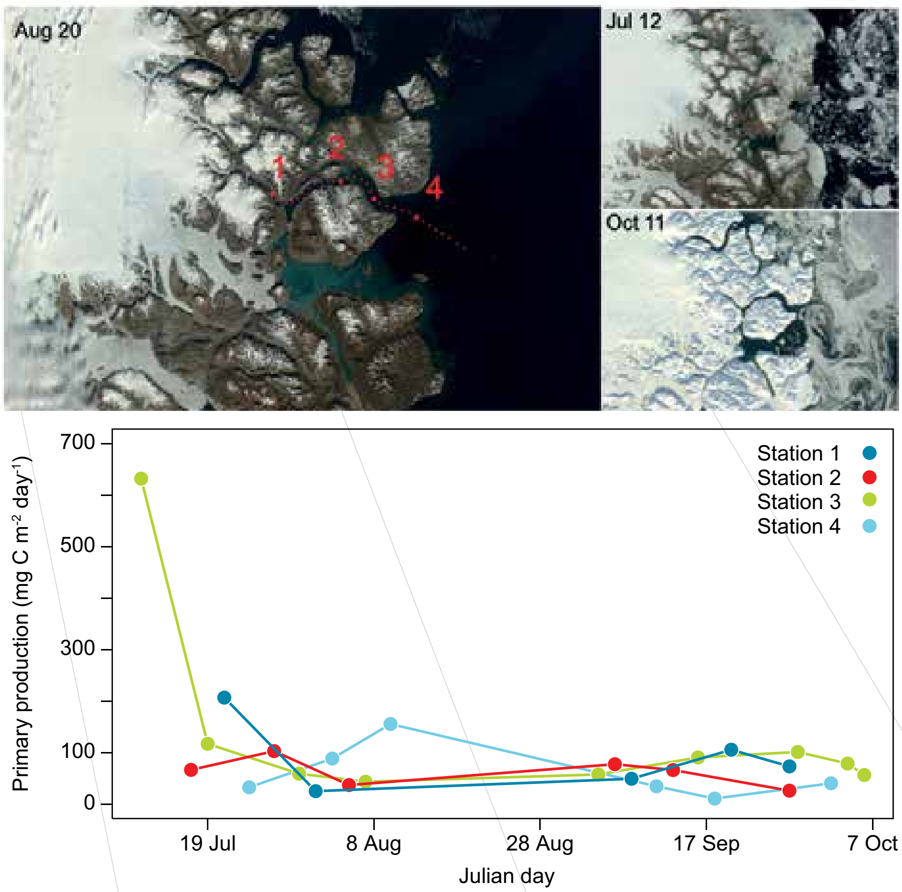

Figure 1. Station map overlaid on satellite images of Young Sound (left). Images in the right panel show the first sampling day when the fjord was still partially ice covered and the last sampling day. Rates of primary production for all stations averaged over the whole 2014 sampling period (bottom). Figure reproduced from Holding et al. (2019).

Authors:

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Arctic Research Center, Aarhus University

Data source:

MarinBasis Zackenberg.

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

GEM
Greenland Ecosystem Monitoring

FJORD IN GREENLAND

Young Sound is a fjord located in North East Greenland (74°N, 19°W) and not connected to the Ice Sheet via marine-terminating glaciers, but rather via several rivers running off from glaciers that are directly connected to the Greenland Ice Sheet, mainly the Tyroler and Zackenberg rivers. Young Sound has been a location of marine research for the last 25 years and a part of the MarinBasis monitoring programme for the last 17 years.

Since it is located so far north, the growing season in Young Sound is very short. Sea ice tends to break up around mid-July (Figure 1), though decadal trends suggest it has been breaking up 0.15 days earlier every year. Though it seems insignificant, actually a few days earlier can make a big difference to how much light is received annually in the water column (Figure 2), especially in July when there is still enough light to make a difference.

River discharge begins in early June, while the fjord is still ice-covered, and usually peaks sometime in August with an outburst flood from a glacial lake and then tappers off after that. So far there is not a noticeable trend of increasing discharge over time. River discharge brings suspended sediments and glacial flour, which along with the short ice-free window, makes Young Sound an extremely light limited environment for phytoplankton.

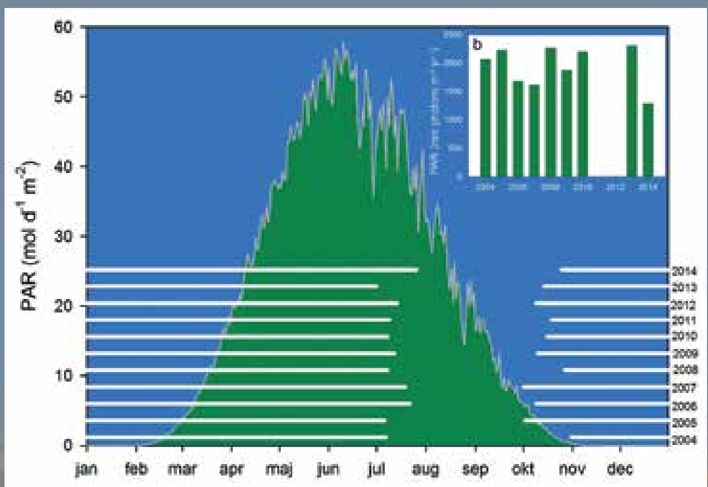

Figure 2. Average (2004-2014) daily sunlight radiation (green curve) – termed PAR in Young Sound over one year (a). White horizontal bars show ice cover dates for the years 2004-2014 (a). Actual PAR per year during the ice-free season (b). PAR data are taken from the Greenland Ecosystem Monitoring (GEM) database, and ice cover is estimated from daily photos taken from a camera situated on land approximately looking down on Station 3 (n.b. ice break up at other main stations likely occurred on different dates). Figure reproduced from Holding et al. (2019).

In 2014, we travelled to Young Sound to measure phytoplankton primary productivity (a measure of photosynthetic activity) over a full growing season. We hypothesized that run-off from the Ice Sheet would render the fjord very stratified, and because this fjord lacked marine-terminating glaciers, there would not be a mechanism mixing nutrients into the surface waters were phytoplankton are growing, and thus less primary production. We also supposed that the turbidity caused by the river run-off would further limit primary producers.

Typical of many Arctic fjords, Young Sound experienced its maximum primary production in the "spring" – which occurs in early July – while ice was still covering the fjord, but thinning, and the first rays of light were allowed into the water column. This bloom was brief however, and after the nutrients were used up primary productivity was low and steady through the rest of the growing season. Apart from the spring bloom, strong stratification from freshwater runoff kept primary productivity extremely low, between 10 and 200 mg C m^{-2} day^{-1}. These rates we see in Young Sound are an order of magnitude lower than rates measured in the tidewater glacial fjord Godthåbsfjord, for example.

Rates of primary production in Young Sound are low throughout the year, though interestingly, they remain rather constant even well into the fall when light is reduced to a quarter of its levels during the spring and the sun angle is low. In Godthåbsfjord, when light decreases this much, there is a corresponding drop in primary production. Thus, this suggests that the plankton community in Young Sound is well adapted to low light conditions. We can also see evidence of low light adaptation in the inner part of the fjord where turbid run-off decreases light levels during the spring as well. Phytoplankton adjust to this by moving toward the surface, but rates of primary production are not much different than those further out in the fjord (Figure 1).

The seasonal patterns of primary production we see in Young Sound could be more commonplace in other fjords in the future as glaciers retreat.

Reference:

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THE FISH POPULATION

2018 marked the tenth year since monitoring of the fish population began in Badesø. Since 2008 the population has shifted from large catches of the salmonid species Arctic char (Salvelinus alpinus) towards decreasing catches of char and larger catches of three-spined sticklebacks (Gasterosteus aculeatus), the other of the two fish species in Badesø.

Fish have been caught every five years in the 80 ha, 36 m deep, nutrient poor Badesø (Figure 1) since 2008, and as such 2018 marked the third catch of the now ten-year long program. Fish were collected overnight using standardized multi filament Lundgren gillnets (1.5 m, consisting of 14 mesh sizes from 6.25 to 75 mm); three littoral (near shore), three profundal (deep bottom) and three pelagic (water column) nets (Figure 2), giving a representative sample of the fish community, size and age structure of Arctic char (*Salvelinus alpinus*). Arctic char is the undisputed top predator in the lake, whereas smaller Arctic char together with sticklebacks compete for the food at a lower trophic level.

Catches are calculated as Catch Per Unit Effort (CPUE) which is average catch per net regardless of fish size. Overall CPUE for Arctic char went down from 15.9 (fish/net) in 2008 to 8.6 in 2013 while three-spined sticklebacks had low catches both years (Figure 3). Char CPUE decreased further in 2018 to 6 fish per net while sticklebacks increased manifold from 2013 to 2018. Total CPUE by number went down from 17 to 10 between 2008 and 2013, but then returned to 16 in 2018, due to the increase in

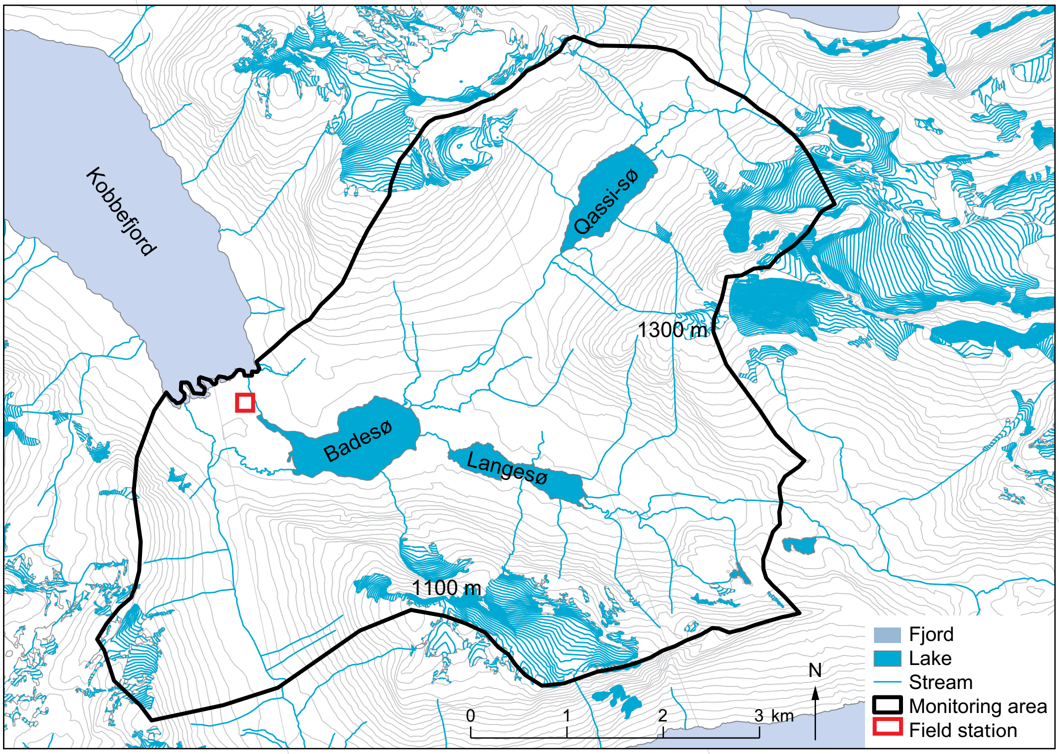

Figure 1. The location of Badesø in the Kobbefjord catchment (black outline) area. The map also shows Langesø and Qassi-sø which are both connected to Badesø.

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[1)] Institute of BioScience, Aarhus University

[2)] Greenland Institute of Natural Resources

Data source:

GEM BioBasis Nuuk.

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

IN BADESØ, KOBBEFJORD

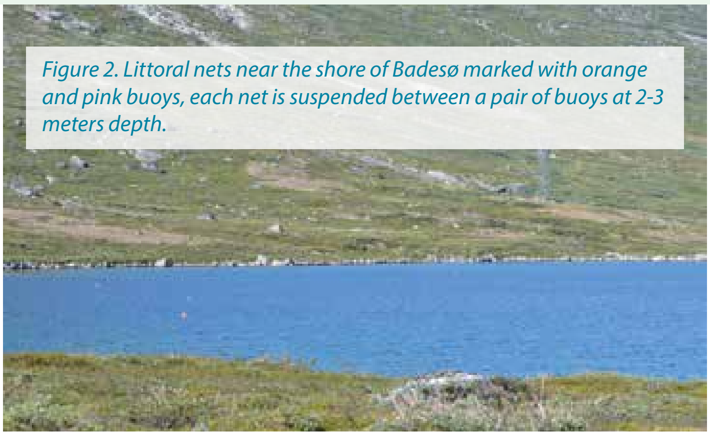

Figure 2. Littoral nets near the shore of Badesø marked with orange and pink buoys, each net is suspended between a pair of buoys at 2-3 meters depth.

