Greenland Ecosystem Monitoring

ANNUAL REPORT CARDS 2021

Title: Greenland Ecosystem Monitoring Annual Report Cards 2021

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Aarhus University

Publisher: Aarhus University, DCE – Danish Centre for Environment and Energy
URL: http://dce.au.dk

Year of publication: 2022

Citation: Marie Frost Arndal, & Torben Røjle Christensen. (2022). GEM Annual report Card 2021. Zenodo. https://doi.org/10.5281/zenodo.6721144. DCE – Danish Centre for Environment and Energy, Aarhus University, 40 pp.

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Layout and figures: Tinna Christensen, Aarhus University

Front cover: Arctic Station with the small town, Qeqertarsuaq in the background. Photo: Charlotte Sigsgaard

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

ISBN: 978-87-7156-701-4
DOI: 10.5281/zenodo.6721143

Number of pages: 40

Printed by: Rosendahls – print · design · media

Circulation: 300

The publication is available through www.g-e-m.dk.

AARHUS UNIVERSITY
DCE – DANISH CENTRE FOR ENVIRONMENT AND ENERGY

GREENLAND ECOSYSTEM MONITORING

ANNUAL REPORT CARDS 2021

PROGRAMME DESCRIPTIONS

GEM

Greenland Ecosystem Monitoring

GEM INTRODUCTION

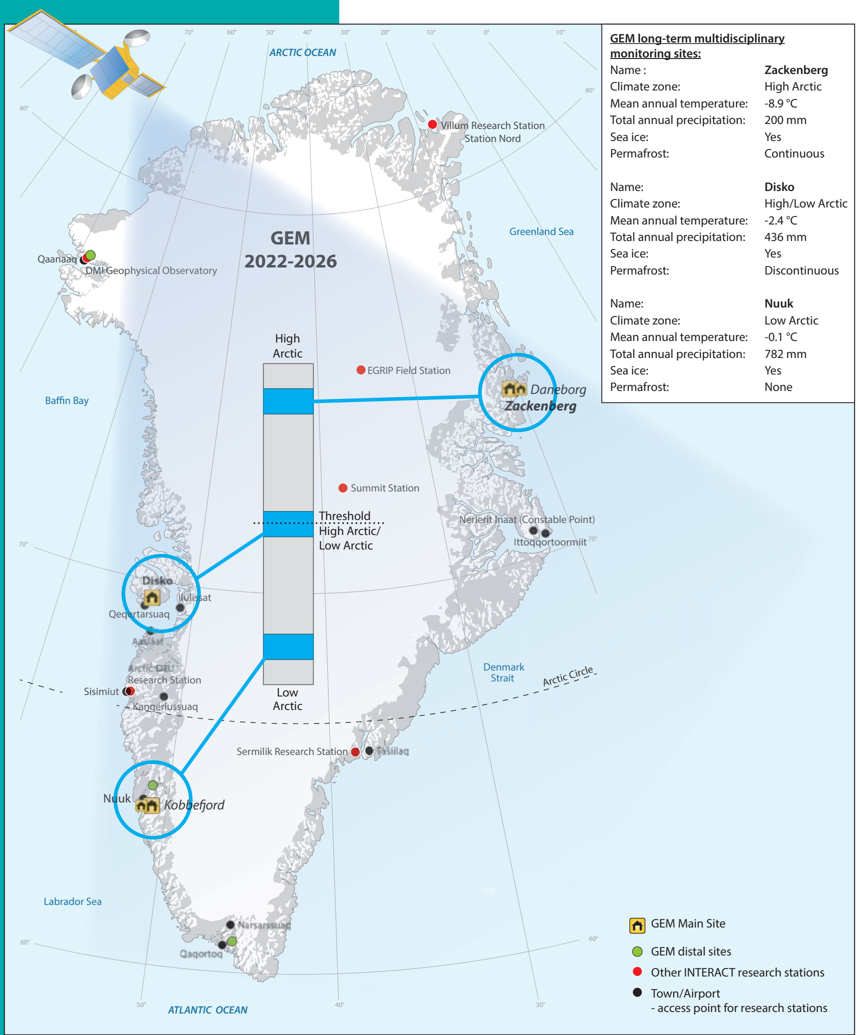

Figure 1. The GEM programme combines intensively studied ecosystems at three main sites (Disko, Nuuk and Zackenberg) with remote sensing and distal sites located along environmental and climatic gradients.

About GEM

Greenland Ecosystem Monitoring (GEM) is an internationally recognized climate and ecosystem monitoring programme in Greenland, operated by research institutions in Denmark and Greenland. It was established in 1995 and thus celebrates more than 25 years of monitoring essential climate and ecosystem variables. Throughout the years GEM has contributed to the working groups of the Arctic Council and the long-term data has improved the scientific understanding of climate and ecosystem change in the Arctic. The programme has developed from a comprehensive climate change and ecosystem monitoring programme at a single site in the National Park of North-East Greenland, to also include two almost equally comprehensive programmes in West Greenland, supplemented with initiatives at other locations (Figure 1).

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

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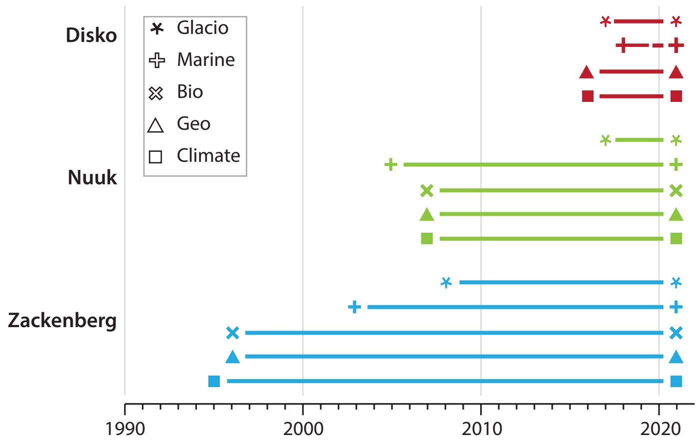
Figure 2. The GEM programme was initiated in 1995 as the Zackenberg Ecological Research Operations (ZERO). In the years 2005-2007 a new main site was established around Nuuk, and in 2016-2018 Disko area was included. All 5 Basisprogrammes are now funded at all three main sites, except for BioBasis at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



GEM
Greenland Ecosystem Monitoring

The vision of GEM

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

International cooperation

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

Education and Advice

GEM also 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.

Free and open access to data

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

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

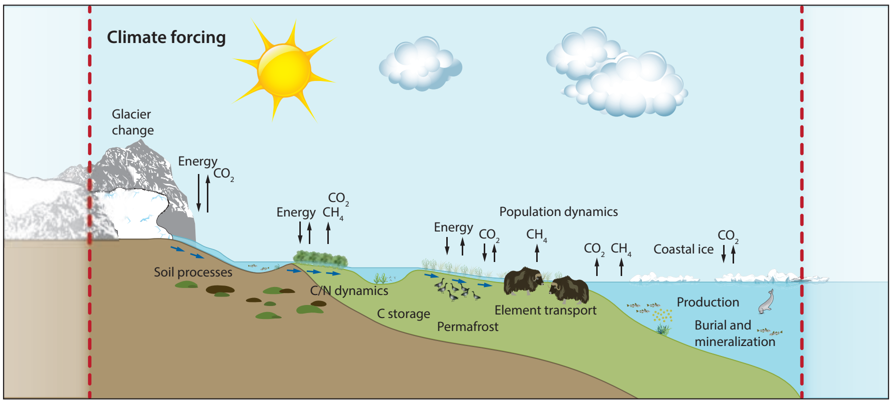


Figure 3. The GEM domain covers the glaciological, terrestrial, limnic and coastal marine compartments of the ecosystem.

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

@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: Charlotte Sigsgaard.

Zackenberg Research Station.

Photo: Daniel Rudd.

Kobbefjord Station.

Photo: Henrik Philipsen.

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GEM at a glance 2021

- Active Basis Programmes in 2021: 14
- Scientists in the field: 65
- Scientific publications: 43
- Conference with GEM representations: 10
- Conference presentations (posters): 11 (4)
- Courses using GEM data: 24

Results and achievements

The 2021 GEM field work season was once again quite Covid-19 affected at some sites. There were still heavy restrictions on travel to Greenland until the end of June which meant several early activities in both Disko and Zackenberg could not be conducted as scheduled. However, as the restrictions were lifted the latter part of the season returned to an almost fully normal operation. The hope is that with this shift in mid-season 2021 we have now seen the last of the Covid-19 impacts on GEM data gathering efforts.

The 2021 season also marked the last year of the strategy period 2017-2021 and a huge effort by all GEM PI's in collaboration with the GEM secretariat lead to the writing of a new strategy for 2022-2026 being approved by the GEM steering committee in June 2021 (link to new GEM strategy). Central to the new strategy is a structure focusing on three science themes under which cross-cutting projects will be conducted over the coming years.

GEM 25 years anniversary

Due to Covid-19, much of the celebration of GEM 25 years anniversary had been postponed to 2021. However, Covid-19 was as mentioned above still a joker in 2021 and major GEM events, such as planned VIP visits at Zackenberg with ministers from Denmark and Greenland and the Board of the Aage V Jensen Charity Foundation, was unfortunately cancelled (the latter due to bad weather though).

Despite cancellations of on-site anniversary events the 25 years was celebrated once properly at a reception during the Greenland Science Week in Nuuk, November 2021 (Photo 1). Highlights from the 25 years of observations and findings were presented followed by the social gathering which attracted 50+ people in the culture center in Nuuk, Katuaq.

Photo 1. Josephine Nymand, Greenland Institute of Natural Resources, gave the welcome speech for the GEM reception - celebrating 25 years anniversary during the Greenland Science Week in Katuaq, Nuuk, November 2021. Photo: Mie S. Winding.

Torben Røjle Christensen,
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2021

Outreach

As part of the publication of GEM annual report card 2020 – the GEM 25 years anniversary, five of the cards was used as background material for separate newspaper articles in *Sermitsiaq* over the summer. In connection with the 25 years of monitoring and the corresponding anniversary for the research station at Zackenberg there were further news media attention and the national public TV channel DR1 broadcastet three news pieces during the autumn about the monitoring at Zackenberg one of which was an in-depth 10 minute piece. Further to this, several international videos were produced about GEM and with interviews of GEM PI's in Kobbefjord (made by Swedish, Austrian and German productions).

Education

Thanks to funding from the Novo Nordisk Foundation, GEM data from the past 25 years will now be made available for high school students in Denmark and Greenland. In 2021-2023 a new educational project aim to give students a better understanding of climate change and maybe inspire them to do their own research, using data from GEM (photo 4). There is a lack of climate-relevant teaching material within the youth educations escpecially in Greenland, and the online material and 3D virtual tours of GEM main sites will be made available in Greenlandic and Danish.

Figure 1. Several outreach products was made to celebrate the 25 years anniversary of GEM: special issue of GEM Annual Report Cards 2020, news paper articles in Sermitsiaq and smaller GEM leaflets in Greenlandic, Danish and English translation.

ANNUAL REPORT

Infrastructure

In 2021 significant new infrastructure developments at the GEM main sites also took place. A multiyear project with renovation of Arctic Station continued and the same for the new accommodation building in Kobbefjord. In Daneborg a new pier was constructed. At Zackenberg the establishment of a solar panel park was initiated as well as funding for improved walkways along the main access roads to the valley was obtained (photo 2 and 3).

The Greenland Integrated Observation System (GIOS) was funded in 2021 for a six-year period under the Danish research infrastructure programme, NUFI. Part of GIOS will use GEM observations at Zackenberg and Daneborg as back-bone for spatial extension of comparable measurements along a gradient down the east coast of Greenland. The tool is autonomously measuring containers capable of remotely controlled transfer of data. The first test containers were in 2021 placed close to GEM operations in Zackenberg valley and at Daneborg for calibration and test purposes.

Photo 2. Kobbefjord Station got a new kitchen and new furniture in 2021. Photo: Henrik Phillipsen.

Photo 3. Modernisation of Arctic station includes establishment of new laboratories and new storage building and renovation and remodeling of main building. Foto: Charlotte Sigsgaard.

2021

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International collaboration

In the Arctic Council context GEM has provided data and senior author inputs to several assessment reports that were due out in 2021. Some have been delayed in their final release for Corona-reasons. A full CAFF report were, however, relased in 2021 and a summary for policymakers of the AMAP Climate Change Update 2021 report and the full technical report as well as a one on short-lived climate forcers are due out medio 2022 with significant GEM inputs (Figure 2).

GEM scientists are using GEM-data in new EU, UArctic and Nordic project contexts that were funded or developed during 2021. These include the EU FACE-IT project and the GreenFeedBack proposal developed and submitted in 2021 which has seen funding and will start medio 2022. GEM-data also form the basis for U-Arctic supported summer schools granted in 2021 for courses to be hosted in 2022 and 2023. The idea behind these courses is to have students do hands-on field work at an easily accessible site in sub-arctic Scandinavia and compare measurements directly with corresponding data from GEM sites in the GEM database.