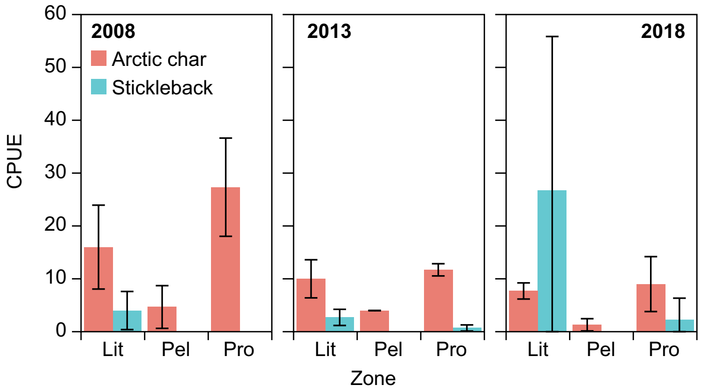

Figure 3. Average fish caught per net (CPUE) for Arctic char and three spined sticklebacks in the three different habitats where nets were placed (littoral, pelagic and profundal). Error bars are standard deviation, n=3.

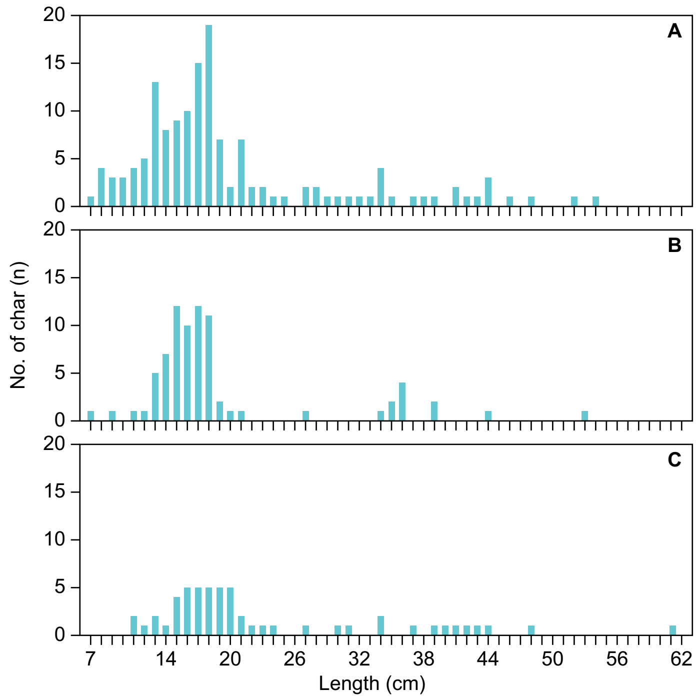

Figure 4. Length distribution of Arctic char caught in 2008 (A), 2013 (B) and 2018 (C).

stickleback catches. The sudden increase in catches of sticklebacks likely reflects an increase in average stickleback size in Badesø, since small sized sticklebacks (<50 mm) are not caught in the gill nets. It is possible that the stickleback population in Badesø is resource limited or predation pressure on sticklebacks has dropped due to the decreasing char population. In combination with the less abundant smaller Arctic char (Figure 4) feeding on similar trophic levels as the sticklebacks may have left a trophic vacuum in the system that is being filled by sticklebacks.

Chars are caught in all lake habitats (littoral, pelagic and profundal), but mostly in the profundal and littoral zone, likely because this is also the preferred habitat for their prey (sticklebacks, zoobenthos and zooplankton). The Arctic char caught in Badesø seem to have a unimodal length distribution centered around 10-20 cm in length. The majority of these fish are not yet sufficiently large to be piscivorous, and, like the sticklebacks, they prefer consuming zoobenthos and zooplankton (unpubl. data by A.S. Berthelsen). However, based on isotopic results from 2008 and 2013 in combination with stomach analysis, we can conclude that there is a piscivorous population of larger char in Badesø (Olsen et al. 2014). Piscivorous char preferentially consumed sticklebacks, but cannibalism has been observed both in Badesø and in the upstream Langesø (Figure 5). In the future, it will be interesting to see how the two-fish system develops in Badesø and to see if the relationship between Arctic char and three-spined stickleback abundance changes again or if the present pattern represents a permanent change in fish population structure.

Figure 5. The stomach of a 40 cm Arctic char containing the remains of another Arctic char that measured 21 cm from the end of its spine to the undigested fork.

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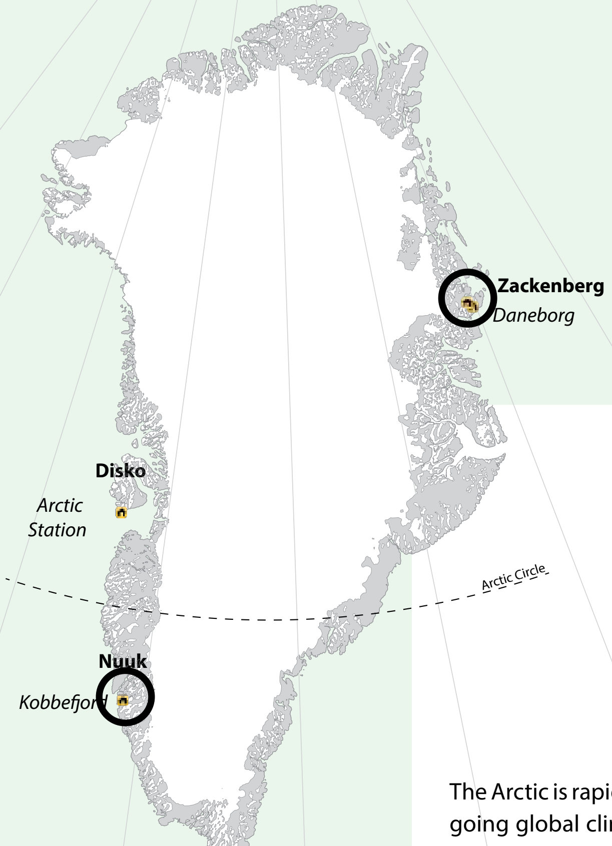
MULTI-YEAR DATA-MODEL
OF NUTRIENT AVAILABILITY



Arctic tundra is a globally important store for carbon (C). Here, we present 9-11 years of flux and ecosystem data across the period 2008-2018 from two GEM sites: Zackenberg (74°N) and Kobbefjord (64°N). Combining ecosystem models with GEM's field observations allow us to study in greater detail the underlying processes of Arctic CO_2 exchange.

The Arctic is rapidly changing; ongoing global climate change has already started to redesign high latitude ecosystems and challenge the functioning and resilience of Arctic tundra (Box et al., 2019).The likely rise in temperatures and precipitation may have multiple effects on CO_2 exchange, and in turn may initiate a series of critical alterations such as changes in ecosystem C sink-source functioning.

The net ecosystem exchange (NEE) of CO_2 between terrestrial ecosystems and the atmosphere is a key descriptor of ecosystem functioning (López-Blanco et al., 2017). Eddy covariance (EC) measurements of NEE are a powerful technique that ensure high temporal resolution and minimal disturbance to the surrounding vegetation. The EC method is however difficult to implement in northern latitudes due to remoteness and harsh conditions. Conveniently, process-oriented ecosystem models can represent complex ecosystem processes shaping the NEE of CO_2 even where data are not available. In recent years we used the Soil-Plant-Atmosphere (SPA) model (López-Blanco et al., 2018; López-Blanco et al., 2020) with extensive GEM datasets to calibrate and validate in-situ terrestrial CO_2 fluxes. For example, we can use vegetation greenness imagery to improve the net C uptake timing at the beginning of the growing season but also leaf nitrogen traits and C stocks data to constrain the model's most sensitive parameters governing the net C exchange.

In this report card we present a decade of EC data at two contrasting sites (Figure 1), recorded over consecutive years during 2008-2018. We ask the ecological questions: *"How different is high Arctic NEE compared to low Arctic NEE in Greenland?"* and *"What are the key driving factors contributing to any identified differences?"* EC measurements of NEE at high temporal resolution are combined with an extensive set of meteorological-, plant phenology- and soil-related measurements, as well as process-based modelling to diagnose the key differences of terrestrial net C sink strength in relation with plant phenology timing, leaf nitrogen (N) traits, and

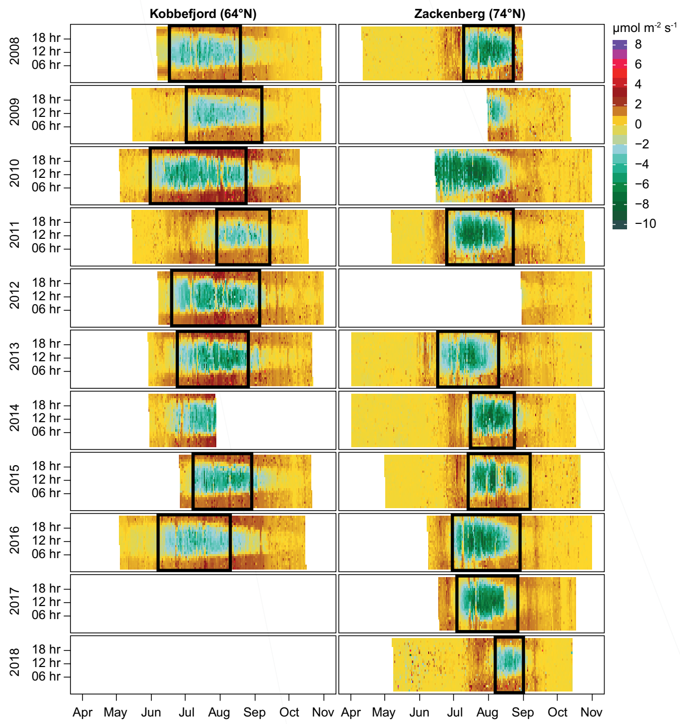


Figure 1. Time series of gap-filled NEE (2008-2018). Green represents C uptake while the orange-dark-red denotes C release. The black box delimits the period between the start and the end of the growing season.

Authors:

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[3] Oulanka Research Station, Oulu University, Kuusamo, Finland

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Data source:

GEM GeoBasis – CO_2 monitoring (Net Ecosystem Exchange)

GEM GeoBasis – Automatic Photo Monitoring (% of greenness and snowmelt period)

GEM GeoBasis – Aboveground and belowground and soil core sampling (C and N pools)

GEM GeoBasis – Meteorology (Soil temperature)

GEM ClimateBasis – Meteorology (Temperature, precipitation, radiation, relative humidity)

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

GEM

Greenland Ecosystem Monitoring

EVALUATION REVEALS THE IMPORTANCE

OVER CLIMATE IN ARCTIC ECOSYSTEM C DYNAMICS

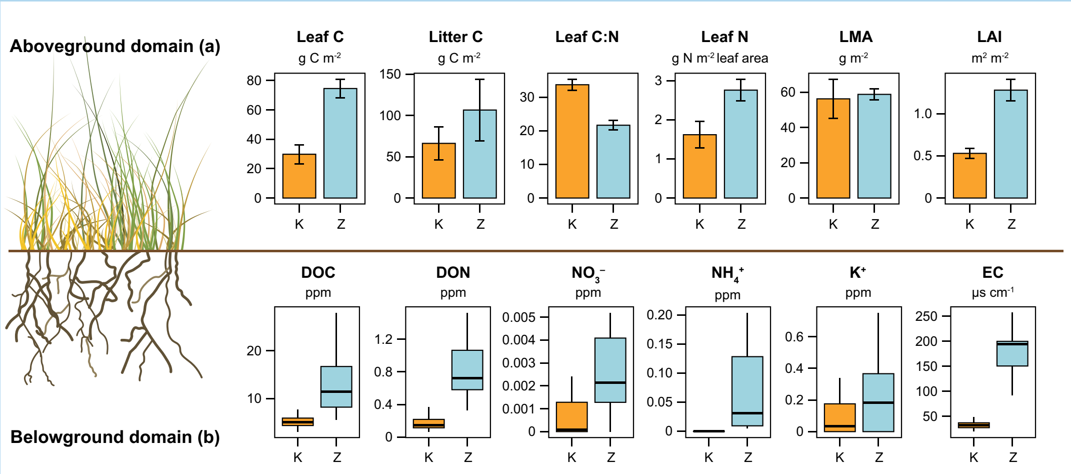

Figure 2. In-situ observations from aboveground biomass (a) and concentration levels of nutrients and minerals in soils (b) from Zackenberg and Kobbefjord fens. The bar plots characterize leaf and litter C stocks, leaf C:N ratio (i.e. plant quality), leaf N, leaf mass per area (LMA), and leaf area index (LAI). The box plots characterize soil water chemistry and catchment exports of dissolved organic carbon (DOC), dissolved organic nitrogen (DON), nitrate (NO_3^-), ammonium (NH_4^+), potassium (K^+), and electroconductivity (EC) at maximum depth of 50 cm.

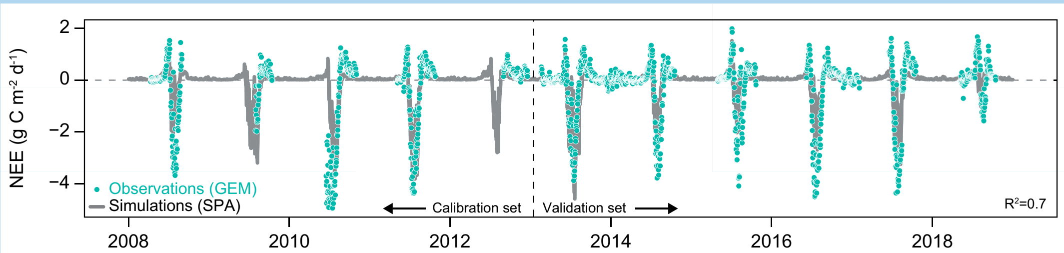

Figure 3. Time series of observed and simulated NEE fluxes using the SPA model in the Zackenberg site for the 2008-2018 period. The model uses the parameterization calibrated for Kobbefjord data (López-Blanco et al., 2018) including modifications of in-situ C stocks, leaf N, and leaf mass per area data from Zackenberg.

organic C and N from soil water (Figure 2). This comparison exercise makes use of a rich GEM dataset to establish a robust baseline framework for model calibration and validation (Figure 3) and to attribute observed flux differences to key processes. Based on our findings we conclude that:

1. Zackenberg fen has a significant higher C sink strength during repeatedly shorter growing seasons compared to Kobbefjord fen.
2. The increased C uptake strength in Zackenberg is associated with 1) systematic higher C and N stocks, plant traits and enhanced plant quality in the aboveground domain, and 2) higher levels in soils of dissolved organic carbon, nutrients such as dissolved organic nitrogen, ammonium, nitrates and potassium, and electroconductivity in the belowground domain.
3. A simple set of parameters from one single field campaign was enough to explain a significant portion of the C flux variability in a very complex ecosystem.
4. More sites for high-temporal monitoring of terrestrial C dynamics are needed to establish robust baselines for model validation and ecological forecasting.

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Photo: Efren Lopez Blanco.

MUSSELS AS OF ENVIRONMENTAL

A long-term marine monitoring programme measured greater growth in mussels during the 2018-19 season than observed in previous seasons. This may be the result of a longer growing season and less ice coverage during the winter.

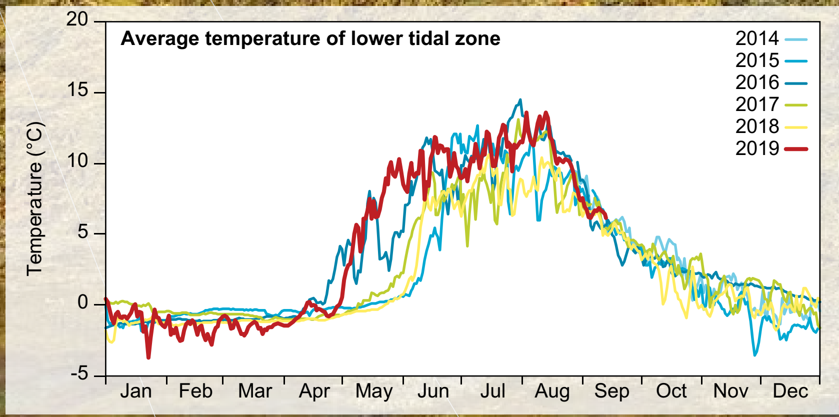


Figure 1. Average temperatures as measured by the data loggers from the lower tidal zone. Data was averaged by day and for all available loggers.

Underwater close-up of blue mussels (Mytlius edulis). Photo: Ole Geertz-Hansen.

Mussels have different strategies to avoid environmental stress, such as altering their heart and filtration rates, or isolating themselves from the ambient water and entering a state of hibernation resulting in changes in survival and growth rates. As such, simple measures of growth and survival of mussels will give clues as to the prevailing conditions within the local marine environment, and possibly to the longterm reactions to changes in climate.

A long-term monitoring programme was established in Kobbefjord using the common blue mussel, *Mytilus edulis*. Experimental mussel plots were set up in 3 locations (inner, middle and mouth of Kobbefjord). In inner Kobbefjord, the mussel plots were deployed at 3 levels: High, mid and low tide. 5 cages, made of plastic netting, were bolted to the rock at each level. Each cage contained 1 temperature logger and 15 mussels between the length of 250-350 mm, which were collected each year on a nearby beach. Individual mussels were measured and numbered. After a year, each mussel in the experimental cages were collected, determined to be either alive or dead and then measured to determine the growth over the season. Individuals from lost cages were presumed dead. New mussels were then collected, measured and placed into the cages in preparation for the next growing season.

Whilst there is no clear pattern with regards to the maximum summer temperature amongst years (Figure 1), the length of the 2019 summer period appears to be longer, with temperatures beginning to rise earlier than previous years. 2016 also showed an earlier start to the summer, but without any indication of a reciprocal increased growth in mussels. The temperature did drop again early in the 2016 season and subsequently follow a pattern like that seen in other years.

Authors:

Maia Olsen, David Blockley, Ole Geertz-Hansen & Thomas Juul-Pedersen

Greenland Institute of Natural Resources

Data source:

MarineBasis Nuuk.

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

INDICATORS
VARIABILITY AND CLIMATE CHANGE

Setting up mussel plots in the intertidal zone of Kobbefjord.
Photo: Ole Geertz-Hansen.

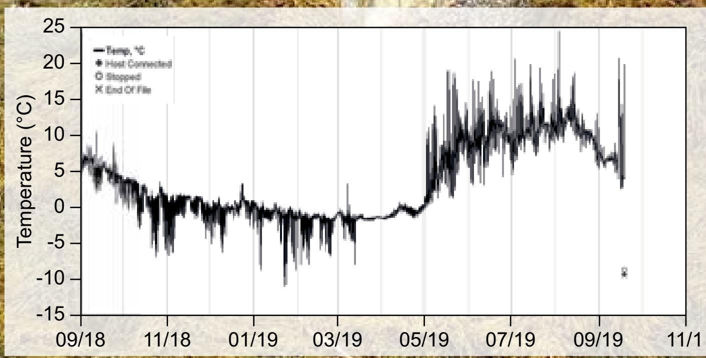


Figure 3. Temperature data from the season 2018-19, from the logger from cage 14 (low tidal zone), as measured every 15 mins.

Only data from the inner fjord are presented here because survival in the mouth and middle of the fjord has been low due to loss of cages, presumably from ice scour removing cages from sites. Total survival (Figure 2) has been increasing over the course of the experiment although without a consistent pattern within any one level. In 2019, all cages were accounted for, with the 2018-19 season showing the greater survival over all levels than in any preceding years. This indicates that ice cover, the greatest observed contributor to loss of cages, during the winter 2018-2019 was not as harsh as in previous years. Although ice also works as a stabilising factor in terms of temperature, shown by the temperature logger graph from when stable ice cover formed in the middle of March until ice break up at the end of April (Figure 3), that protects organisms from colder atmospheric temperatures during winter it is evident that the weight and movement of the ice may be a stronger negative factor on survival than the insulation it affords.

Likewise, growth (Figure 4) was higher in 2018-19, more than twice that in other monitored years, with an average growth of 2,61 mm (0-7,8 mm). This could be explained by the early warming in 2019 and longer summer period. As mussels only feed when submerged and mussels at the low tidal level showed the greatest increase in growth, this supports that water temperature may have been influencing this. Whilst the total length of the 2016 season was similar to 2019, the sudden drop in temperature early in the season may explain why there was not was not the same increase in growth observed. There is likely to be additional environmental factors that are influencing growth, such as stability of temperatures. Further research will help elucidate how changes in environmental conditions will affect the biology and ecology of these marine organisms.

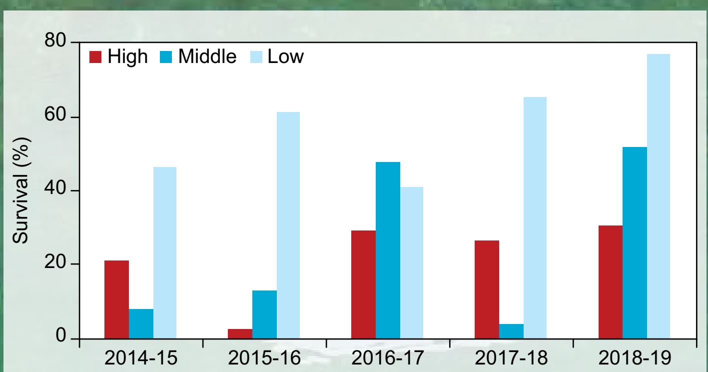


Figure 2. Average percent survival of mussels per season (September – September) for each level.

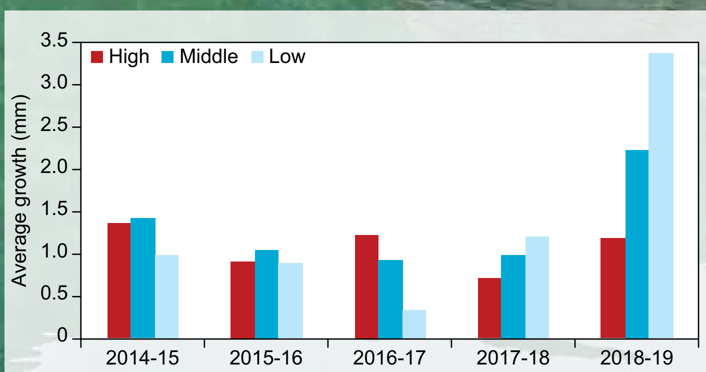
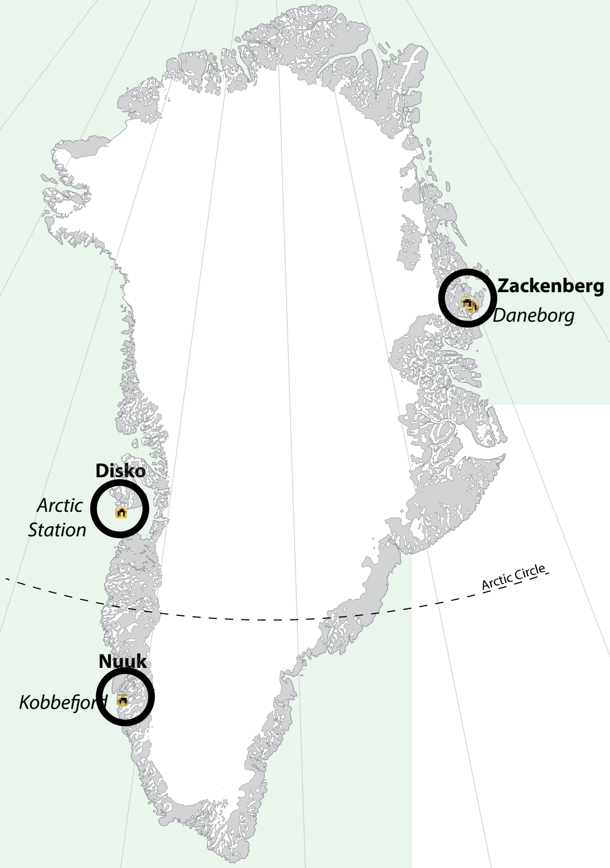


Figure 4. Average growth of mussels per season (September – September) for each level in mm.



ESTIMATING THE
FROM 1979 TO 2017

Over the past decades, rising global temperatures and accelerating ice melt has led to increased water runoff from Greenland. The increased fresh water input into the fjords and ocean has multiple implications, from global sea-level rise [1], to enhanced local hydropower potential [2], but the extra freshwater also influences a wide range of physical, chemical, and biological systems [3]. In order to understand the effect of this increased freshwater input, it is first necessary to quantify it.