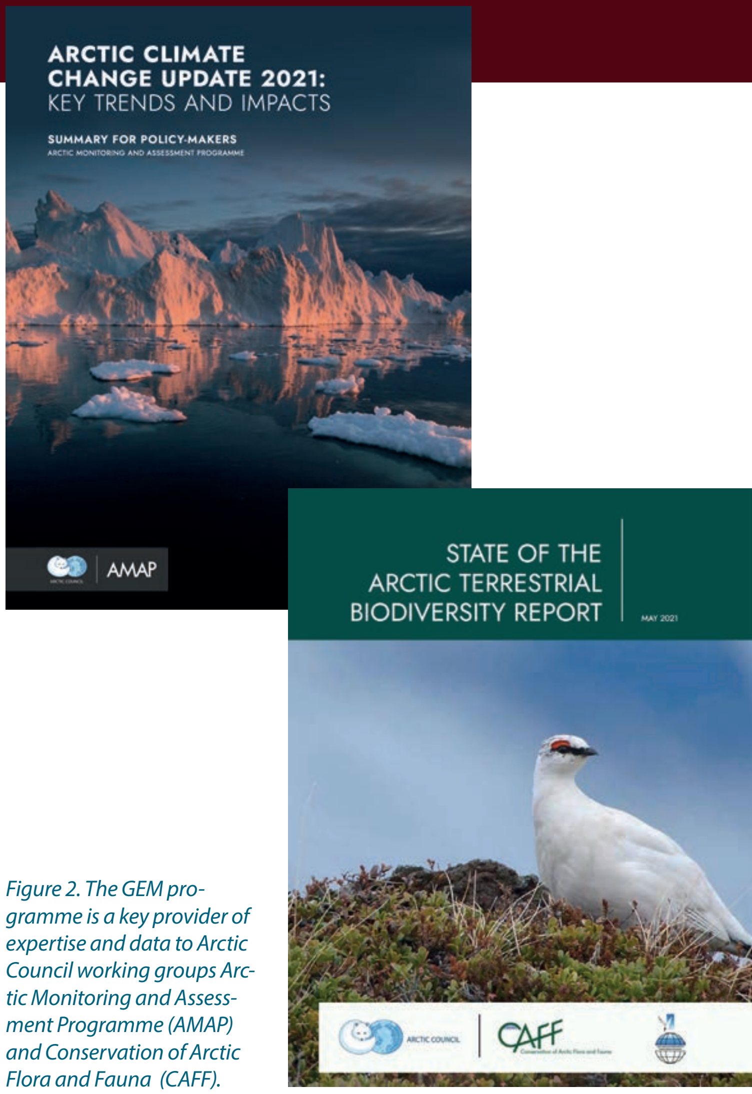
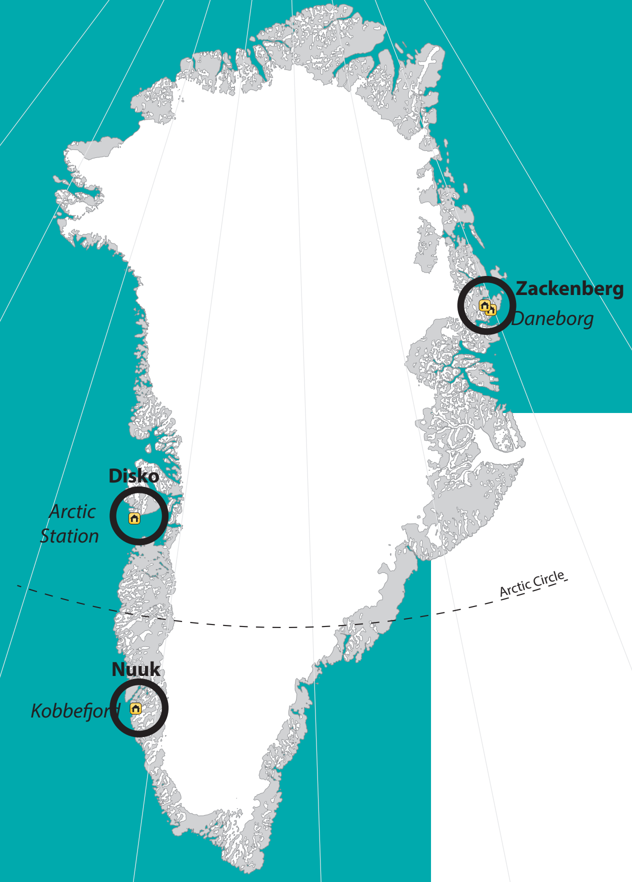


Figure 2. The GEM programme is a key provider of expertise and data to Arctic Council working groups Arctic Monitoring and Assessment Programme (AMAP) and Conservation of Arctic Flora and Fauna (CAFF).

GEM database

The GEM database and the timeseries data collection continue to grow and find use in research and education at a steady pace. In 2021 users performed more than 1000 downloads of datasets. With the arrival of new remote sensing products and drone imagery there is increasing storage needs – this works continue with integrating and sharing these types of big data in the years to come.

Photo 4. A new educational project, funded by Novo Nordisk Fonden, aims to give high school students in Denmark and Greenland access to up-to-date teaching material with the latest data from GEM. The online material will include videos of field work and measurements and interviews of GEM researchers. Interview with Niels M. Schmidt from Aarhus University in Zackenberg. Photo: Torben R. Christensen.



Annual Report Card 2021

STRENGTHENING

Monitoring of the carbon balance includes measurements of CO_2 exchange between the tundra and the atmosphere. GeoBasis are responsible for these flux measurements and uses the eddy covariance technique. This technique builds on measurements of the turbulent exchange in the boundary layer between the surface and the lower part of the atmosphere. This is an important task in GeoBasis and provides some data that many users are interested in. Such measurements are made all across the World, but experiences have shown, that even if the techniques are similar small differences in instrumentation, setup or processing of the data, may turn out to be important for the measured flux.

Integrated Carbon Observation System, ICOS, is a European-wide greenhouse gas research infrastructure, which has the mission to provide international researchers with the best standard of flux measurements. Since this is also one of the ambitions for the GeoBasis programme, it was decided to try to get the three main flux stations in Nuuk, Disko and Zackenberg certified under the ICOS protocol, with the two latter once representing the northernmost edge in the ICOS network. This would give visibility to both data and GEM programme and allow easy access to flux data from the three sites through the ICOS Carbon Portal. After a couple of years, with financial backup from the Danish research infrastructure program and in collaboration with ICOS, both Kobbefjord Fen site (Nuuk) and Disko are now certified ICOS associated ecosystem stations. This means that the fluxes are processed in an identical way with same flux instrumentation, and data are now also available through the ICOS database as well as in the GEM database. The Fen site in Zackenberg is next up and will be certified under the "class 2" label, which is even more strict with respect to instrumentation, setup and data quality.

The combination of strict measurement protocol and the difficult logistics at the three Greenlandic sites has been a challenge for the certification process, especially in Zackenberg. But putting

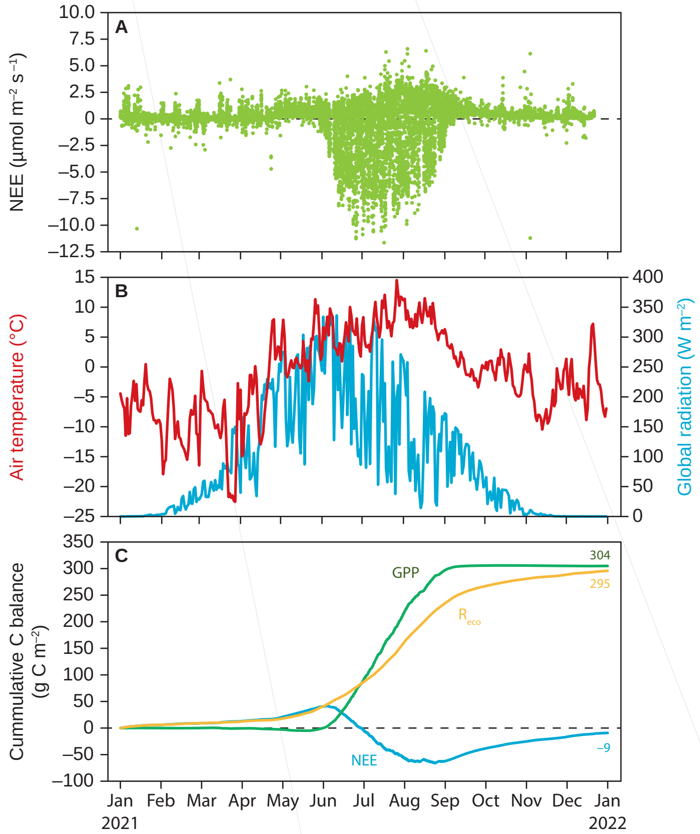


Figure 1. First joint GEM/ICOS data from the station in Østerlien, Disko 2021. A) Net ecosystem exchange of CO_2, B) Air temperature (red - left axis) and Global radiation (blue - right axis), C) accumulated values of net CO_2 exchange (blue), Gross primary productivity (green) and ecosystem respiration (yellow).

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[3]Aarhus University, Department of Ecoscience

GEM sub programme

GeoBasis

Data source:

GeoBasis Disko-> Flux Monitoring -> Gas Flux.

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

https://doi.org/10.17897/0D1B-2F33

Greenland Ecosystem Monitoring

THE FLUX MEASUREMENTS

Greenland on the ICOS map has also been important for the European infrastructure project, with Zackenberg being the northernmost station in the network, so far. It is the hope that both the GEM programme and ICOS can benefit from the collaboration and sharing sites in Greenland, in a way where more researchers will be able to benefit from the data in all the Basis programmes and beyond the GEM community. In addition to the three GeoBasis stations an atmospheric station at Station Nord was certified by ICOS in 2021.

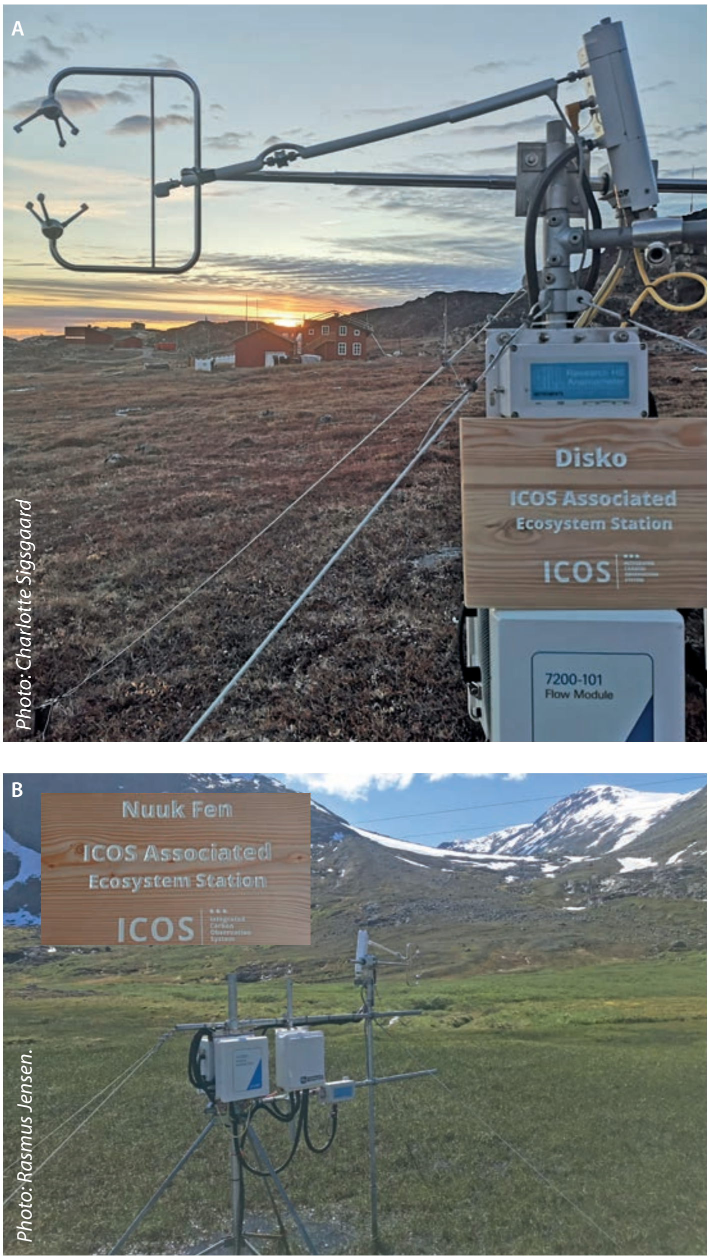


Figure 2. A) The flux station in Østerlien, Disko. B) The flux station in Kobbefjord.

The flux data from ICOS stations are to a large extend used for "ground truth" for ecosystem, land surface and climate modelling, and data from the three sites will be able to reach a larger audience, through the ICOS collaboration. The new certification under ICOS will also allow for more precise comparisons of the data between the three sites in the future.

The first flux data to appear in the ICOS database for the site in Disko is shown in Figure 1 and is a nice illustration of how the CO_2 flux may provide annual carbon budgets for the site. As shown in the lower panel the net CO_2 exchange (NEE) from the site in Østerlien, Disko was close to zero in 2021 because a photosynthetic uptake (GPP) of a bit more than 300 g C m^{-2} was nearly balanced out by the ecosystem respiration (R_{eco}) which was just marginally smaller. The CO_2 balance is a measure for the effect that the ecosystem has on the atmospheric content of this greenhouse gas, which in 2021 turned out to be a very small uptake 9 g Cm^{-2}. This balance may very well vary from year to year and the dynamics over the year does reveal a lot of information about the climatic parameters controlling the opposite directed processes.

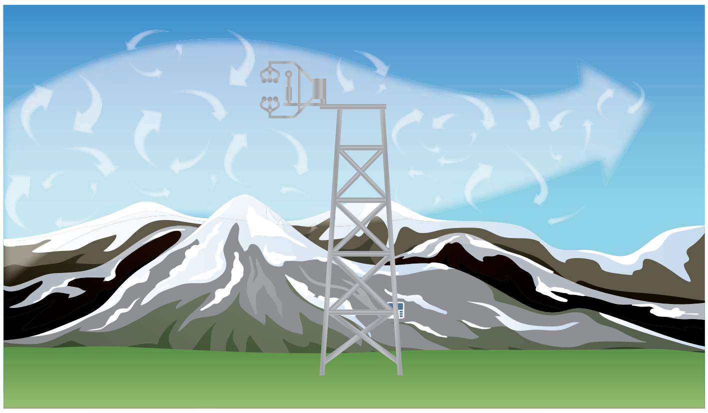
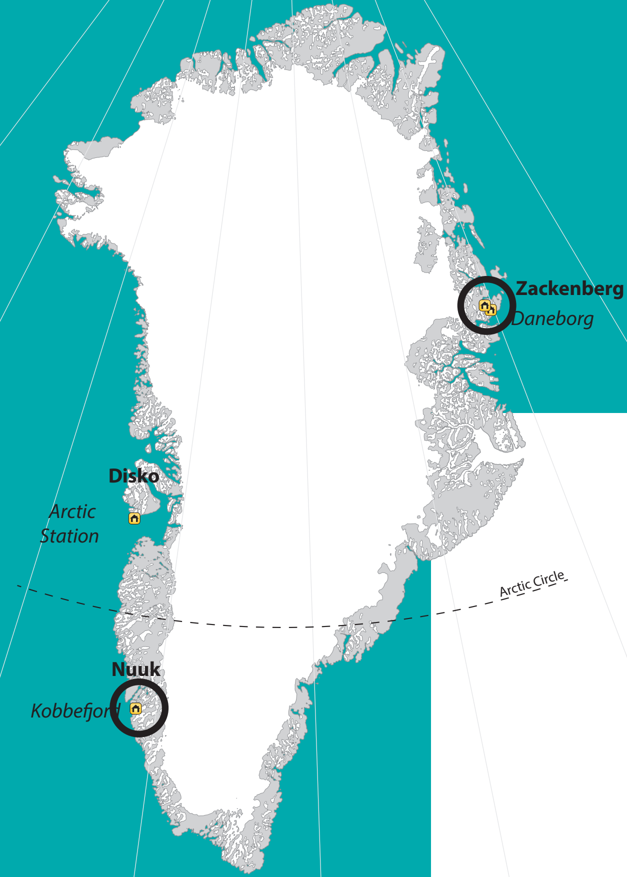


Figure 3. The eddy covariance technique is a key atmospheric measurement technique to measure and calculate vertical turbulent fluxes within atmospheric boundary layers.