Figure 1. Station connected to field discharge measurements in Kobbefjord (Asiaq, 2017).

Field measurements of runoff are carried out in Greenland (Figure 1), and have played an important role in the development of the hydropower and drinking water resources managed by Nukissiorfiit. However, the size of the country and sparse infrastructure means that these measurements are temporally and/or spatially limited. One way to address this when attempting to estimate the runoff from Greenland is to make use of models to estimate the runoff and compare the model results to actual field measurements.

In order to get a Greenland wide estimate of the freshwater runoff from 1979 to 2017, a recent study (in review, [4]) has done just this. The entire Greenland, including ice sheet and land areas, has been divided up into drainage basins using traditional hydrologic routing algorithms. The surface used is the 100 m ArcticDEM digital elevation model [5]. These drainage basins provide the basis for defining where the runoff is expected to leave the land or ice and enter the ocean (Figure 2). Having defined where the water will flow, the next step was to model how much runoff there is at any given place and time. For this, two regional climate models were considered, the Modèle Atmosphérique Régional (MAR; [6], 15 km resolution) and the Regional Atmospheric Climate Model (RACMO; [7], 5.5 km resolution), both regridded to 1 km resolution with daily temporal resolution.

The model results estimate an annual average Greenland runoff from ice basins of 400 ± 30 km^3 ranging from 136 ± 10 km^3 in 1992 to 785 ± 59 km^3 in 2012 (Fig. 3). The minimum runoff from ice basins in 1992 is likely due to the Mt. Pinatubo eruption, and the 2nd lowest runoff year, 1983, due to El Chichón eruption. The run off from the glaciers/icesheet is effected by volcanic eruptions due to the atmospheric cooling associated with ash injection into the atmosphere. It is evident that ice runoff varies widely but increases in both magnitude and variability over the duration of the time-series. The land runoff contributes an additional 35 % to the ice runoff on average, with a range from 18 % during the 2012 high ice-runoff year, to 83 % during the 1992 low ice-runoff year (Figure 3).

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Data source:

GEM ClimateBasis.

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

WATER RUNOFF FROM GREENLAND

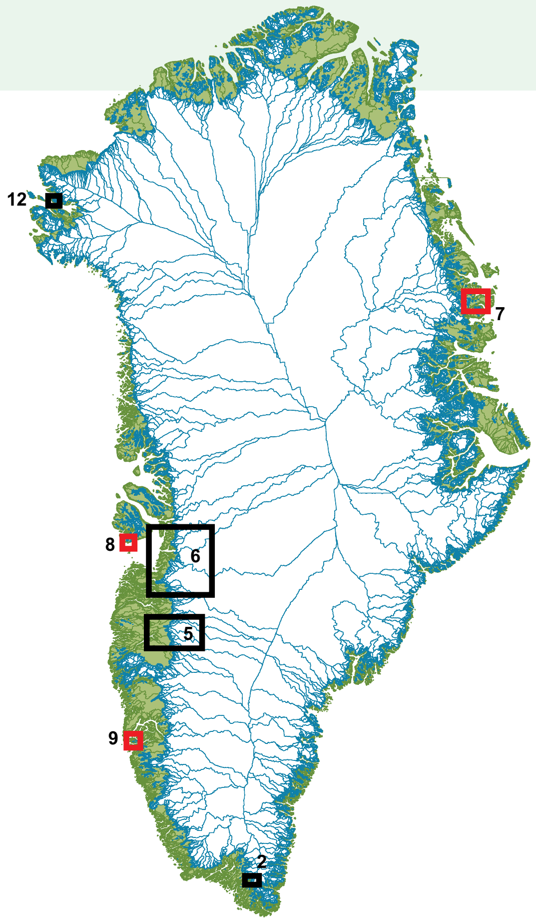

Figure 2. Overview showing ice basins (blue) and land basins (green). Red boxes indicate the GEM sites used for validation. (Adapted from Figure 1. Mankoff et al. in review. Numbers refer to figures in the paper, but are not shown here).

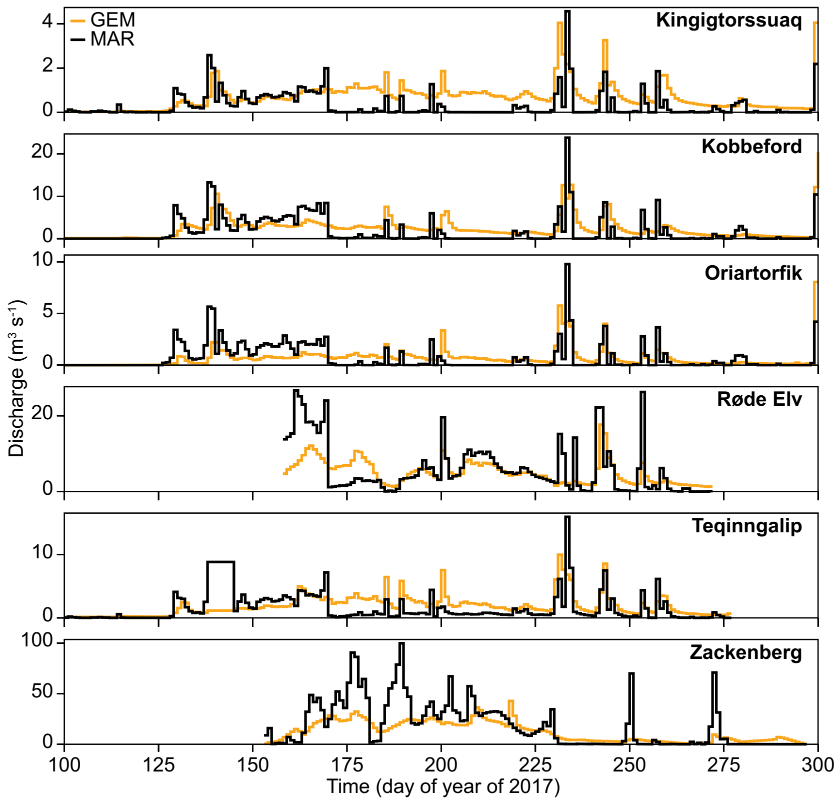

Figure 3. Discharge measured in the GEM drainage basins (orange) compared to the modelled runoff (black) for the year 2017. (Adapted from Figure 10. Mankoff et al. in review).

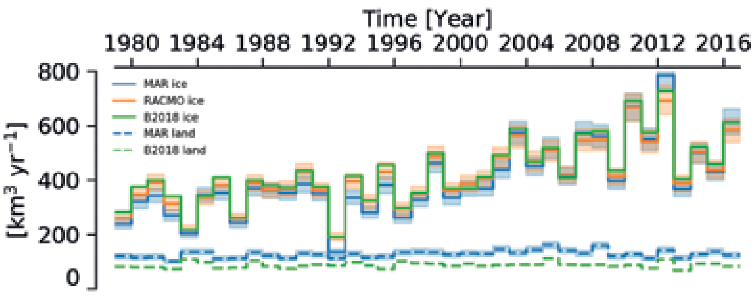

Figure 4. Top panel: Annual Greenland ice sheet runoff from RACMO and MAR as calculated in this product, and B2018 (Bamber et al., 2018). Dashed lines show runoff from land. (Adapted from Figure 3. Mankoff et al. in review).

To assess how well the models perform, the results are compared to publicly available measured discharge datasets, such as those provided by GEM. The modelled data released with the study is a timeseries of average daily runoff for each drainage basin. Comparing the modelled and measured daily average runoff for all of the GEM monitored basins we see general agreement in the magnitude and timing of the run-off, but also notable discrepancies (Figure 4). The GEM sites provide 6 of the 8 available validation datasets, highlighting how important the long-term monitoring program is for model validation.

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SURFACE-BASED
DISKO ISLAND

Surface-based inversions (SBI) occurs when atmospheric temperature increases with height from surface, and are frequent features in the Arctic boundary layer. Temperature inversion stops atmospheric convection and influence vertical mixing of energy, moisture, pollutants, cloud formation and hence precipitation. Their climatic variability is often related to sea ice and surface albedo which are important climate feedback mechanisms, and they often have a strong influence on the distribution of the vegetation.

Radiation inversions are the most common type of inversion, where cooling of the ground surface results in an increase in temperature with height in the atmosphere. The condition is called an inversion because it is the reverse of a normal air pattern (i.e., warmer air below and cooler air above).

Radiation inversions at Østerlien on Disko Island (Figure 1) dominates in the winter time because of the highly negative radiation balance that occur over snow and ice, and because of no or small amounts of solar radiation (Figure 2).

In the summer months inversions occur during night time with low solar radiation and as a result of strong contrasting conditions in the landscape between still-present melting of sea ice and the surrounding snow-free terrain. This effect generates wind, blowing toward land and brings cold air inland (Figure 2).

At Østerlien, SBI=T_{a3}-T_0 was calculated using ground temperature data (T_0) measured just above the ground with a radiation sensor (CNR4) and air temperature data (T_{a3}) measured with a temperature sensor placed 3 m above ground.

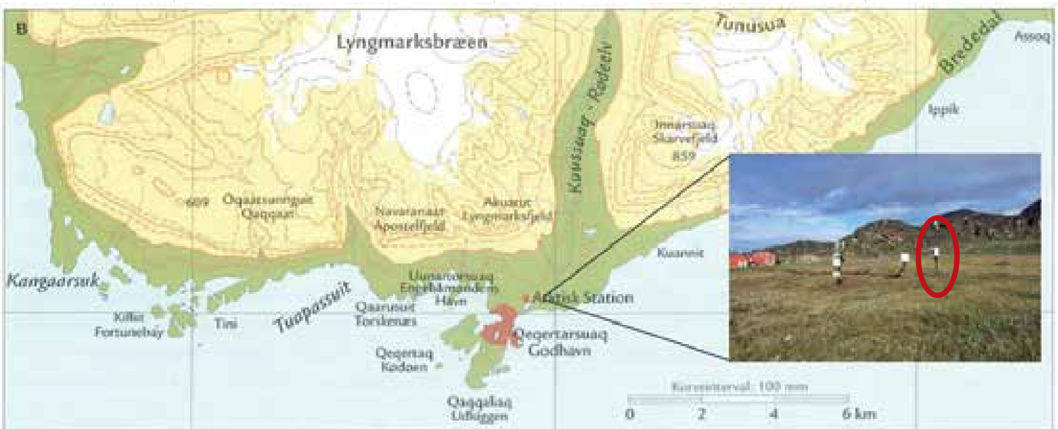

Figure 1. Topographic map of the area around Østerlien with Blæsedalen valley in the North between the mountains Lyngmarksfjeldet and Skarvefjeldet and the river Rødeelv running through. The insert photo shows the AWS-2 situated 100 m east of the Arctic Station (69°15′12.558″ N, 53°30′50.863″W) at 25 m.a.s.l. The data used were retrieved from relevant sensors, placed on the meteorological mast.

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Data source:

GeoBasis Disko.

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

INVERSIONS AT ARCTIC STATION,

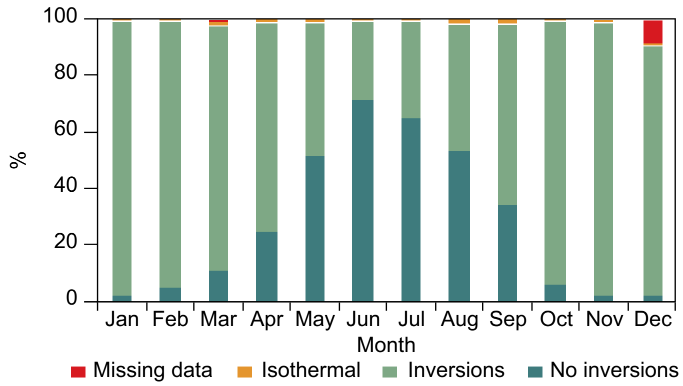

Figure 2. Average proportion of radiation inversions compared to no inversions pr. month in the time period 2013-2018.