For a monitoring programme, the quality and comparability of the measured data is essential, because the users may not have visited the site and are not experts in the measurement, they have to rely on data to be good and representative.



Annual Report Card 2021

HOW MUCH WATER

The snow water equivalent (SWE) is a particularly important quantity when it comes to determining the role of snow in the hydrological cycle. The SWE is the amount of water contained in the snowpack. Due to differences in snow density, the same snow depth can lead to different SWE in the respective column. A state-of-the-art model that aims at determining SWE from snow depth has been applied to Zackenberg and Kobbefjord and validated using unique manual snow monitoring data.

Recent modelling advancements (Winkler et al., 2021) allow for a simple method to estimate SWE using snow depth as the only input. Despite its simplicity when it comes to input, it resolves several complex processes, such as compaction or vertical mass distribution of melted snow considering multiple layers. The measured snow depth data from the Zackenberg and Kobbefjord ClimateBasis stations has been used as input to model daily SWE at the two sites. At both sites field-based snow surveys are undertaken every year, where detailed information on snow distribution as well as snow depths, density and physical characteristics are recorded. This data allows for a validation of the modelling approach.

Figure 1 shows the time series of modelled SWE and the annual measurements (left) as well as a scatter of measured vs. modelled SWE (right) in Kobbefjord. The Pearson Correlation Coefficient is 0.86 for uncorrected and 0.95 when the values were corrected depending on the measured snow depth in the snow pit compared to the climate station, which confirms an excellent model performance.

We applied a similar approach for Zackenberg (Figure 2), where validation data goes back further in time and there are several validation measurements per year. The uncorrected data shows a somewhat larger deviation, however, with the correction

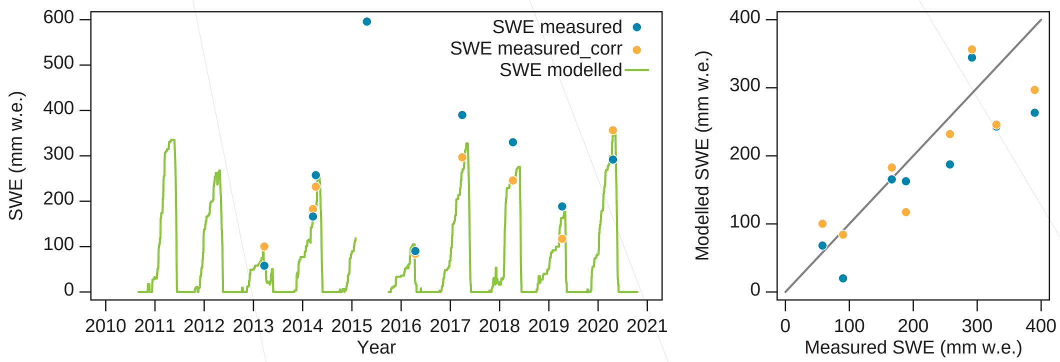


Figure 1. Measured and modelled SWE at Kobbefjord. Left: Time series with the respective measurements and a depth correction depending on the difference in snow depth at automatic weather stations (AWS) and at the nearest snow pit. Right: scatter: measured vs. modelled for uncorrected and corrected values. Note, that there were two snow surveys in 2014 and that modelling was not possible in 2015 as there was a data gap that did not allow physical continuity.

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GEM sub programme:

ClimateBasis and GeoBasis

Data source:

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

Zackenberg ClimateBasis – Precipitation – Snow Depth
Nuuk ClimateBasis – Precipitation – Snow Depth
Zackenberg GeoBasis – Snow Properties – Snow Density
Nuuk ClimateBasis – DensityTemperature_SnowPit

The project is supported by NIS, Greenland Research Council

IS HIDDEN IN THE SNOW?

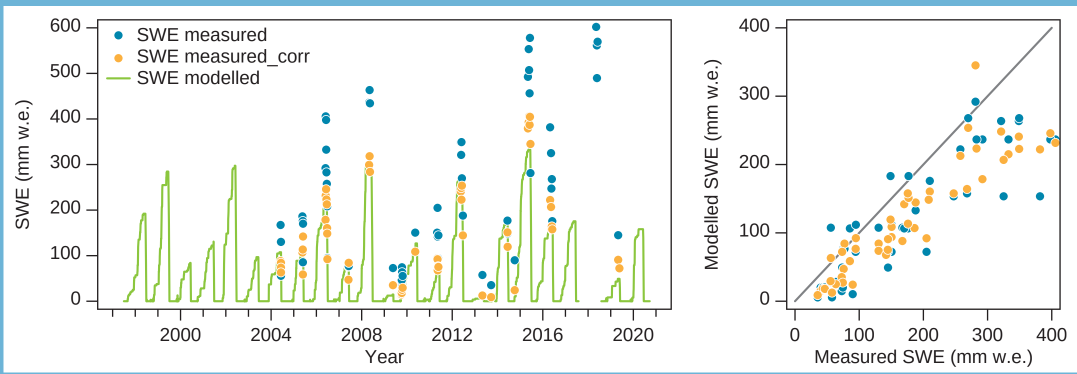

Figure 2. Measured and modelled SWE at Zackenberg. Left: Time series with the respective measurements and a depth correction depending on the difference in snow depth at AWS and at the nearest snowpit. Right: scatter: measured vs. modelled for uncorrected and corrected values.

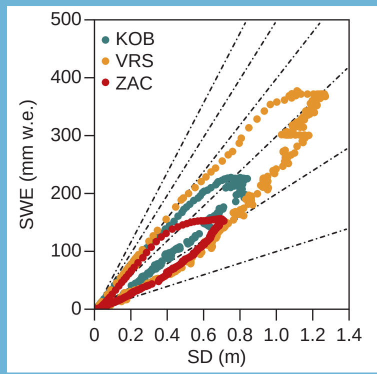

Figure 3. Mean annual snow depth vs. mean annual SWE for KOB, ZAC and VRS.

depending on the snow depth measured at the ClimateBasis automatic weather stations (AWS) we also reach a Pearson correlation coefficient of 0.96. In general, SWE seems to be underestimated by the model.

The combined measurement and modelling approach allows for investigating the relation between snow depth and SWE (Figure 3) as reported in other studies (e.g., Gugerli et al. 2019). The way to read Figure 3 is that each snow depth recorded has two respective SWE values (one during the build-up of the snow cover, one during the melting). Naturally, snow-metamorphosis and compaction lead to the respective higher values during the falling limb of such a curve. Figure 3 shows this connection for Kobbefjord (KOB) and Zackenberg (ZAC) as well as for the North-Eastern Villum Research station (VRS) with lines of constant density shown in grey from 100 to 600 kg/m^3. The dots should be understood to be temporally connected counter-clockwise. During snowpack increase, it is evident, that KOB shows higher densities than ZAC and VRS that are exposed to a drier and more polar climate. Whereas VRS and ZAC show typical mean densities of 150-200 kg/m^3 during this phase, KOB's values are rather closer to 250 kg/m^3. During the falling limb phase of the snowpack differences between the high polar snowpack and the lower Arctic are less, indicating densities of between 350 and 400 kg/m^3. In the future, it is relevant to explore, how stable this relation is, since it would be valuable information to relate snow depth with SWE for hydrological purposes.

Photo: Kirsty Langley

A simple snow model is able to adequately represent the hydrologically important quantity SWE (how much water is stored in the snowpack?). The good match between model and observation is somewhat surprising since the snowpack is build up in a very heterogeneous way in Greenland due to complex topography.

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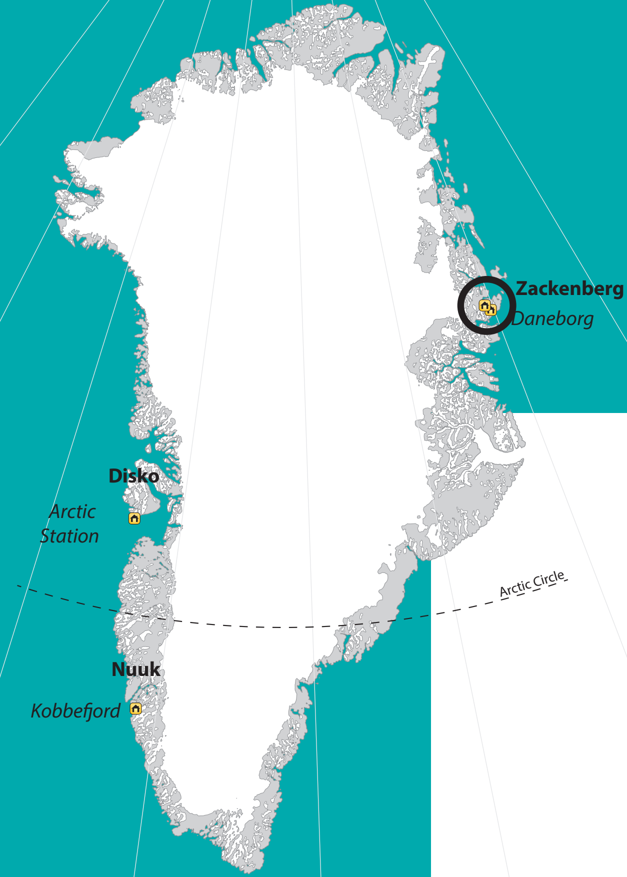

CAN SATELLITE IMAGERY COMPETE
A CASE STUDY OF SNOW COVER

Terrestrial snow cover is an essential feature of the Arctic, controlling several ecosystem processes such as phenology, hydrology, energy exchange, carbon fluxes and permafrost. Due to its strong influence on the Arctic ecosystem, this variable and the associated feedback mechanisms are important to monitor to understand the impact of a changing climate.

The use of time-lapse cameras for snow cover monitoring in Zackenberg has been part of the GeoBasis programme since 1997. These cameras are located on the east-facing slope of Zackenberg Mountain, observing the central valley (Figure 1), capturing one image a day at noon. Throughout the years, the setup has developed in regards to both cameras and setup. Based on these images snow cover fractions throughout the season can be extracted for different zones in the valley.

Since the initial setup of the cameras was established, there has been significant development of satellite-based technologies, delivering freely available imagery for the research community. These technologies start to reach a level in spatial and temporal resolution where they might be able to compete with ground-based camera observations. One of such satellite systems is the Sentinel-2, which is a part of the Copernicus programme and consists of two identical polar-orbiting satellites. An advantage of working with this satellite data type in the Arctic is the increased number of observations due to the overlapping swaths, and as Zackenberg is located at 74 degrees north, daily observations can be obtained from the Sentinel-2 satellites.

Using multiple orbits to increase the number of observations might introduce an offset on pixel geolocation due to the different viewing angles and not perfectly orthorectified satellite images. However, since the upgrade of the Geographical Reference Image and Digital Elevation Model in 2021, these misalignments are reduced and the use of multiple orbits is now more fit for use in multi-temporal analyses. Each Sentinel-2 scene has a file size of approx. 650 MB, and in 2021 Sentinel-2 captured a total of 230 scenes of the Zackenberg valley, from mid-February to mid-October. This accumulates to a total data size of 150 GB. To process this large amount of satellite data, an automatized algorithm was written in Google Earth Engine (cloud computing). The algorithm consists of cloud filtering, snow classifi-

Figure 1. Image of the automatic camera setup observing the Zackenberg valley.

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GEM sub programme

GeoBasis Zackenberg

Data source:

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

WITH GROUND-BASED CAMERA OBSERVATIONS?

IN ZACKENBERG 2021

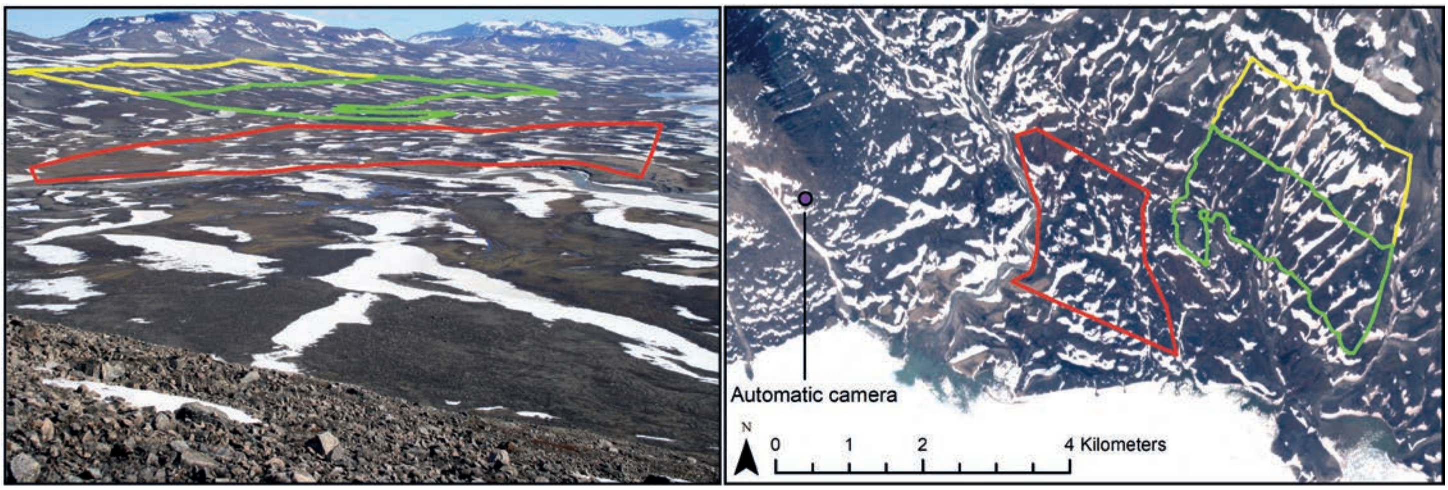


Figure 2. A side-by-side visualization of an image taken by one of the automatic cameras (left) and part of a Sentinel-2 scene (right). Both observations are from 16 July 2021. Each image contains the three areas where the snow cover fractions are derived from: Central area of the Zackenberg valley (red zone), lower part of the Aucella slope (green zone) and middle part of the Aucella slope (yellow zone).

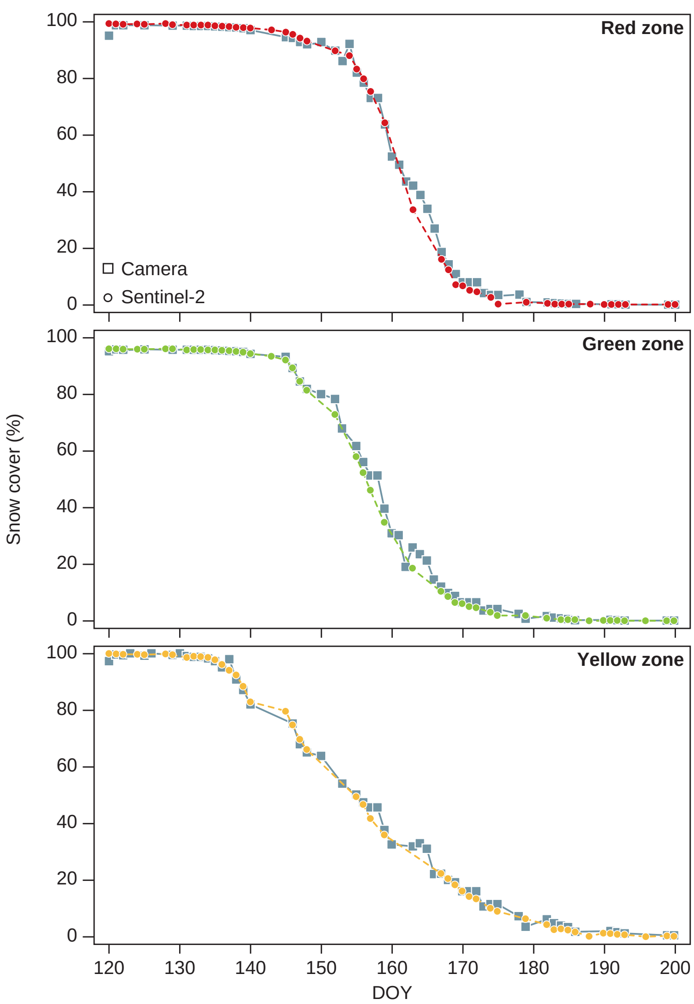


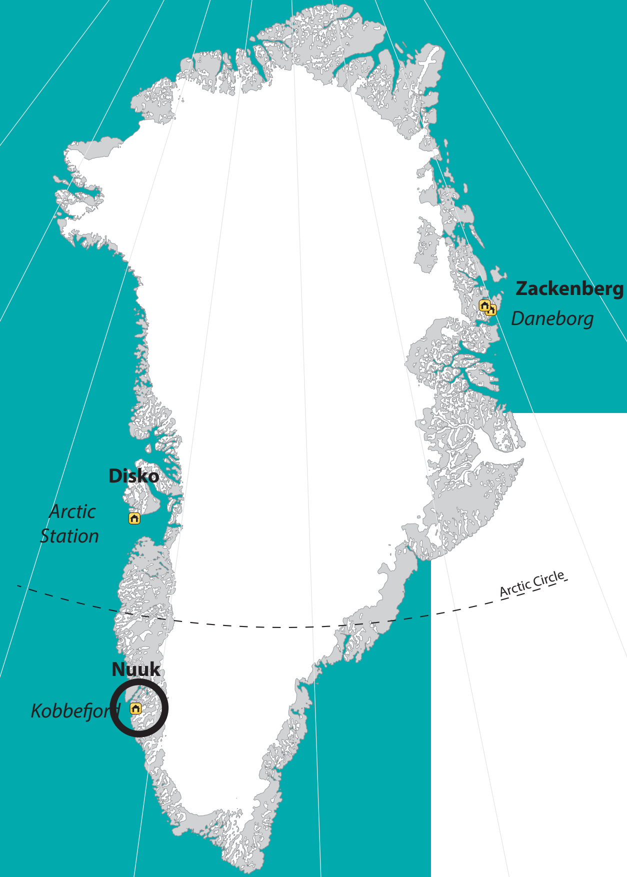
Figure 3. Comparison of the two observation methods, automatic ground-based camera and Sentinel-2, for producing snow cover fractions in 2021.

cation, and a statistical output, and it is capable of processing the data in a few minutes. Images taken from the two observation systems and the areas of interest can be seen in Figure 2.

Comparing the two methods of deriving snow cover fractions (Figure 3) shows a significant agreement with a root mean squared error (RMSE) of 3.9 (red zone), 3.7 (green zone), and 1.7 (yellow zone) when only considering same-day observations and snowmelt period (Snow cover between 5 and 95 %). This demonstrates that the use of Sentinel-2 for snow cover monitoring in Zackenberg is a valid method, which is in line with ground observations from cameras. A drawback of satellite-based observations is the risk of cloud contamination for consecutive days during snowmelt, thereby creating gaps in the time series. However, a clear advantage of using Sentinel-2 is that it measures other parts of the light spectrum, e.g. near-infrared, red-edge, and short-wave infrared radiation. Besides being an advantage for the precision with which one can distinguish snow from other bright objects on the ground, it also allows for improved analyses of core GEM activities such as vegetation productivity and type.

Changing the area of interest to lower latitudes, such as Kobbefjord or Disko, would decrease the temporal resolution down to 4-6 observations a week. This increases the chance of gaps in the time series due to cloud contamination. Nevertheless, the use of Sentinel-2 allows for expansion beyond the valley and the limited view of land-based cameras.

GEM is continuously adapting its monitoring efforts to exploit advances in data sources and sensor technologies. Snow monitoring can be improved and streamlined using newer satellite sources.



Annual Report Card 2021

MAPPING BARE ICE

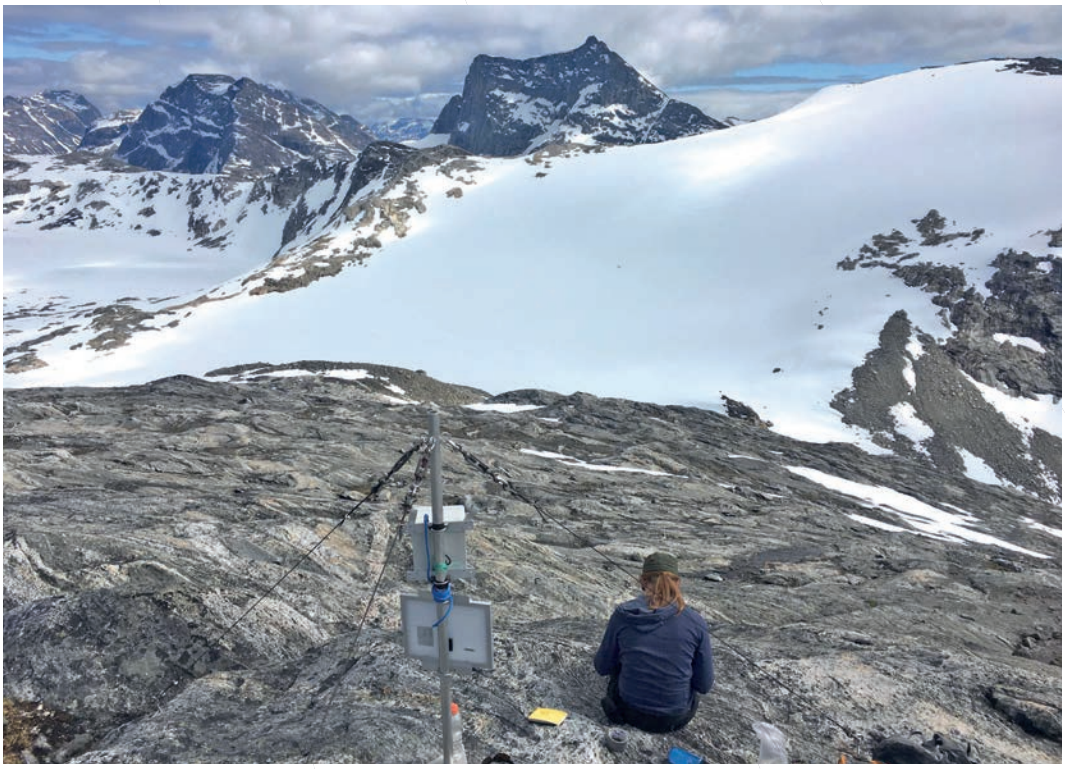
Greenland's peripheral glaciers cover ~5 % of Greenland's area, yet account for 13 % of the global glacier mass loss and contribute significantly to sea-level rise. Currently only five glaciers are monitored in Greenland, three of these under the GEM umbrella. We are investigating ways to make our monitoring strategy more robust and to give a broader spatial and temporal understanding of snow and ice melt.

Only 5 of the peripheral glaciers in Grrenland are currently monitored, three of which are within the GEM GlacioBasis programme. In addition to the traditional glaciological mass balance approach to monitoring surface mass balance, we are investigating a number of alternative approaches to help give a broader spatial and temporal understanding of the melt processes, and to make our monitoring programme more robust. Here, we use images from an automated time lapse camera to map the appearance of bare ice on the glacier during the melt season and thus follow the snow line retreat up-glacier during the summer melt season (Figure 1).

The snowline is typically defined as the boundary between fresh snow or firn and bare glacier ice at the end of the melt season, or the boundary between the wet-snow and superimposed-ice zones (Colgan 2011, Racovitneau 2016). End-of-season snowline altitude of a glacier can be considered to approximately represent the Equilibrium Line Altitude (ELA), the altitude at which annual glacier mass balance is zero (Cuffey 2010). As such, it is a useful proxy on glaciers with no monitoring programme.

As can be seen from Figure 2, the snowline is rarely a line, but rather snow melts out in patches depending on topography, wind redistribution and shadows. Because of this we refer to bare ice area instead of snowline. The snow and ice areas have been classified using manual and automated approaches, using the open source photo-

Figure 1. Automatic time lapse camera overlooking the Qasigiannguit glacier. Photo: Kirsty Langley.



Authors:

Kirsty Langley[1], Alexandra Messerli[1], Jennifer Arthur[1,3], Penelope How[2] & Jakob Abermann[4]

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GEM sub programme:

GlacioBasis Nuuk

Data source:

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

EVOLUTION ON GLACIERS

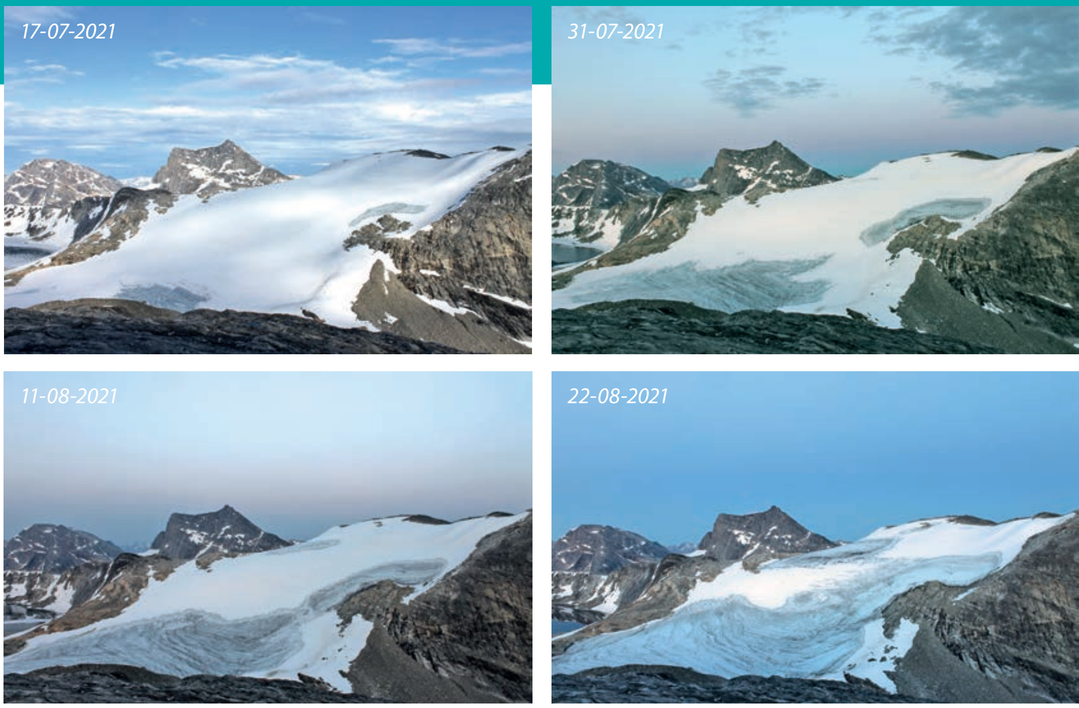

Figure 2. Time-lapse camera images of Qasigiannguit showing evolution of bare ice (snow-free) areas through the 2021 melt season.

grammetry toolbox called PyTrx (How et al. 2017; 2020). The camera takes 4 images per day, and despite not being able to see the glacier on some days due to snowfall, clouds or fog, the results look promising. Figure 3 shows how the fraction of snow covered and bare ice areas developed during the summer of 2021. The estimated fraction of bare ice at the end of the summer 2020 and 2021 was 76 % and 59 % respectively. The final data point for 2021 is currently 26th August, the remaining data for the year will be collected during the next visit to the station in spring 2022. The upper elevation of the mapped bare ice area coincides with the mass balance stake derived ELA, and the net mass balance for the two years, also showed more melting in 2020 than in 2021.

The time series of the bare ice evolution is a useful validation tool for glacier modelling, and for linking melt to atmospheric conditions. As an extension of this work, similar methods are being applied to Sentinel-2 satellite imagery in order to be able to extend the analysis to un-monitored local glaciers, thus extending our knowledge of the temporal and spatial patterns of melt.