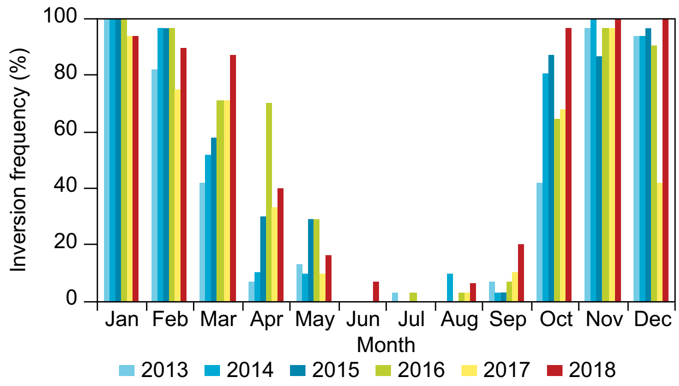

Figure 3. Monthly mean of inversion frequency at noon for each year in the time period.

During the period 2013-2018, monthly SBI frequencies show large variations (Figure 3). Especially March displayed a monotonic trend with a significant increase in inversion frequency compared to other months, from 72.4 % in 2013 to 96.4 % in 2018, or approximately 33 % increase over time (see Table 1).

The March time series of SBI also revealed a significant decrease in their average intensity from 3.0 °C in 2013 to 1.9 °C in 2018 as seen in Table 1, but their intensity could in shorter periods of days be as great as 10 °C. The decreasing intensity indicates a lack of favoring conditions for strong SBI (e.g. low temperatures, dry air and cloud-free conditions).

The time series also showed an increasing relative humidity caused by increasing air temperatures and decreasing sea ice extent in Disko Bay, both due to climate change (Klein et al., 2015). The number and frequency increased in March during Easterly winds. Due to these easterly winds, cloud formation increases and condensation level or cloud bases were lowered from 525 meters in 2013 to 335 meters in 2018.

Increased humidity has shown to weaken radiation intensity as diurnal temperature extremes is reduced (Williams & Thorp, 2015). With a significant increase in relative humidity and decrease in the cloud base, the temperature difference (ΔT) between the cloud base and surface temperatures decrease from 18.5 °C in 2013 to 3.8 °C in 2018. This significant change in ΔT has a strong influence on the net longwave radition that went from –58.1 W/m^2 in 2013 to only –10.3 W/m^2 in 2018. In periods will no or almost no solar radiation (winter and spring) the change in net longwave radiation is considered to be a major influencing factor to surface warming in the Arctic (Williams & Thorp, 2015; Bintanja, Graversen, & Hazeleger, 2011).

Increased warming over the Arctic is of great international concern and 2020 has just been named "Year Of Polar Prediction" where meteorological measurements along the coast and in the air by radiosondes with be intensified to improve the future climate models, and a special focus will be on inversions, such as those described here.

Tabel 1. Detected changes in SBI-related climate parameters in March during the period (2013-2018).

Year	Inversion frequency (%)	SBI=(T_{a3} - T_0) °C intensity	LR net (Wm^{-2})	RH (%)	Condensation level (m)	ΔT (T_{a3} - T_{cloud}), °C	Easterly winds with inversions (%)
2013	72.4	3.0	-58.1	70.4	524.6	18.5	28.0
2014	84.7	3.3	-46.3	68.0	559.8	15.9	28.6
2015	87.8	2.7	-26.9	75.5	397.4	9.6	30.5
2016	88.6	2.1	-21.1	76.4	412.4	6.9	26.7
2017	91.9	2.1	-20.9	78.9	339.8	7.3	43.1
2018	96.4	1.9	-10.3	79.4	335.0	3.8	61.5
r	0.93	-0.91	0.96	0.91	-0.90	-0.96	0.74

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AUTOMATED MONITORING TO STUDY PLANT PHENOLOGY

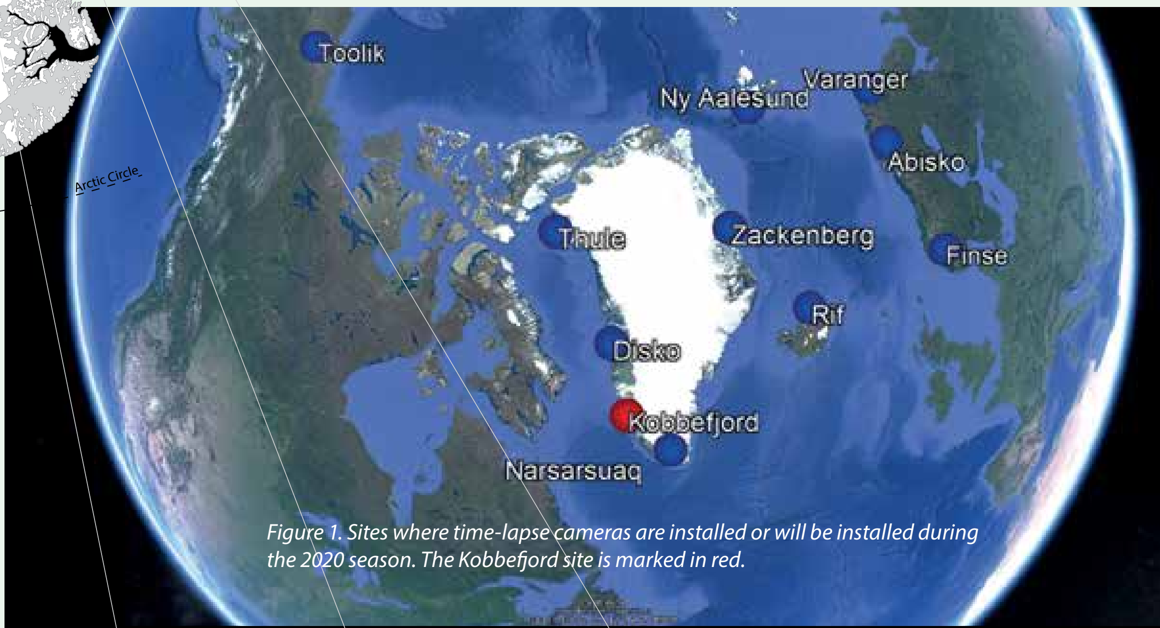

Figure 1. Sites where time-lapse cameras are installed or will be installed during the 2020 season. The Kobbefjord site is marked in red.

Cameras can record seasonal development of flower and fruits of Arctic plants and even track individual insect visits to flowers. In a new project, researchers are using state-of-the-art machine learning and computer vision methods to study the role of climate in plant-pollinator interaction with unprecedented accuracy at Kobbefjord and other Arctic field sites.

Figure 2. Steel mount with camera recording the flowering of the moss campion (Silene acaulis) insect visitors at Kobbefjord, West Greenland.

Arctic flowering seasons are becoming shorter in response to climate change (Høye et al. 2013, Prevéy et al. 2019) and flowering times are changing at different rates in response to warming across the tundra biome (Prevéy et al. 2017). Climate-driven temporal mismatches between flowering time and flight seasons of pollinating insects (Høye et al. 2013, Gillespie et al. 2016) could be driving the rapid decline of pollinator abundance and diversity observed at the Zackenberg research station, North-East Greenland (Loboda et al. 2018). Yet, we know little about how climate affects the strength of interactions among organisms (Schmidt et al. 2017). At Kobbefjord, field workers are meticulously counting flowers and recording their developmental stages in permanent plots at weekly intervals. However, the weekly observation frequency is insufficient to quantify climatic sensitivity of interactions among plants and their pollinators (Rasmussen et al. 2013, Gillespie et al. 2016). With time lapse cameras and computer vision technology, we can increase this frequency to minutes and automate the recording procedure to gain novel insights into climatic impacts on biotic interactions.

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Data source:

GEM BioBasis Vegetation Monitoring component.

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

GEM
Greenland Ecosystem Monitoring

USING TIME-LAPSE CAMERAS
AND PLANT-POLLINATOR INTERACTIONS

Figure 3. Example of a sequence of images taken during the flowering season at Kobbefjord during the 2018 growing season.

The use of image-based observations of plants and animals is on the verge of transforming research in ecology (Wäldchen and Mäder 2018, Weinstein 2018). Recent advances in computer vision and machine learning have resulted in very effective analysis pipelines, which are opening up new opportunities for automated monitoring of species, their interactions, and how they respond to environmental variation (Van Horn et al. 2017). In this project, we quantify flower season dynamics and visitation rates by using a large number of time-lapse cameras located across Arctic field sites (Figure 1 and 2). This enables a uniquely high temporal resolution of data across the full growing season (Figure 3). We focus on circum-Arctic, common, insect-pollinated plant species, such as the moss campion (*Silene acaulis*) and species of the genus *Dryas*. The first step in the project is to train deep neural network models to detect flowers and insects in the vast amount of image data. For a subset of the images, flowers are manually annotated to facilitate the training and to evaluate how well the neural network performs in the task of detecting flowers in images (Fig. 4). Data for the project are collected across a large number of sites with support from INTERACT, Nansen foundation, Villum Foundation, and the Independent Research Fund Denmark. The project aims to demonstrate how the implementation of new technology can improve the study of long-term effects of climate change in the Arctic. The expected outcome is comparable, standardized, and detailed information about how Arctic ecosystems are responding to climate change.

Figure 4. Annotation of images to extract examples of flowers of moss campion (Silene acaulis) for training a deep learning model.

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Annual Report Card 2019

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 run-off 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. A challenging focus is put on the establishment of reliable stage-discharge relations, whose temporal stability depends on the river bed. At the river Zackenberg for instance, repeated glacier outburst floods require an updated stage-discharge relation every year, where the related field work is performed together with the GeoBasis sub-programme.

In 2019, the annual mean temperature was higher than the 2008-2019 average at all three stations (0.1°C, 1.5°C and 1.3°C at Zackenberg, Disko and Kobbefjord, respectively). Disko experienced 4 of the warmest months of this period, while Zackenberg experienced both its warmest April and its coldest March. Comparing 2019 to all years in the GEM database for each station, Zackenberg experienced the coldest March and Disko, the warmest May.

Monitored parameter groups

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

Switching the water level instrumentation from the summer to winter set-up in Kobbefjord. Photo: Sille M. Myreng.

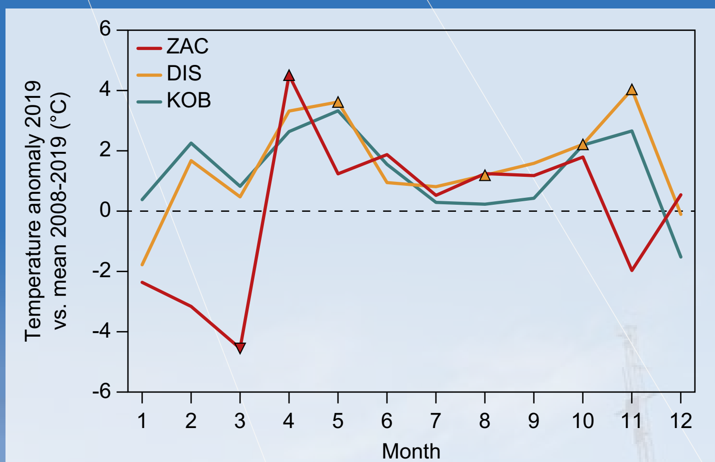

Figure 1. Monthly air temperature anomaly for 2019 compared to the common reference period 2008-2019 for Zackenberg (ZAC), Disko (DIS) and Kobbefjord (KOB). The triangles in the figure mark months whose mean temperatures have been more extreme than those of the corresponding months in any other year from 2008-2019. If the triangle points upward, the month has been the warmest in this period, while if it points downward, it has been the coldest.

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Climate stations in Kobbefjord. Photo Asiaq

PROGRAMME DESCRIPTION

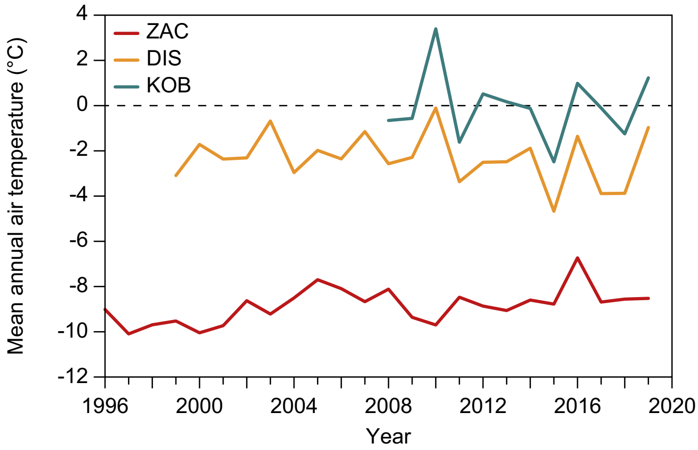

Figure 2. Mean annual air temperature at the three GEM sites Zackenberg (ZAC), Disko (DIS) and Kobbefjord (KOB).

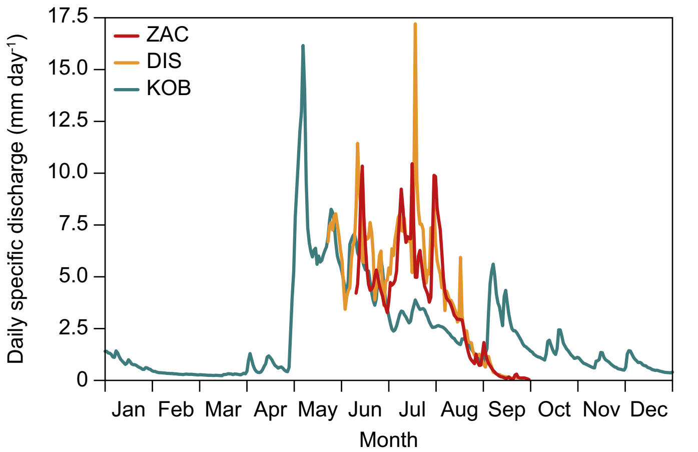

Figure 3. Specific daily discharge (runoff per unit area) at the three GEM sites: Zackenberg (ZAC), Disko (DIS) and Kobbefjord (KOB) for 2019. In winter, ZAC has no flow and DIS no winter instrumentation, while KOB shows year-round discharge. In most years, the specific discharge at Zackenberg is lower than in Kobbefjord, corresponding to a drier climatic regime. The summer of 2019 has been unusually long and dry, in particular in southern Greenland, rendering the timelines more similar to each other.

Annual reference test of the sensors on the Climate masts, Zackenberg. Photo: Kirsty Langley.

2019 was on average a notably warmer year on the West coast (Kobbefjord and Disko) compared to 2018, while on the East coast (Zackenberg), the mean annual temperature was only slightly warmer than in 2018. The temperature record highlights the very different temperature regimes found at the 3 locations with mean annual temperatures way below zero at Zackenberg, a few degrees below zero at Disko and around zero in Kobbefjord. The interannual variability in Zackenberg is notably less than at the other two stations.

This year flow onset in Zackenberg occurred on 14th of May, one of the earliest on record, and over 1 month earlier than in 2018. There was a glacier lake outburst flood from A.P.Olsen glacier, which peaked on July 17. Disko experienced a similar very early onset to flow on the 5th May. In Kobberfjord there was a notably low flow throughout the summer season due to the long and dry summer. Field work for discharge in Zackenberg and Disko is undertaken in tight collaboration with GeoBasis.

In 2019, the snow depth at Zackenberg and Kobbefjord was lower than in 2018; and in Zackenberg, only the winter of 2012/13 experienced even less snow than 2018/19. Outgoing shortwave radiation drops abruptly after the snow melt each year, since snow-free ground is far less reflective than snow. In 2019, the snow melt happened earlier at both stations than in the average for 2012-19 (end of April in Kobbefjord and end of May in Zackenberg). The mean annual net shortwave radiation for both stations was larger in 2019 than the 2012-19 mean, while for 2018 it was lower; in Zackenberg, this is almost exclusively accounted for by the difference in outgoing radiation, whereas in Kobbefjord, changes in incoming and outgoing radiation have been of similar magnitude and direction.

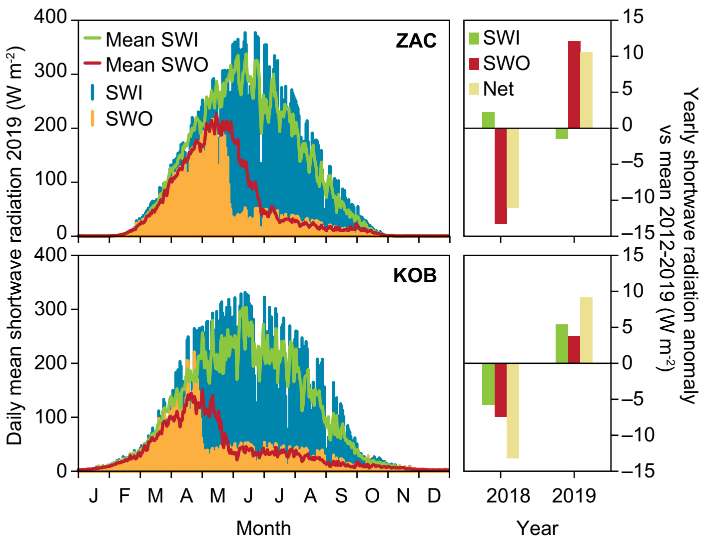

Figure 4. Main plots: Daily mean shortwave incoming radiation (SWI) and shortwave outgoing radiation (SWO) in 2019 with their respective daily means for the period 2012 to 2019 (SWI mean and SWO mean) for Zackenberg (ZAC) and Disko (DIS). Bar plots (right columns) show yearly mean anomalies for the two most recent years, with outgoing radiation (SWO) taken to be negative, so that the net radiation is simply the sum of SWI and SWO.

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GEM GEOBASIS

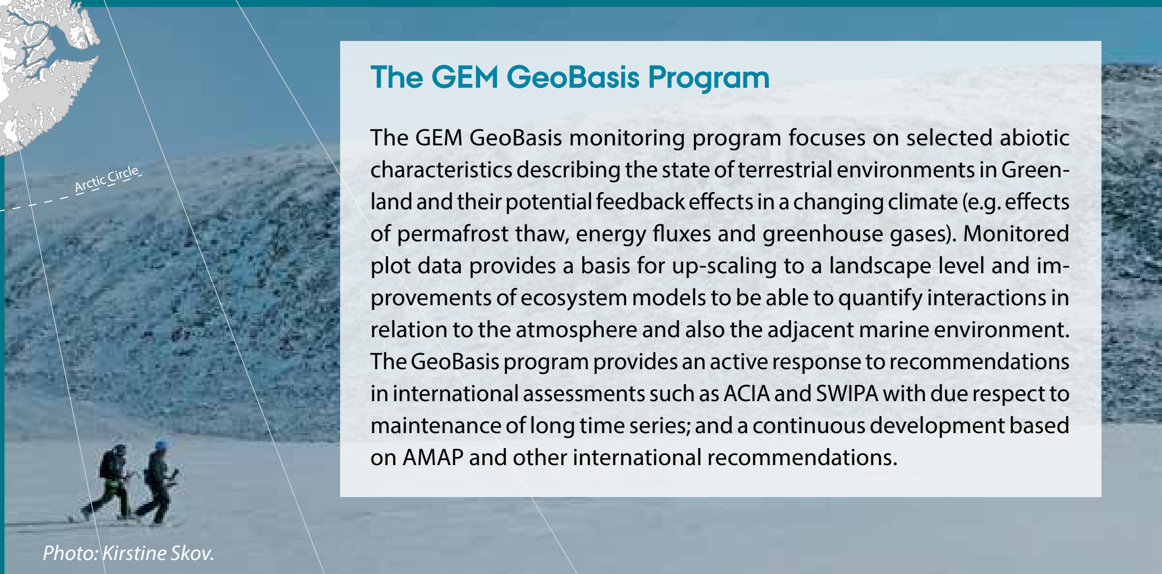


Photo: Kirstine Skov.

The GEM GeoBasis Program

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

Monitored parameters

Snow properties
- Snow cover
- Snow depth
- Snow density

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

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

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

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

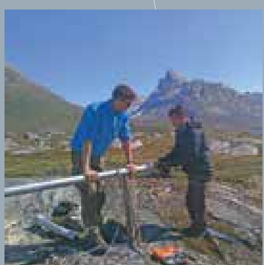
Geomorphology
- Shore line mapping
- Mapping of landscape dynamics and erosional features

The 2019 spring showed below average snow depths, with subsequent early snow melt dates across the three GEM sites (Figure 1).

The summer season was relatively warm across all sites, with Disko experiencing record monthly mean temperatures from May – November compared to the period 2012-2019 (Figure 2). The early date of snow free ground combined with relatively high air temperatures is clearly observed at all three sites in the early onset of positive ground temperatures, as well as early peak in soil moisture (Figure 2).

In Zackenberg, the mean maximum permafrost thaw depth was 85 cm, following the decreasing long-term trend (–0.7 cm per year), from which 2018 deviated as a result of very late snowmelt and low summer temperatures (Figure 3).

Zackenberg: Inspection of meteorological station in 500 meters elevation. Photo: Malin Ahlbäck.



Kobbefjord: Fixing a broken windmill in the Kobbefjord fen, June 2019. Photo: Kerstin Krøier Rasmussen.

Zackenberg: Time-lapse photography installation used to determine snow cover and vegetation greenness of the Valley floor. Photo: Daniel Alexander Rudd.

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PROGRAMME DESCRIPTION

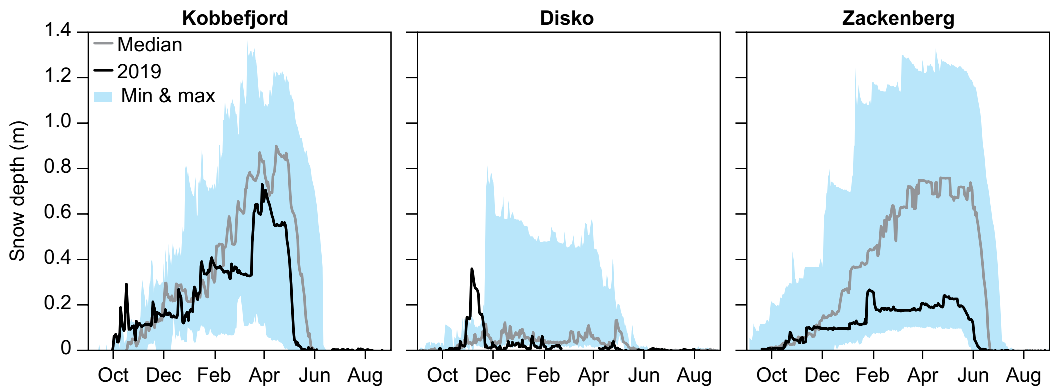

Figure 1. Daily snow depth measurements in Kobbefjord (left), Disko (middle) and Zackenberg (right). Black lines are snow depth in 2019, grey lines are median and shaded area is min and max for the historical record. Snow is a key parameter in Arctic ecosystem functioning. Thus, several different monitoring methods are put in place to get information on spatial distribution and temporal patterns in snow cover, across the three GEM sites. Methods include time-lapse photography, transect surveys, snow density measurements and, as shown here, long term point-based monitoring of snow depth. Data used in the figure: Kobbefjord: 2008-2019, Disko: 2012-2019 and Zackenberg: 1996-2019.

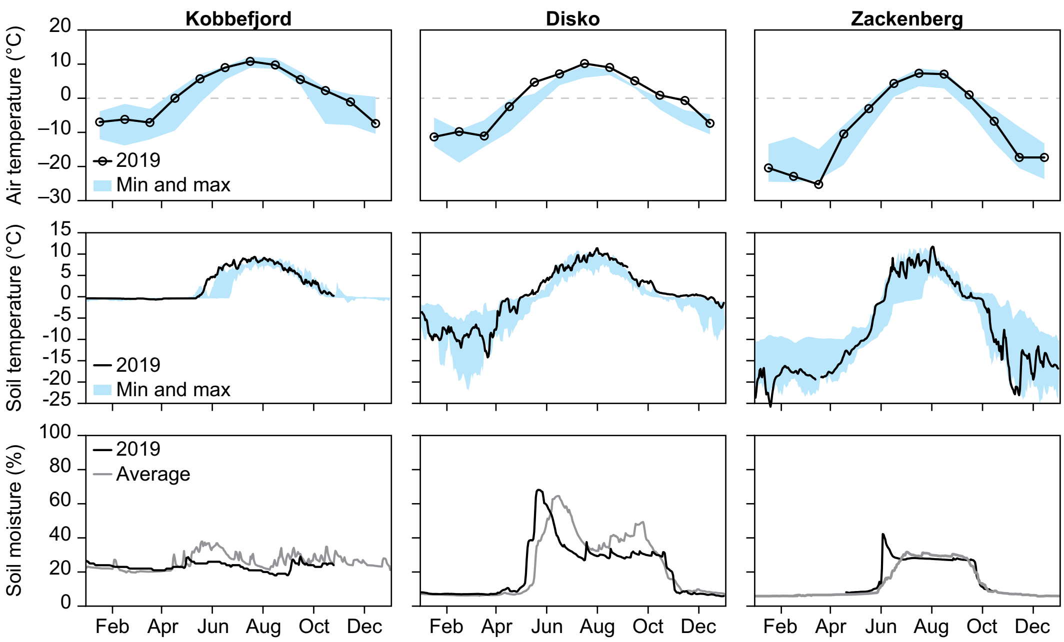

Figure 2. Mean monthly air temperature across sites (top panel) in 2019 compared to minimum and maximum (shaded area) in historical data. Heath soil temperatures in 10 cm (middle panel) in 2019 compared with minimum and maximum (shaded area), and soil moisture within the top 10 cm, shown together with average (lower panel). 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 program. Data used in the figure: Top panel: Kobbefjord: 2008-2019, Disko: 2012-2019 and Zackenberg: 1996-2019. Middle panel: Kobbefjord: 2012-2019, Disko: 2012-2019 and Zackenberg: 2014-2019. Bottom panel: Kobbefjord: 2013-2019, Disko: 2012-2019 and Zackenberg: 2005-2019.