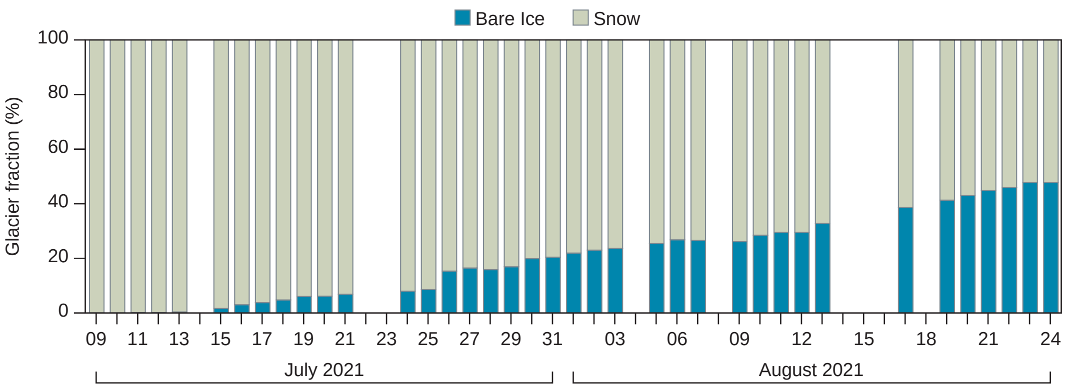

Figure 3. Evolution of snow covered and bare ice fraction over the melt season in 2021 derived from the time lapse imagery.

With so few of Greenland's peripheral glaciers being monitored, the datasets obtained from the GEM sites are key to understanding what is happening to these icey bodies in a changing climate.

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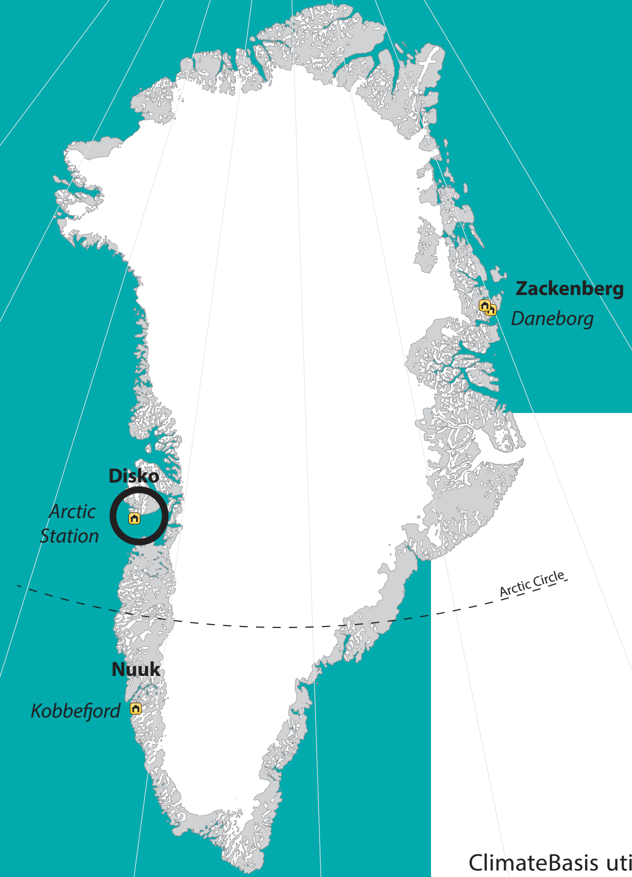

CLOUD OBSERVATIONS

Clouds bring precipitation, block direct sunlight and radiate heat. Thereby, their presence or absence affects terrestrial and marine ecosystems, surface temperatures, the mass balance of glaciers and river runoff. The frequency and type of clouds in the Arctic is impacted by global climate and environmental changes which bring higher atmospheric temperatures, a loss of sea ice, changing atmospheric circulation patterns and moisture transport pathways, and an increase in atmospheric aerosol loadings. ClimateBasis and the programme in Remote Sensing are developing a time series of fractional cloud cover at GEM sites from ground-based cameras and satellite imagery.

ClimateBasis utilizes high-quality meteorological instruments to provide reliable general climate data. But it also tests and improves innovative low-cost technologies to address specific scientific questions. One such application is the monitoring of cloud cover by means of hemispherical cameras. The presence of clouds depends on the distribution and transport of temperature and moisture in the atmosphere and in turn affects precipitation patterns and atmospheric heating, snow cover and sunlight at the earth's surface. Changes in cloudiness and their consequences are one of the least well understood aspects of man-made climate change (Ceppi and Nowack, 2021; https://isccp.giss.nasa.gov/role.html).

Cameras have been deployed so far at the ClimateBasis locations in Zackenberg, Disko and Qaanaaq, and a further one will be installed in Nuuk. The models used are designed for security applications and both cost-effective and robust with respect to environmental conditions. More sophisticated scientific instruments have certain advantages, such as motor-driven shading from direct sunlight and known mathematical models for the fisheye distortion of the recorded image, but are frequently not robust enough to operate in polar conditions.

At ClimateBasis, we are actively improving the algorithm we use to detect clouds on the recorded images, based on the one developed by Wacker et al. (2015). Simultaneously, the GEM subprogramme in Remote Sensing is developing a cloud cover product based on satellite images (Frey et al., 2008; Ackerman et al., 2008, 2010), which can be validated against the data from the ground-based cameras (Figure 1). The ground cameras only work in conditions of sufficient daylight, whereas the satellite product can use infrared radiances at night (and during polar

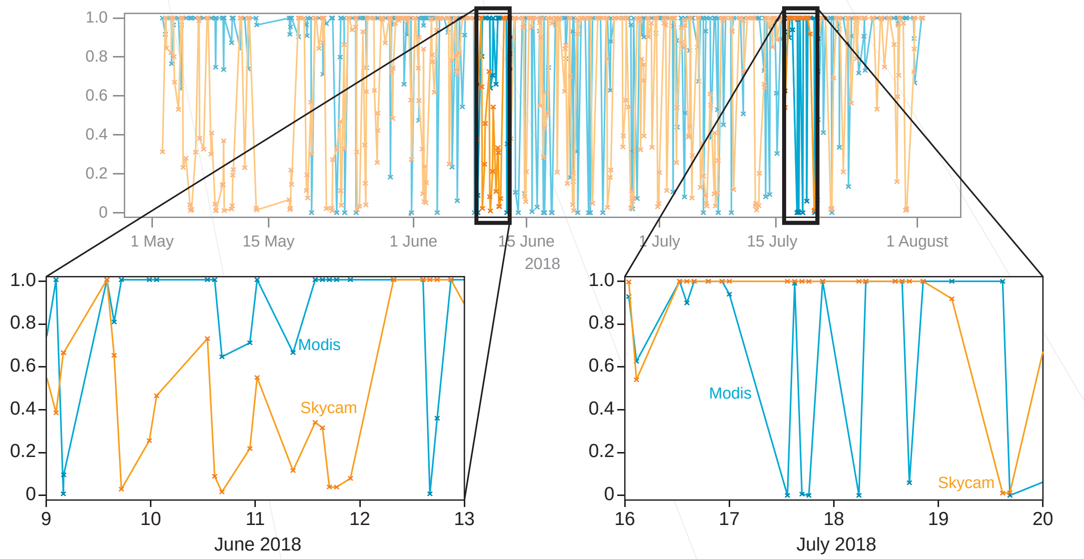

Figure 1. Time series of cloud fraction in Qeqertarsuaq during summer 2018 as detected by camera (skycam) and by satellite (MODIS). The insets show two smaller time periods from which the examples in Figure 1 have been taken. The satellite-derived cloud fraction is often erroneous compared with the ground-based camera, underscoring the latter's usefulness as a validation tool.

Authors:
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Asiaq, Greenland Survey

GEM sub programme:
ClimateBasis and Remote Sensing

Data source:
Data are currently available on request from Asiaq, since the product and its integration into the GEM database are still under development.

BY CAMERA AND SATELLITE

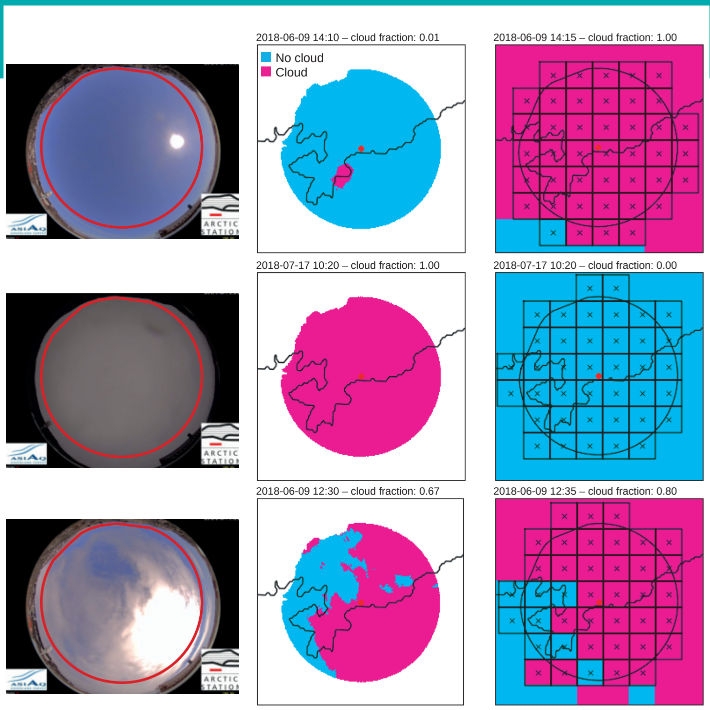

Figure 2. Three examples (rows) of cloud detection by ground-based camera in Qeqertarsuaq and by satellite. The left column shows the camera image, the middle one the cloud/no cloud classification based on the camera image, and the right one the classification based on the satellite image (MODIS). The quasi-circular cutout indicates that part of the camera image that is used, and the grid in the right column the pixel boundaries of the satellite image. The middle and right columns are maps with the coastline and the camera position (red dot) indicated. In the top two rows the camera detection classifies the sky correctly as cloud-free and completely cloudy, respectively, whereas the satellite algorithm misclassifies the scene. The bottom row shows an example of a partly cloudy sky. Note that the sun is currently still detected as "cloud" – we are working on a solution.

night). However, it is much less reliable during nighttime conditions as well, so that one extension of our current research will be the calibration of cloud-detection methods based on other ground-based instruments which also work at night (in particular pyrgeometers, which measure radiation in the long-wave part of the spectrum, and the microwave atmospheric profiler installed at Disko).

The cloud-detection algorithm for the hemispherical camera classifies each image pixel as either clear sky or cloud based on its color. Subsequently, there are several steps in the process of comparing ground-based to satellite-derived estimates of cloud cover. First, an approximate model of how a point in the real world is projected onto the camera image needs to be derived. This model can then be used to map each image pixel to a geographical coordinate. The satellite product also associates geographical coordinates with pixel values, except that each pixel corresponds to a much larger area with respect to the ground than for the camera (Figure 2).

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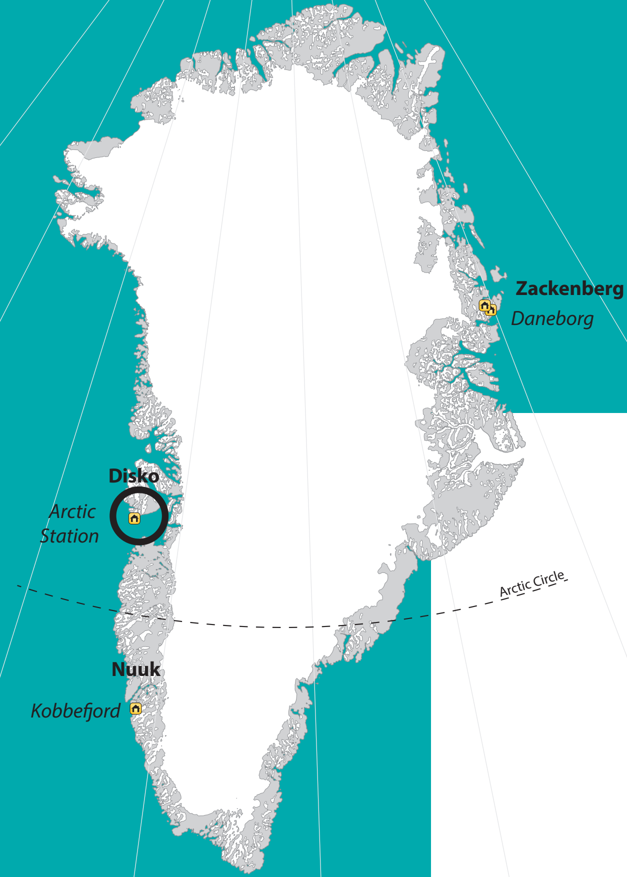
Both algorithms – one based on satellite imagery and one based on photos taken by a camera on the ground – misclassify pixels, that is, consider a pixel cloudy when it is clear in reality or vice versa. Our goal is to improve the camera-based algorithm such as to minimize the number of misclassifications, to then be able to give an estimate of the reliability of the satellite-based cloud-cover product. Reliable knowledge of cloud conditions is a useful input into many GEM research activities: Ecosystem dynamics are affected by changing radiation conditions, precipitation and the temperature modulation caused by clouds (Wilson and Jetz, 2016); glacier mass balance depends equally on the way clouds affect the energy received at the glacier surface (Conway et al., 2022); and remote sensing applications are greatly affected by whether a pixel contains clouds or not.

Figure 3. The hemispherical camera mounted near Arctic Station, Qeqertarsuaq.

Clouds are tightly related to many physical and biological processes monitored by GEM activities; information on cloudiness is highly relevant both for process studies and for the validation and quality control of other monitoring products.

HARMFUL ALGAE



The GEM Marine monitoring programme allows year-round seasonal studies of biodiversity. Several toxin-producing phytoplankton species and their corresponding toxins have been found in the Arctic in single samples or transect studies, but how much their development is seasonally affected in Arctic environments is unknown.

An almost complete yearly study on toxic phytoplankton species and their toxins in Disko Bay revealed the presence of minimum 11 potentially toxic taxa based on eDNA metabarcoding (Bruhn et al. 2021). As expected, the toxic phytoplankton species were all found in the microplankton (>20 µm). The toxic dinoflagellate *Alexandrium ostenfeldii* was the most abundant dinoflagellate, peaking in July, after the spring bloom (Figure 1), representing up to 60 % of the total number of OTU (Operational Taxonomic Units) reads. This agrees with an overall occurrence of dinoflagellates after the spring bloom. The highest peak in particulate spirolide toxins (SPX) in July coincided with the peak in *Alexandrium ostenfeldii*, presently the only known source of SPX. In the water column, the peak in SPX was found later in the year, in Oct-Nov, suggesting that the toxins are primarily kept intracellular, and subsequently released into the water when the cells are dying.

The most prominent toxic diatom genus, *Pseudo-nitzschia*, peaked in May, during the late spring bloom (Figure 2). This coincided with presence of the neurotoxin, domoic acid (DA) in the particulate fraction. The toxin had one of the highest concentrations of all algal toxins found in the study. A combination of limitation of silicate and phosphate and relatively high levels of ammonium as well as presence of herbivorous copepods at the same time most likely explains the high levels of domoic acid, as all these factors are known to enhance production of toxins in *Pseudo-nitzschia* species (Lundholm et al. 2018).

Several other algal toxins were recorded, e.g. paralytic shellfish toxins (PTX), okadaic acid (OA) and Yessotoxins (YTX), which could not directly be linked to the occurrence toxic plankton organisms. Potential causative taxa were recorded, but without agreement in time between species and toxins. One explanation

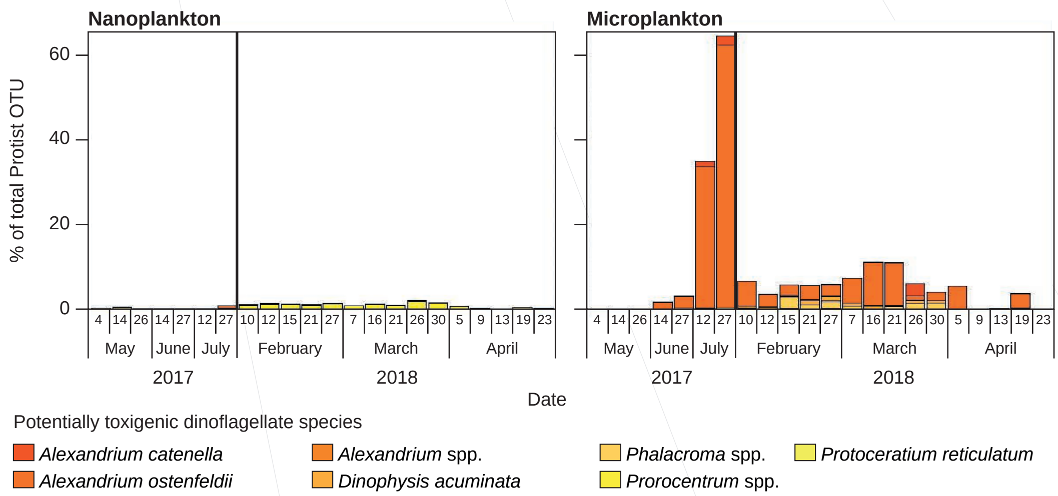


Figure 1. Relative abundance of toxic dinoflagellate taxa in Disko Bay from May 2017 to April 2018.

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[3]Alfred Wegener Institute, Germany

GEM sub programme

MarinBasis Disko

Data source:

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

IN THE ARCTIC

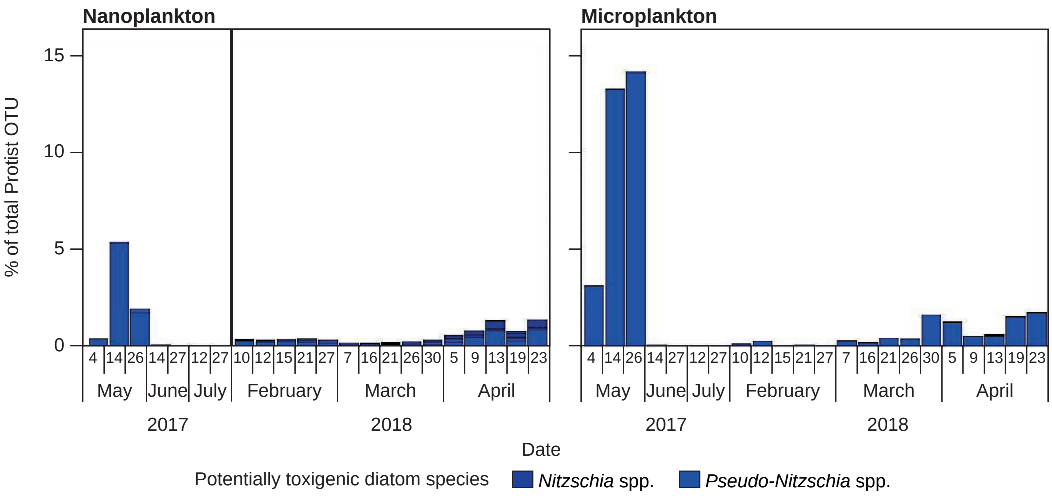

Figure 2. Relative abundance of toxic diatom taxa in Disko Bay from May 2017 to April 2018.

could be that the organisms were present at the time of the toxins, but not detected in the samples, because they e.g. occur in thin layers in the water column. Organisms producing these toxins found in Disko Bay comprise *Dinophysis acuminata* (OA, DTX, PTX), *Dinophysis* spp. (OA, DTX, PTX), *Gonyaulax spinifera* (YTX), *Prorocentrum* spp. (OA) and *Protoceratium reticulatum* (YTX), but no temporal agreement between organisms and presence of toxins were found. Another explanation could be that the causative organisms not yet have been identified as being toxic. Furthermore, three types of gymnodimines (GYM) toxins were found in the water column during January-March. The organism producing the toxins were not identified possibly because the winter period was not studied, or the producing organisms may be unknown. Gymnodimines are produced by *Karenia selliformis*, which was not found in our metabarcoding analyses, and *A. ostenfeldii*, which was only found in summer.

The monitoring revealed presence of several toxic phytoplankton species and algal toxins, and indicated the presence of yet unknown toxic species. The observed seasonal dynamics of toxic phytoplankton and their toxins are the first in Arctic waters, and may serve as baseline for evaluating the Harmful Algal Bloom (HAB) potential in Greenland. The strong seasonality of the Arctic environment was found reflected in the presence of the different toxic species, and similarly, but slightly delayed, in the presence of their respective toxins.

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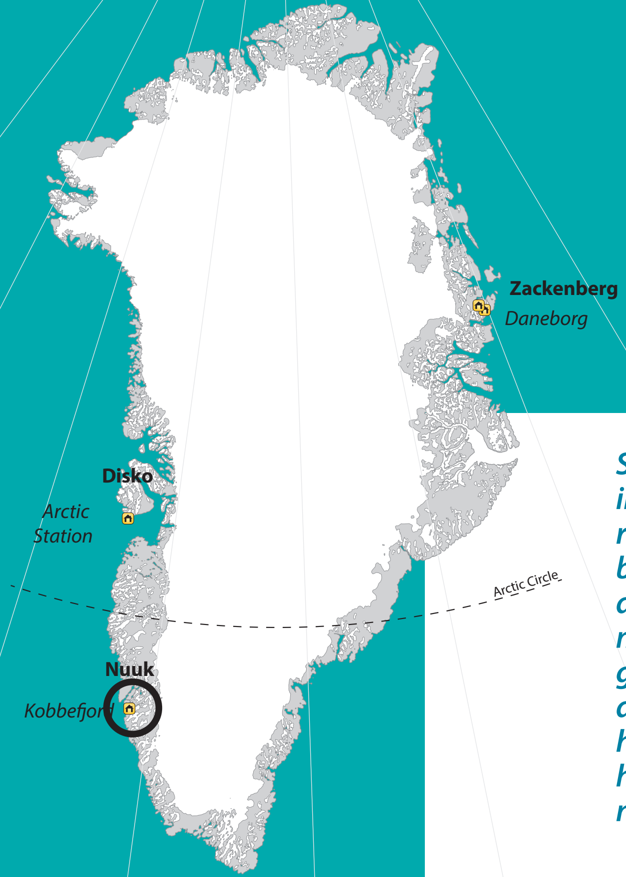
Photo: Paolo Verzone.

Toxin-producing phytoplankton species and their corresponding toxins have been found in the Disko Bay. The toxins levels were relatively low in the present study, but as toxic phytoplankton are known to vary considerably in abundance from year to year, long-time studies are needed to assess their potential for affecting organisms at the top of the food web.



A PERIOD OF FRESH AND PHYTOPLANKTON REGIME

Since the beginning of the MarineBasis Nuuk monitoring programme in 2005 the hydrographic conditions in Nuup Kangerlua have remained remarkably stable, compared to the global warming trend. However, between 2010 and 2012 the fjord was warmer and substantially less saline due to freshwater inputs. We suspected that these warm and fresh years may have triggered a regime shift in the plankton ecosystem. At a first glance, the productivity and biomass of phytoplankton, alongside the dominant phytoplankton taxa appeared unchanged. However, about half of the rarer phytoplankton genera disappeared, which may still have key ecosystem functions. At the same time, nitrate, the key limiting nutrient, was significantly reduced throughout the following years.

The MarineBasis Nuuk monitoring programme has been running for more than 15 years with a monthly resolution in the data produced. This timeframe allows us to investigate the time series beyond interannual and seasonal variations, but also to look at long-term trends and regime shifts. With a globally warming climate and increased melting of the Greenland ice sheet, we might expect a warming and freshening sea surface in the fjord system. At the same time non-linear changes, such as regime shifts can be expected. Thereby a gradual change or a period with extreme conditions may trigger a change in ecosystem diversity and/or function.

Trend analyses of pelagic data over the 15-year time series detected only weak or non-significant gradual changes in surface temperature salinity (publication in preparation, by Vonnahme et al.). However, between 2010 and 2012 the salinity was lower than in in any other year, driven by high volumes of freshwater in the summer surface layer (Figure 1B). Simultaneously, summer sea surface temperatures were higher than usual (Figure 1C). Earlier studies discuss winter flooding of the fjord with unusually high amounts of subpolar mode water as main reason for the high temperatures and large glacial freshwater inputs (Mortensen et al., 2018).

In the absence of strong trends, these anomalous years may have triggered a regime shift in the plankton ecosystem and ca. 48 % of the rare phytoplankton genera disappeared (Figure 1A). In contrast, the phytoplankton primary production and biomass

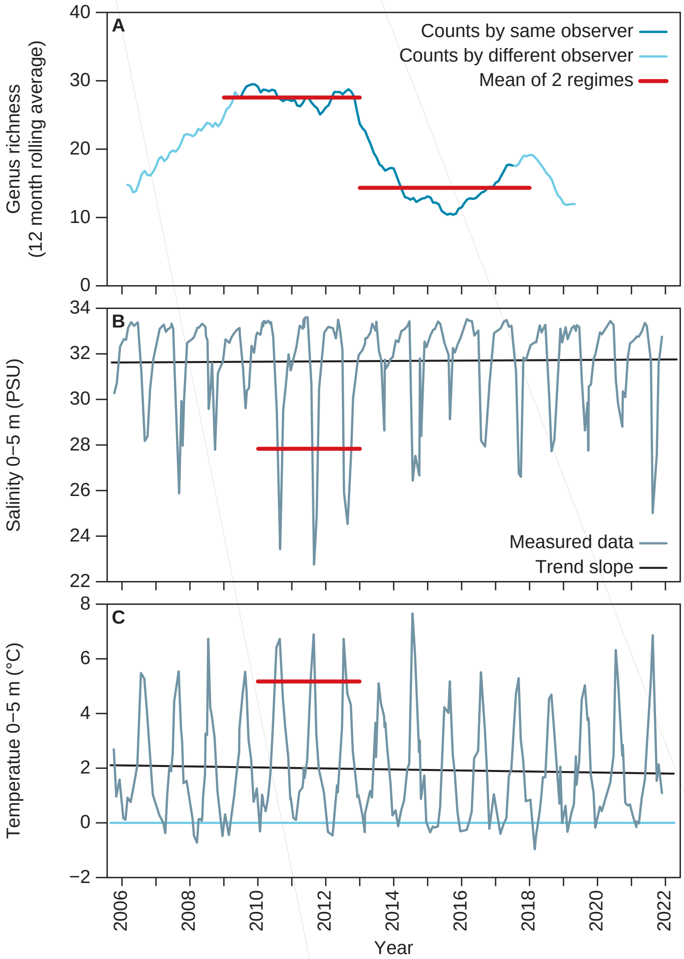


Figure 1. A) number of different phytoplankton genera (genera richness) since 2006. B) Surface (upper 5 m) sea temperature since 2005. C) Surface (upper 5 m) salinity since 2005. Red lines mark different regimes (A) or events (B,C) discussed in the text. Black lines show trends over the time series.

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GEM sub programme:

MarinBasis Nuuk

Data source:

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

https://doi.org/10.17897/KMEK-TK21
https://doi.org/10.17897/3NQX-FA50
https://doi.org/10.17897/TQQV-VJ76
https://doi.org/10.17897/Y3A4-9D86
https://doi.org/10.17897/1QK2-6B74

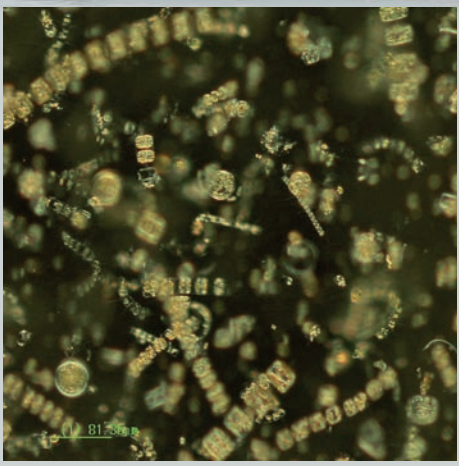
GEM

Greenland Ecosystem Monitoring

WARM SURFACE WATERS LIKELY TRIGGERED A **SHIFT IN NUUP KANGERLUA**

Water sampling in Nuup Kangerlua (Godthåbsfjord) as part of the MarineBasis-Nuuk programme. Photo: Thomas Juul-Pedersen.