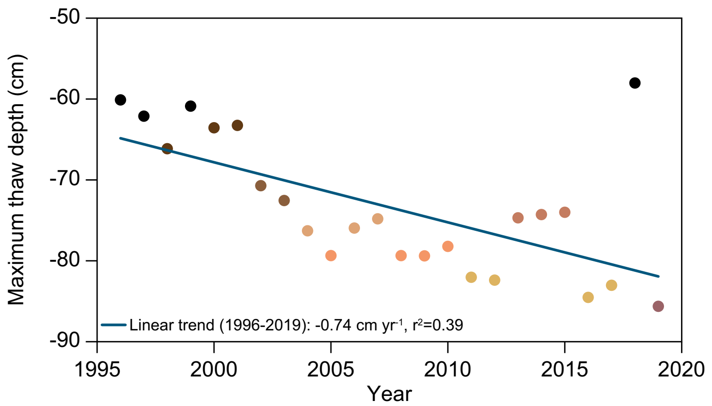

Figure 3. Long-term trend in annual maximum soil thaw depth in Zackenberg Circumpolar Active Layer Monitoring grid # 1 (ZEROCALM-1). Soil thaw and active layer depth are studied under different vegetation types. Monitoring methods include manual probing and borehole temperature recordings.

Disko: River break-up 5 May 2019. One month earlier than in 2018. Photo: Kirsty Langley.

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GEM BIOBASIS

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

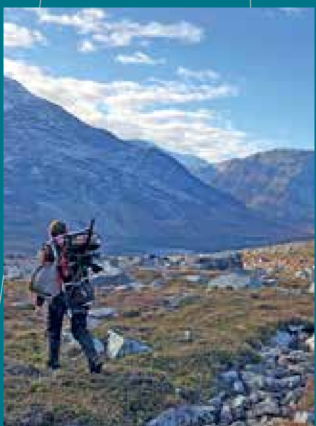

Photo: Katrine Raundrup.

Photos: Lars Holst Hansen.

Monitored parameters

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

Arthropods and microarthropods
- Abundance
- Emergence phenology
- Herbivory rates

Birds
- Abundance
- Reproductive phenology
- Reproduction and predation rates

Mammals
- Abundance
- Spatial distribution
- Reproduction and predation rates

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

General
- Tissue sampling
- Plot-scale abiotic parameters

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PROGRAMME DESCRIPTION

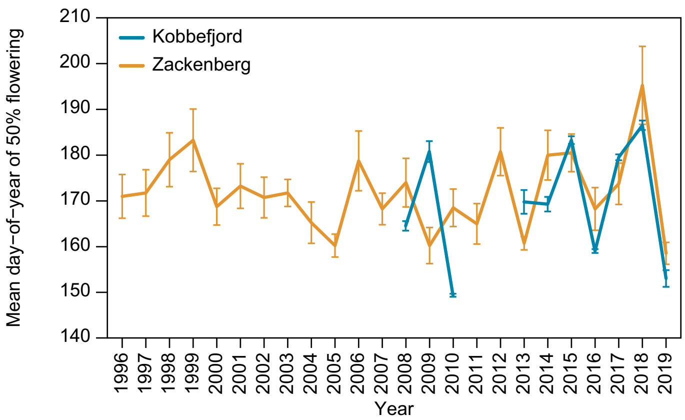


Figure 1. Day of 50% flowering is indicative of the effect of climate variability on the timing of flowering. The timing of plant growth and flowering is important for e.g. insects and herbivorous animals.The graph shows inter-annual variation in mean Salix *flowering phenology in selected permanent plots in Kobbefjord and Zackenberg 1996-2019. Note that no flowering was observed in Kobbefjord in the years 2011 and 2012 due to insect outbreak.*

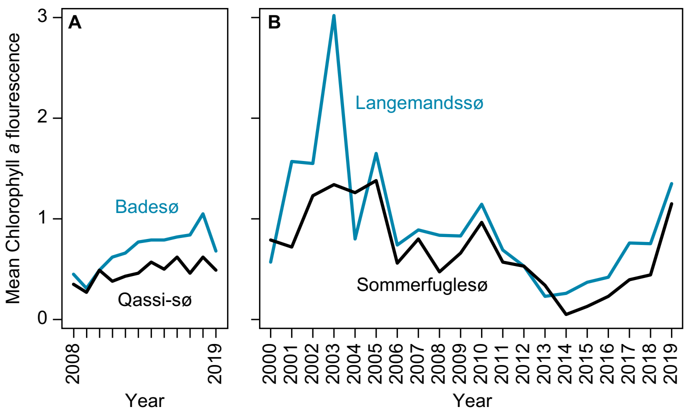


Figure 2. Chlorophyll fluorescence is a measure of productivity in the limnic ecosystem. The graphs show inter-annual variation in chlorophyll fluorescence in lakes at Kobbefjord and Zackenberg 2000-2019. Blue lines indicate lakes with fish, black lines lakes without fish.

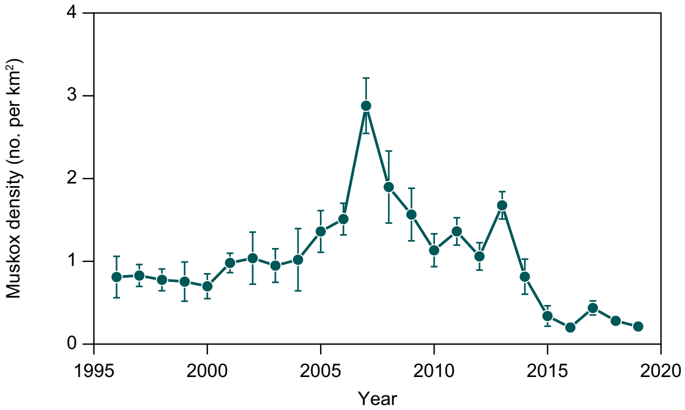


Figure 3. Inter-annual variation in muskox population dynamics at Zackenberg 1996-2019.

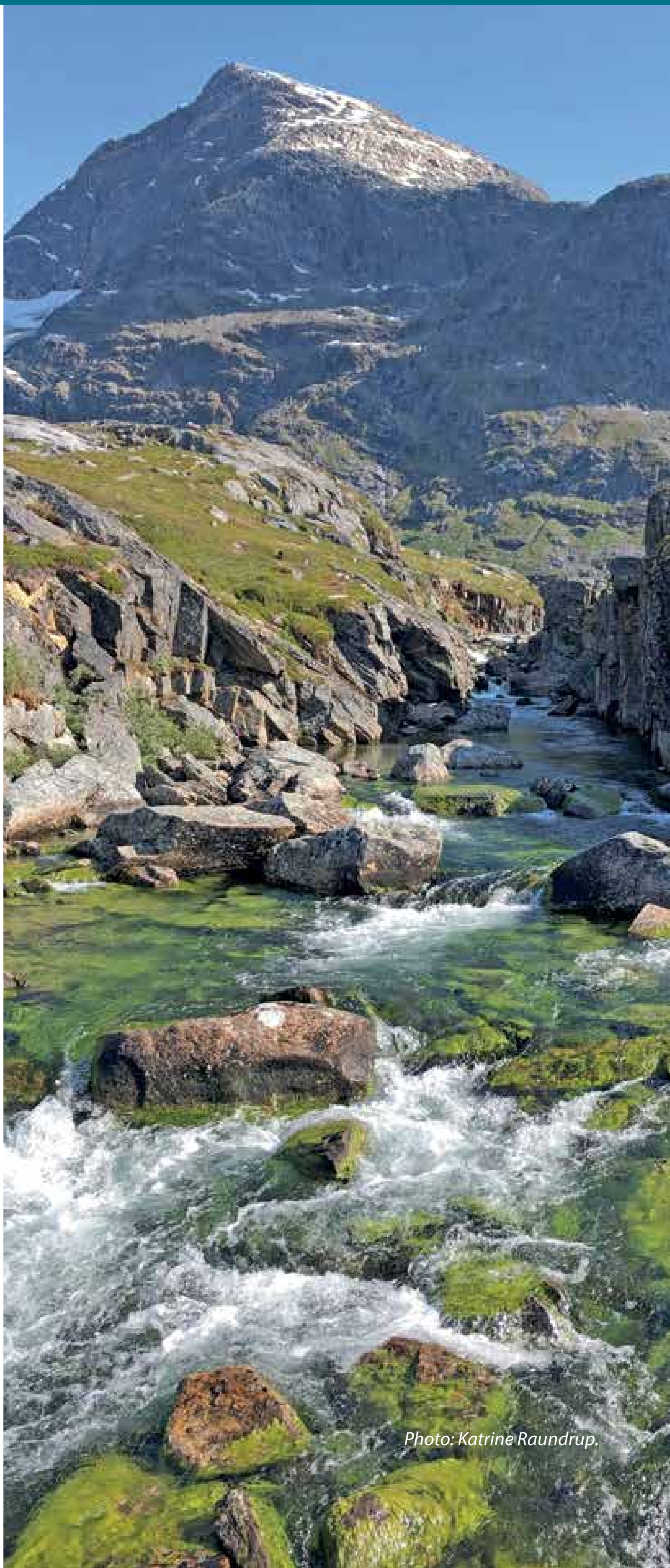
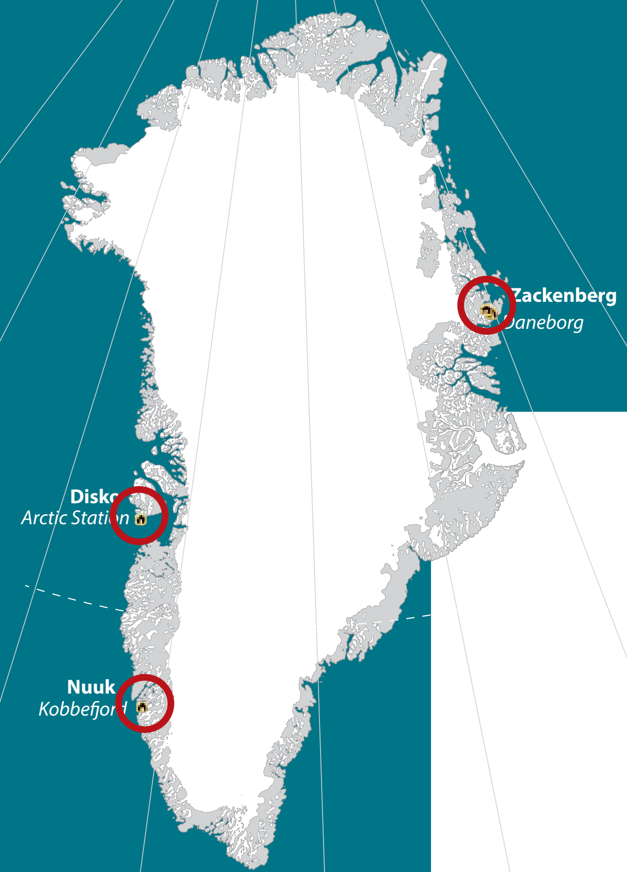


Photo: Katrine Raundrup.



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GEM MARINEBASIS

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

Photo: Torkel Gissel Nielsen.