Increasing temperatures at high latitudes may lead to a loss of plankton species richness. MarinBasis Nuuk shows a regime shift in the plankton ecosystem where ca. 48% of the rare phytoplankton genera disappeared after a warming period in the fjord in 2012-2013. Continuous monitoring will reveal if this new regime if stable, or if the lost taxa can be reintroduced.



Phytoplankton community showing colonies of centric diatoms in a water sample. View from an inverted microscope; scale is given in the bottom left corner. Microscope photo: Diana Krawczyk

Colony of an ice-associated, pennate diatom in a water sample. View from an inverted microscope. Microscope photo: Diana Krawczyk

(i.e. Chlorophyll a) did not change. Also, the phytoplankton community appeared unchanged regarding the most abundant taxa. A change-point analysis revealed that this collapse of alpha diversity happened not gradual, but in stepwise function following the warm and stratified years until 2012. Identification and counting biases are a potential non-ecological explanation for shifts in species composition, but between 2009 and 2017 the samples were counted by the same person. Exclusion of these biases therefore validate the theory of an ecological regime shift. Earlier studies showed, in theory, that increasing temperatures at high latitudes may indeed lead to a loss of plankton species richness (Benedetti et al., 2021), but to our knowledge, this is the first time series that shows this decrease in nature. Continuous monitoring will reveal if this new regime if stable, or if the lost taxa can be reintroduced by advection from the coast, or resuspension of cysts from the sediment, if the hydrographic conditions remain stable.

Besides genus richness, also nitrate concentrations decreased in a stepwise function (publication in preparation). Nitrate drawdown in summer is consistently higher than before the regime shift and winter upwelling supplies only little new nitrate compared to the pre-2013 conditions. In Arctic coastal ecosystems, nitrate is typically the key limiting nutrient. Thus, it is surprising that neither phytoplankton primary production, nor biomass appear to be affected. One explanation could be that the annual productivity and biomass is determined (limited) by nutrient supply, rather than species composition, while other drivers such as grazing, and sedimentation may also contribute to keeping the system in balance.

Ongoing analyses, including zooplankton, sedimentation, and lab experiments will help to study the ecological consequences of nitrate reduction and the loss of rare taxa in greater detail. In collaboration with the EU funded project FACE-IT (EU Grant number: 869154), we will include higher temporal and spatial sampling resolution, including experiments on drivers of phytoplankton diversity. The MarineBasis Nuuk monitoring programme will show if the new regime is stable, or if the system will return to previous conditions.

References:

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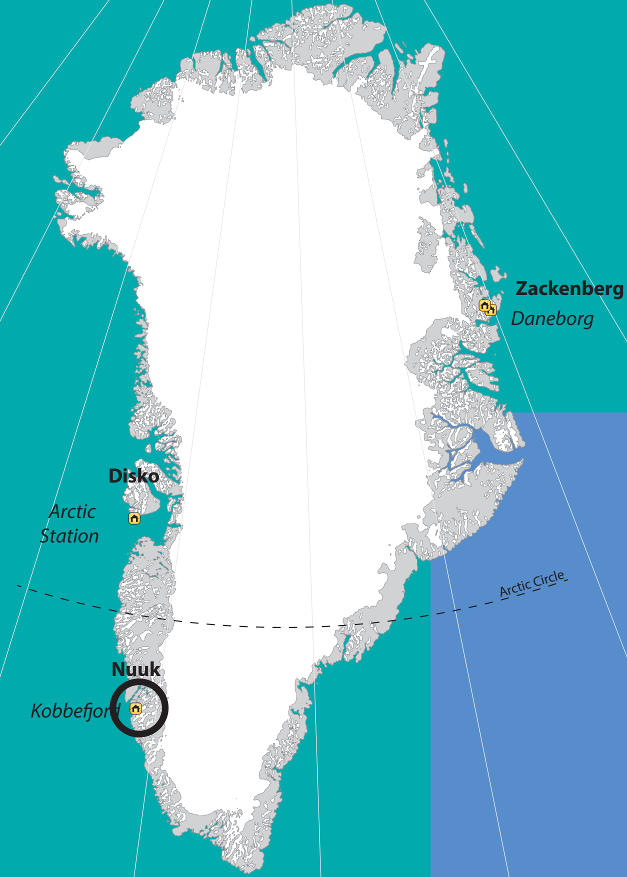

BIODIVERSITY – NEW OBSERVATIONS OF

Since the permanent vegetation transect, the NERO-line, was established in 2007 (Bay et al., 2008), the transect has been resurveyed twice. While the objective of the vegetation transect is to monitor future changes in the location of boundary lines between vegetation zones as well as changes in the species composition of the plant communities, other measures will have to be taken into use if the arrival of new species are to be detected.

Since the start-up of the monitoring programme in Kobbefjord thousands of field work hours has been conducted by the BioBasis-staff as well as other researchers. This work has led to the discovery of nine species of vascular plants new to the area of which none were discovered on the NERO-line.

New species

From the initial survey of the NERO-line and additional ground truthing, a species list for the entire Kobbefjord area of 138 taxa of vascular plants was made. Since then, 9 species have been found in Kobbefjord including *Draba nivalis* (Yellow arctic draba), *Botrychium boreale* (Boreal moonwort, Figure 1A), *Botrychium lunaria*

Authors:

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Greenland Institute of Natural Resources

GEM sub programme:

BioBasis Nuuk

Data source:

Monitoring component in Kobbefjorden, West Greenland.

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

(NOT) ON THE LINE
VASCULAR PLANTS IN KOBBEFJORD

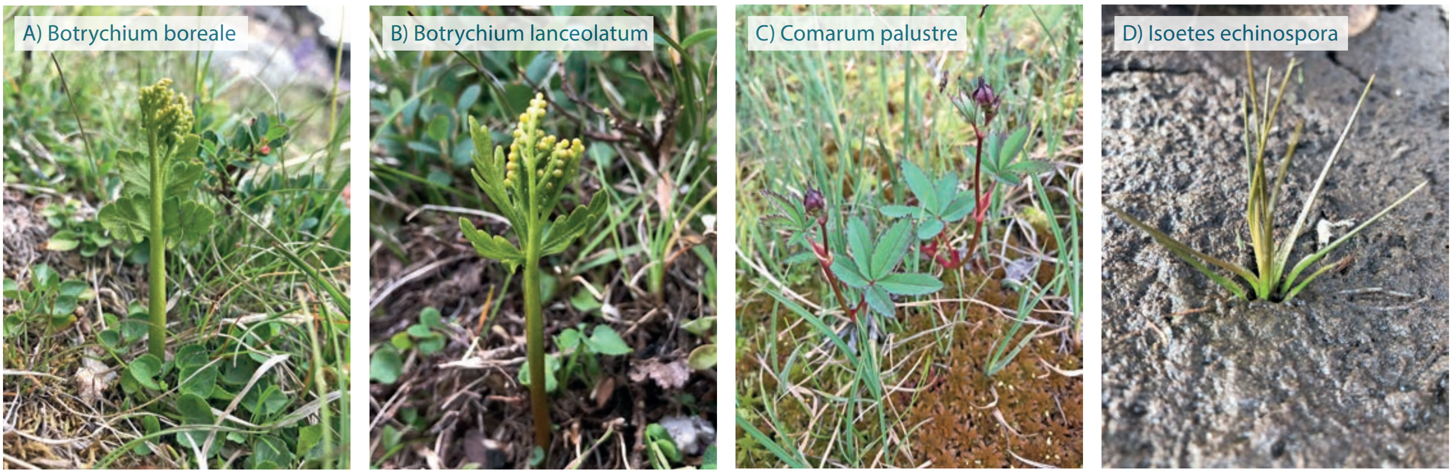

Figure 1. A) Botrychium boreale, Kobbefjord, July 4, 2019. B) Botrychium lanceolatum, Kobbefjord, July 4, 2019. C) Comarum palustre, Kobbefjord, August 11, 2020. D) Isoetes echinospora, Kobbefjord, July 3, 2019. Photos: Ida Bomholt Dyrholm Jacobsen.

(Common moonwort, Figure 1B), *Carex magellanica* (Boreal bog sedge), *Comarum palustre* (Marsh cinquefoil, Figure 1C), *Viola selkirkii* (Selkirk's violet), *Isoetes echinospora* (Spring quillwort, Figure 1D), *Myriophyllum alterniflorum* (Alternate-flowered water-milfoil, Lauridsen et al. 2019), and *Lupinus nootkatensis* (Nootka lupin).

Two of the new species found in Kobbefjord, *Carex magellanica* and *Myriophyllum spicatum*, are assessed on the Greenland Red List to be *Near Threatened* (NT) (Boertmann & Bay, 2018). Hence new observations of these species provide valuable information on their distribution.

The good and the bad

While it is generally considered good news to observe new species, especially new locations of red listed species, it is worth noting that these observations were not made as part of the NERO-line surveying. The NERO-line in itself does thus not provide the basis for detecting the arrival of new species. While the NERO-line will be documenting changes in species compositions and boundaries of vegetation types it has not captured the current arrivals of new species in the area.

Figure 2. Map of the monitoring area with markings of the NERO-line as well as positions of the new vascular plant species.

The presence of Nootka lupine in Greenland is considered to be troublesome and debated but have not yet reached the invasiveness as seen in e.g., Iceland. With a population present in Kobbefjord, approx. 8 km from the monitoring area, monitoring and or controlling a problematic potential invasive species might be in the future of the BioBasis programme. Aside from the nine new species that have been found since 2007, there is still potential for finding more not yet detected species. Literature and herbariums document species that may very well be found in Kobbefjord but have evaded the eyes of researchers as of yet e.g., *Galium triflorum*. While the list of observed taxa will continue to be part of the documentation for BioBasis and the NERO-line, species are also being digitally documented. Though it does not yet include all species known from Kobbefjord, most have been documented in the online platform iNaturalist (https://www.inaturalist.org/places/kobbefjord) which connects to GBIF.org.

The discovery of nine new vascular plant species found outside the permanent vegetation transect may call for adaptive monitoring to ensure that methods are adjusted to capture the arrival of other new species.

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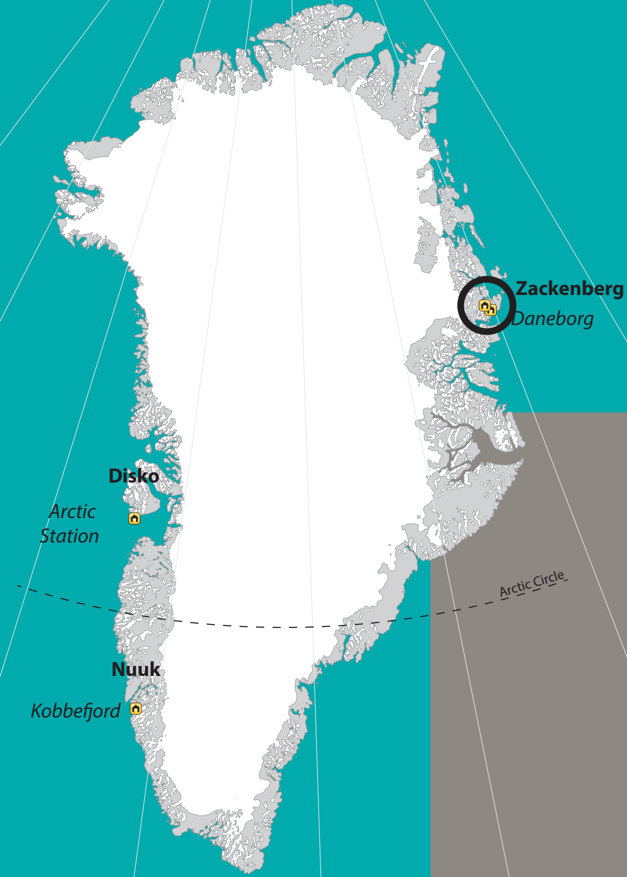

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SALIX SNOW BEDS
AN ARCTIC KEY SPECIES IN

The collared lemming is a key species in the tundra ecosystem, and thus also at Zackenberg. Being the only small mammal in arctic Greenland, the species is the preferred prey for most local predators. Changes to the lemming population may thus have knock-on effects on the entire community. Understanding the determinants of lemming habitat choice and how this may be impacted by climate change is therefore key to the vertebrate community in the high Arctic.

The collared lemming (*Dicrostonyx groenlandicus*) inhabits the North and Northeastern parts of Greenland. Though the otherwise well-known, regular population cycles appear to be a transient phenomenon, population sizes still vary markedly from year to year. By mapping the number and location of the nests that lemmings build in winter, BioBasis Zackenberg has been able to quantify not only the population dynamics of lemmings, but also lemming winter habitat selection and the consequences for demographics and the impacts of predation during more than two decades with highly variable climatic conditions.

Lemmings actively select for *Salix* snow beds, when moving from their summer habitats (exposed *Dryas* heaths) to their winter quarters. The *Salix* snow beds are characterized by large accumulation of snow, providing insulating cover with favorable micro-climatic conditions for breeding, whilst also providing some protection from predators. Other habitat types are utilized less intensively, but this pattern depends greatly on the overall abundance of lemmings as even the less preferred habitats are used extensively in years when lemming densities are high.

Photo: Lars Holst Hansen.

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GEM sub programme:
BioBasis Zackenberg

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

AS A HABITAT SELECTION OF
A CHANGING CLIMATE

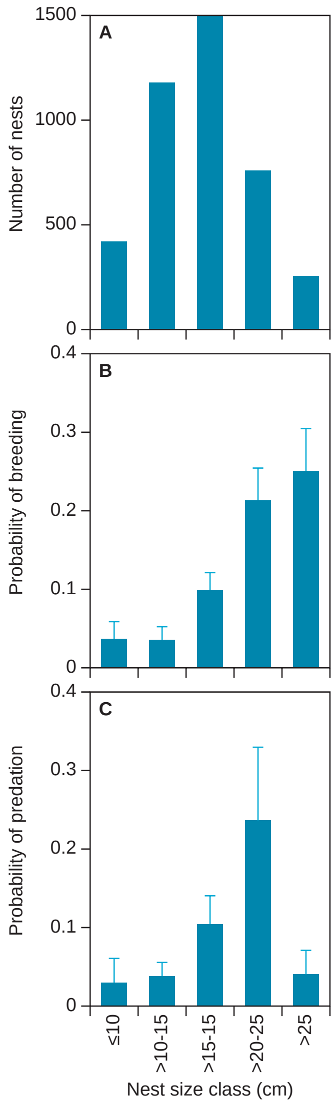

Figure 1. Lemming nest size distribution (A), the relationship between nest size and probability of nests being used for breeding (B), and the relationship between nest size and probability of nests being depredation by stoat (C). Modified from Schmidt et al. (2021).