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PROGRAMME DESCRIPTION

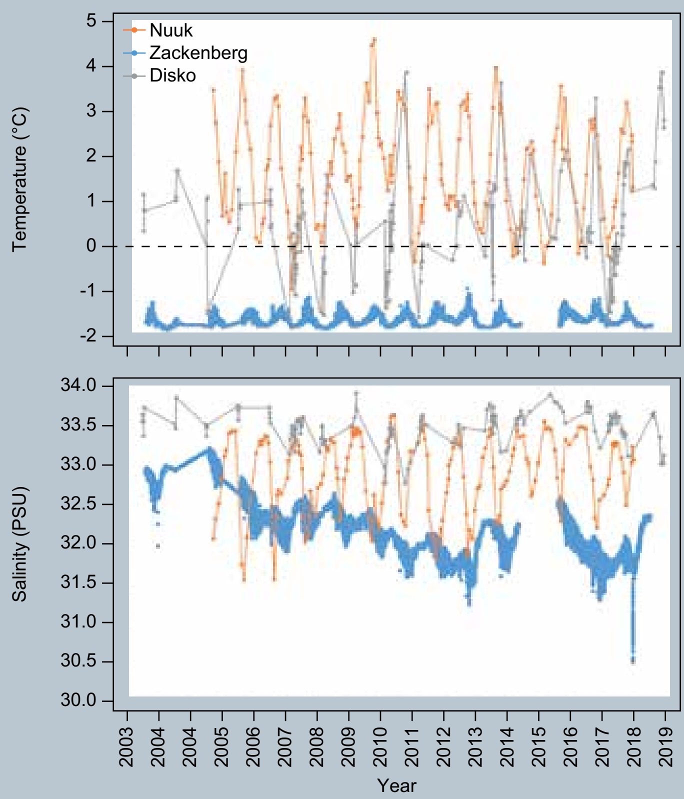
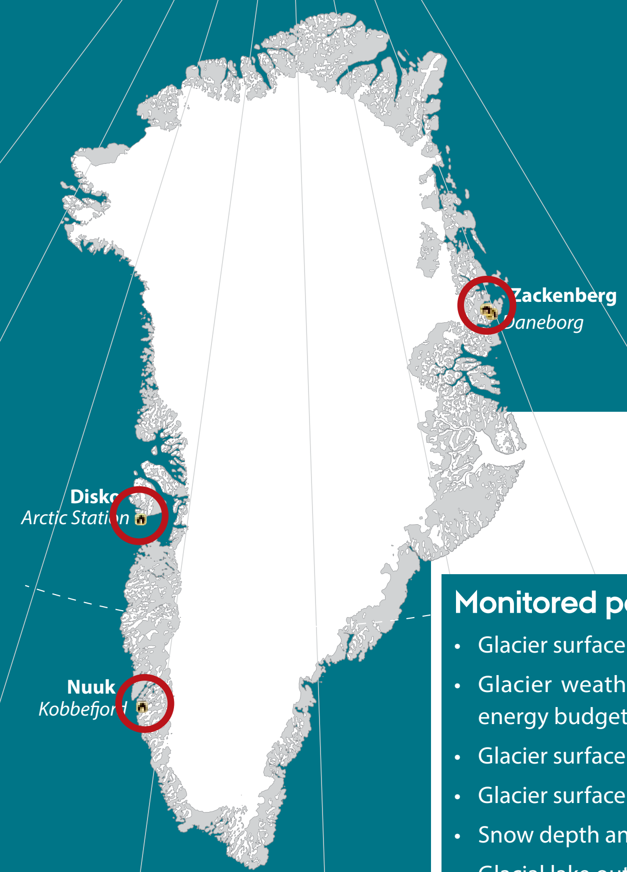


Figure 1. Water temperature and salinity at the permanent monitoring stations in Nuuk, Disko and Zackenberg. The time series from Nuuk and Disko represents one depth (63 m) selected from a monthly profile covering the entire water column. The time series from Zackenberg represents an autonomous mooring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

Photo: Mie Winding.

Photo: Mie Winding.



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GEM GLACIOBASIS

GlacioBasis monitors the surface mass balance and the surface energy budget of glaciers at the Zackenberg, Kobbefjord and Disko GEM sites to quantitatively understand the climatic drivers of glacier change. Glaciers and ice caps distinct from the Ice Sheet account for 14-20% of Greenland's total contribution to sea level rise and are therefore of global policy relevance. At the river catchment scale, glacier runoff is a key component of the hydrological balance and contributes to the freshwater input to the sea. GlacioBasis activities started with the 2007/2008 mass balance year at the A.P. Olsen ice cap in Zackenberg, followed by Qasigiannguit glacier in Kobbefjord (since 2012/2013) and Chamberlin glacier, a sector of Lyngmarksbræen ice cap on Disko Island (since 2015/2016).

GlacioBasis manual and automatic *in situ* observations implement standardized protocols and best practices from WMO GCW (World Meteorological Organization's Global Cryosphere Watch) and WGMS (World Glacier Monitoring Service). All sites use the same automatic weather stations used by GEUS for PROMICE, the Programme for the Monitoring of the Greenland Ice Sheet, simplifying technical support. The GlacioBasis time series provide *in situ* calibration and validation data for the GEM Remote Sensing Initiative and offer a platform for external project like EU-H2020 INTAROS. GlacioBasis is operated by GEUS (Zackenberg and Disko) and Asiaq – Greenland Survey (Kobbefjord). In addition to closely collaborating with the other GEM Programmes, with PROMICE, and with DMI, GlacioBasis has a strong collaboration with ZAMG (Vienna) and is represented in the Steering Group of WMO GCW.

Monitored parameters:

- Glacier surface mass balance
- Glacier weather and surface energy budget
- Glacier surface elevation
- Glacier surface velocity
- Snow depth and density
- Glacial lake outburst floods

Detail of the Qasigiannguit glacier AWS carrying a high accuracy GNSS receiver developed at GEUS within the INTAROS project. The system is self powered and records daily datasets suitable for accuracy. Several more units will be installed at GEM and PROMICE AWS during 2020. Photo: Michele Citterio, GEUS.

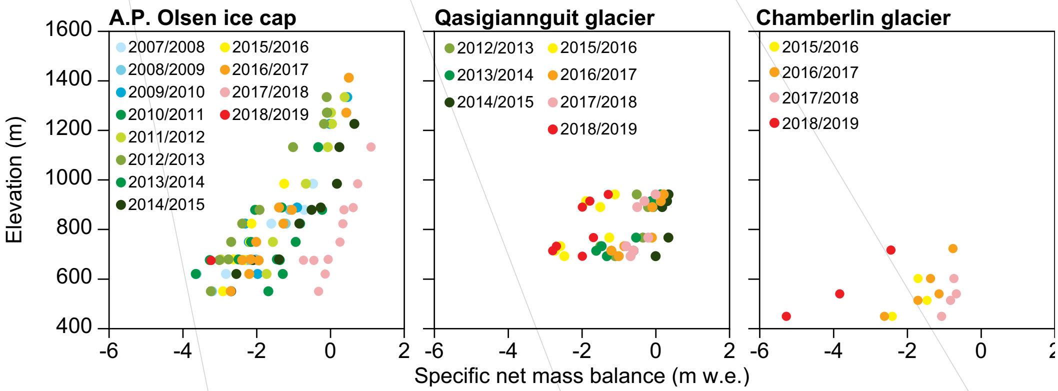

Figure 1. Glacier surface mass balance vs. elevation at the stakes on A.P. Olsen ice cap (Zackenberg, 14 stakes), Qasigiannguit glacier (Kobbefjord, 9 stakes) and Chamberlin Glacier (Disko, 7 stakes). For A.P. Olsen the stake readings will become available after the 2020 field campaign.

The 2018/2019 mass balance year was dominated by limited accumulation and very intense ablation, resulting in a strongly negative mass balance for all three monitored glaciers on par or exceeding the most negative mass balance years on record since the start of GEM glaciological monitoring. A very early start of the melt season made it impossible to carry out the planned snow survey at Chamberlin glacier. Testing of an automatic snow water equivalent sensor based on counting of neutrons produced by cosmic rays has started at Chamberlin to mitigate similar problems in the future. During the summer, ablation exceeded 5 m w.e. (water equivalent) at the lowermost stake on Chamberlin. Several stakes fell and were redrilled. The ablation meter on the automatic weather station remained in operation throughout the year, but additional automatic sensors should be installed to reduce loss of data during high melt years. Qasigiannguit glacier expereinced similar losses to the very negative 2015/2016 mass balance year. In Zackenberg, snow depths on A.P Olsen were lower than average which led to enhanced melt of the darker underlying glacier ice.

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GEM
Greenland Ecosystem Monitoring

PROGRAMME DESCRIPTION

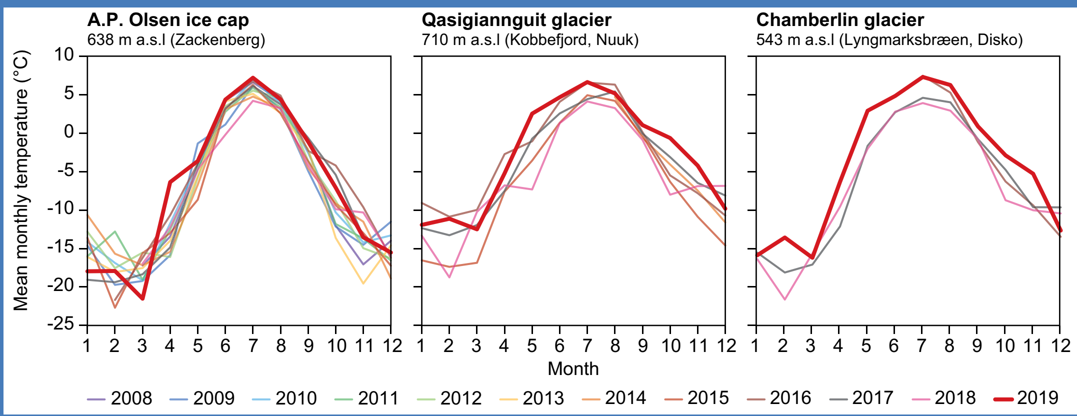

Figure 2. Mean monthly air temperatures from automatic weather stations in the ablation zone of the monitored glaciers at the three GEM sites.

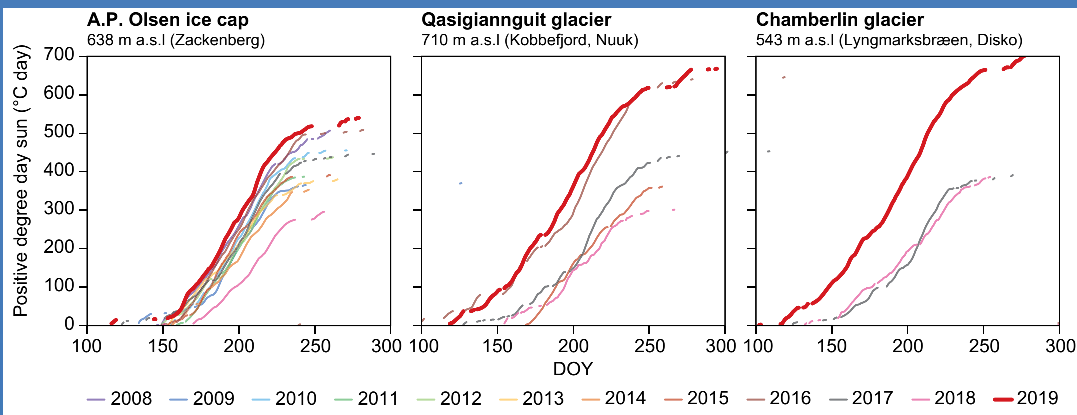

Figure 3. Positive degree day (PDD) sums from GlacioBasis automatic weather stations in the ablation zone of the monitored glaciers at the three GEM sites. Only seasons with complete data coverage are shown, gaps visible in the plots indicate sub-freezing daily mean temperatures.

Mean monthly air temperatures were amog the highest on record at all three glaciers. Record high mean tempratures started already in April at A.P. Olsen and Chamberlin, and in May at Qasigiannguit, and remained above most or all previously recorded years. This is in contrast with 2017/2018 when summer temperatures had been consistently lower at all the GEM glaciers. The winter months were also warmer than average, except for A.P. Olsen which recorded the coldest March since measurements started in 2008.

Positive degree day (PDD) sums provide a simple tool to highlight the interannual variability in the intensity and timing of snow and ice ablation. The differences of climate at the three GEM sites is clearly reflected in these plots, even though the length of the Qasigiannguit and Chamberlin weather timeseries is still rather short. At all sites the 2019 ablation season accumulated the highest PDD which is reflected in the strongly negative surface mass balance. Chamberlin glacier experienced the largest departure from the few earlier years recorded to date, with uninterrupted melt conditions berween the last week of May to the first week of September.

Towing a snow scooter with a pulley upriver across blue ice near the terminus of A.P. Olsen. Photo: Daniel Binder, GEUS.

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.

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.

www.g-e-m.dk

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