Lemming habitat selection is, however, more than just preferring specific habitats in winter: the habitat selection of lemmings at Zackenberg is also indirectly linked to vital demographic parameters, such as breeding and mortality through predation. Hence, the most preferred habitat holds the largest lemming winter nests. And as larger nests are associated with higher probabilities of being used for winter breeding, the Salix snow beds also appears to be the most important breeding sites for collared lemmings. On the other hand, the larger lemming nests and in particular the nests used for breeding are depredated more often by stoats (*Mustela erminea*) than the smaller, non-breeding nests. Lemming habitat selection is thus a delicate interplay between access to the most favorable abiotic winter conditions and forage, allowing lemmings to breed, whilst avoiding predation by stoats. The long-term monitoring data from Zackenberg clearly suggest that the density-dependent habitat selection of lemmings acts to balance fitness across the various habitat types in the valley.

With its dependency on adequate winter snow conditions, lemmings may face difficulties as the arctic climate changes. In Northeast Greenland, predicted future climates involve warmer and wetter conditions. As long as the precipitation falls as snow, it will be beneficial to lemmings, at least in the short term. However, if future climates involve more frequent autumn freeze-thaw events with precipitation falling as sleet, this may result in the formation of ground ice, providing less insulating cover and ultimately limiting the access to the plants that lemmings consume. Though such changes in snow properties may be detrimental to lemmings as it can lead to a reduction in the availability of preferred winter habitats in the future, the large habitat heterogeneity characterizing the Arctic at the local scale may to some extent act as a buffer against the detrimental impacts, and thus provide some refuge for the lemmings.

Photo: Lars Holst Hansen.

The Arctic is changing and with that the livelihoods of the species adapted to life under the harsh climatic conditions there. However, to understand the full extent of arctic change on biodiversity in the Arctic, one has to take a true ecosystem approach, incorporating the full range of interactions taking place between climate, topography and biota.

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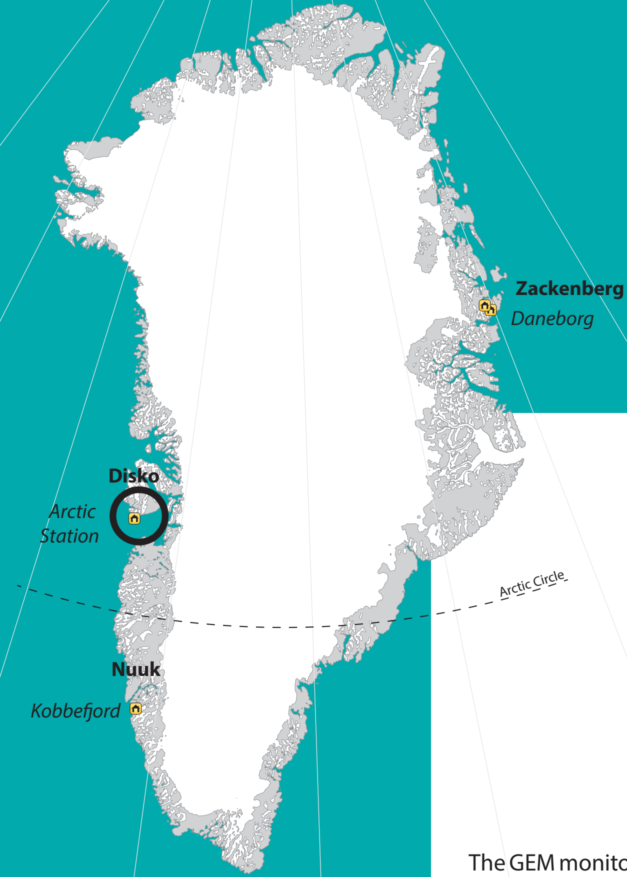

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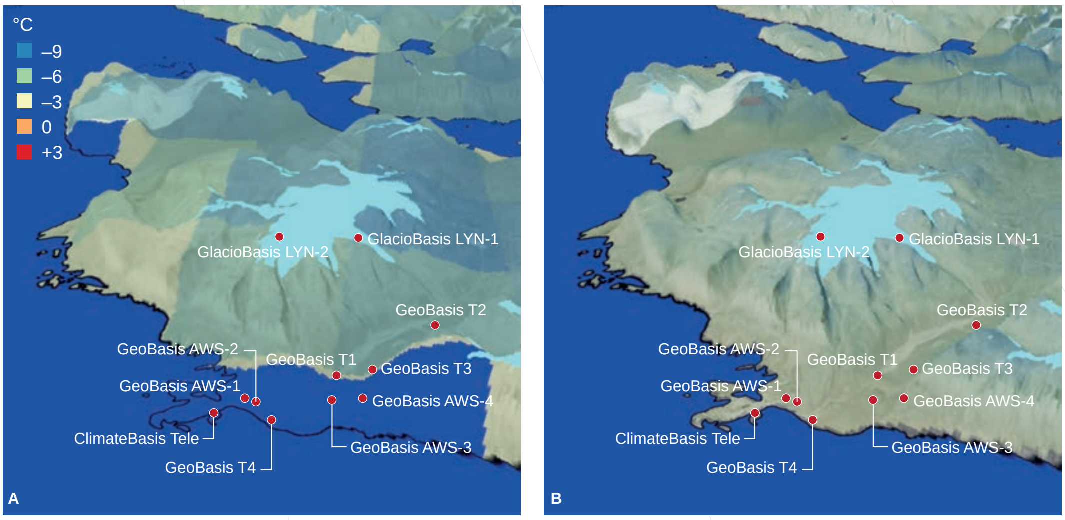
DOWNSCALING FROM CLIMATE MODELS

Climate has a major impact on ecosystem processes that are challenging to model across complex landscapes using only point-measurements from GEM weather stations. By downscaling the HIRHAM5 regional climate models (RCM) from 5.5 km to 100 m resolution, we calculate the 1980-2016 mean annual air temperature over the entire landscape surrounding the town of Qeqertarsuaq, and predict a warming between 2 °C and 6 °C by 2100 relative to the 1980-2016 average.

The GEM monitoring timeseries from Zackenberg, Nuuk and Disko accurately document ecosystem processes at the location where each instrument is installed, but most of Greenland and the Arctic are very sparsely monitored. Climate models provide a continuous coverage over all Greenland and are widely used over large and comparatively uniform surfaces like the Greenland Ice Sheet, but their km-scale resolution is a severe limitation over more complex landscapes (Figure 1A). Here we show how HIRHAM5 RCM products can be processed to refine their spatial resolution from 5.5 × 5.5 km to 100 × 100 m, enabling direct comparison with GEM *in situ* measurements.

A method developed within GlacioBasis for modelling the A.P Olsen ice cap and the Zackenberg River catchment for downscaling air temperatures has been extended to include the effects of terrain slope and aspect as well as shadows cast by the surrounding topography. This downscaling scheme was run over the ice-free land surrounding Arctic Station (Disko Island), where some of the longest GEM weather time series exist. Downscaling over glaciers and the sea will be the next phase of this work, in order to produce a seamless coverage of all three GEM sites and, in the future, all Greenland.

Figure 1. A) Synthetic 3D view of the input 1980-2016 mean annual 2 m air temperature data from the RCM, color coded over grayscale satellite imagery from Google Earth and then draped over a digital elevation model (DEM). Note how the coarse 5.5 × 5.5 km grid cells attribute the same temperature to very different elevations, and the missing input data over the entire town of Qeqertarsuaq and most of the GEM automatic weather stations (red dots) due to the RCM classifying that grid cell as sea. B) Downscaled air temperatures at 100 × 100 m resolution closely reflecting the actual topography, including shadows on the steep NE-facing slopes, and the filling of the 'sea' grid cell with temperature estimates based on the surrounding land areas. Looking direction is towards NW and the closest shoreline crossing the figures is ca 15 km.



Authors:

Michele Citterio[1], Arno C. Hammann[2], Birger Ulf Hansen[3] & Charlotte Sigsgaard[3]

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GEM sub programme:

ClimateBasis, GeoBasis and GlacioBasis

Data source:

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

https://data.g-e-m.dk/Datasets?doi=10.17897/A22W-9Z72

https://data.g-e-m.dk/Datasets?doi=10.17897/19SC-2708

1980-2100 TEMPERATURES

In the case of air temperature it is reasonable to assume that they decrease from sea level to mountain tops, and that this relation between near-surface (2 m) air temperature and elevation (lapse rate) can vary over time but it is similar within adjacent grid cells of the same surface type (land, sea, ice). At any grid cell and time step the lapse rate can thus be found by best fitting of the lapse rates from the surrounding RCM grid cells. This lapse rate is then used for correcting the bias due to the elevation difference between real topography and the coarse digital elevation model used by the RCM. In addition to increasing the spatial resolution to properly reproduce the real topography, the downscaling procedure can also fill gaps along the coastline and glacier margins, where the coarse resolution RCM only provides information for one or the other land surface type (Figure 1B).

The downscaled 1980-2016 mean annual air temperatures (MAAT) from HIRHAM5 driven by ERA-Interim reanalysis climate can now be compared with a long GEM *in situ* time series like GeoBasis AWS-1 (see link under Data source). The interannual variability and decadal warming trend are very similar to the field measurements, confirming the usefulness of the downscaling procedure (Figure 2). The systematic ca. +2 °C offset between measurements and model shows an example of the local biases known to exist in RCM products, which can be corrected when *in situ* measurements are available. Finally, RCM can model future climate based on different trajectories of greenhouse gas concentrations (Representative Concentration Pathway RCP4.5 and RCP8.5 (Figure 3A and 3B, respectively) showing MAAT warming by 2080-2100 under these two scenarios of ca. 2 °C and 6 °C relative to the 1980-2016 average.

These seamless, high resolution grids of climate parameters can be used for transferring the detailed process understanding obtained over the last decades at the GEM research sites to wider parts of Greenland, as well as future climatic conditions.

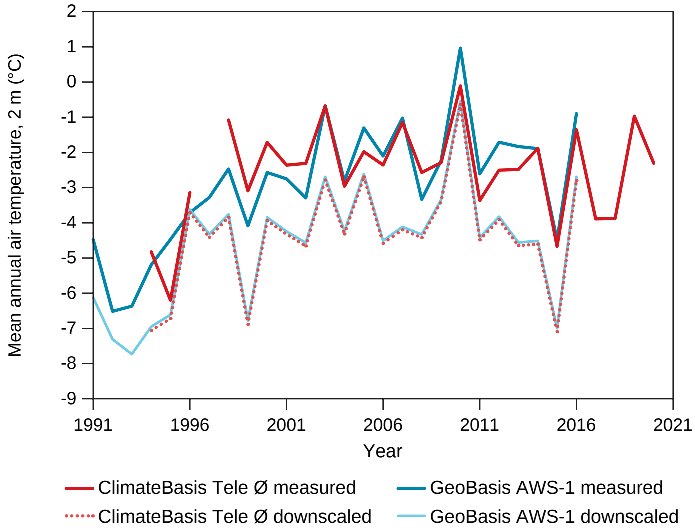

Figure 2. Comparison of measured and modelled mean annual air temperature for two long GEM timeseries from the ClimateBasis 'Tele Ø' and the GeoBasis AWS-1 automatic weather stations on Disko Island.

When applied on the area surrounding Arctic Station and the town of Qeqertarsuaq, our preliminary results show that the lowest elevations and a significant part of the south-facing mountain slopes will experience positive mean annual air temperatures by the end of the century.

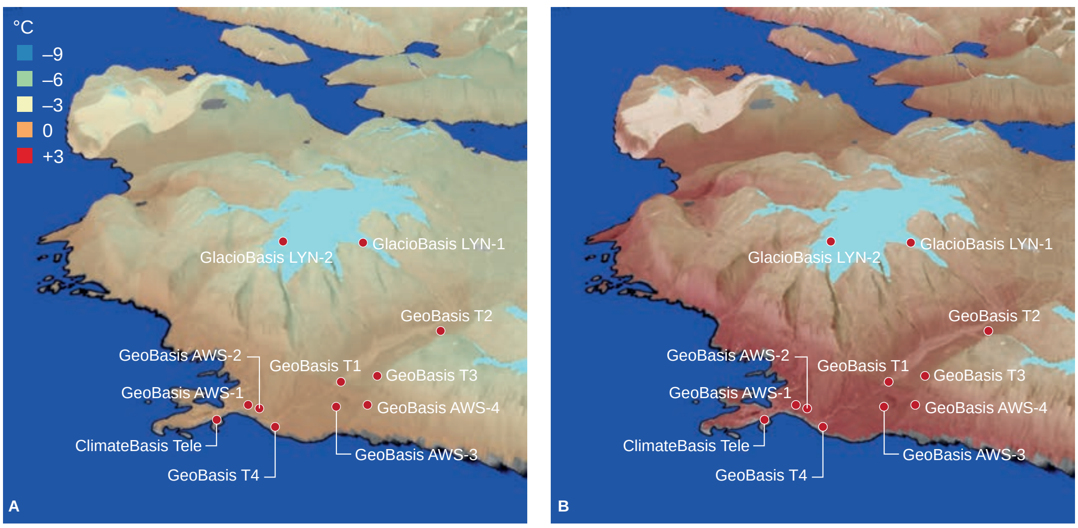

Figure 3. A) Predicted mean annual air temperature at the end of the century (2080-2100) based on the RCP4.5 and B) RCP8.5 greenhouse gas concentrations trajectories, indicating a warming of ca. 2 °C and 6 °C relative to the 1980-2016 average.

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GEM CLIMATEBASIS

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

In 2021, the annual mean temperature was warmer than the 2008-2021 average at all three GEM sites (by 1.7 °C, 1.0 °C and 0.7 °C at Kobbefjord, Disko and Zackenberg respectively). A number of records were broken, both on the east and on the west coast.

In Zackenberg the monthly mean temperatures exceeded the averages for the period 2008-2021 during all months except in January and November. July was exceptional in both the mean and the extreme temperatures. While the previous record for monthly mean temperature was set in July 2016 with 8.7 °C, July 2021 experienced 9.2 °C, and on July 28th, the highest absolute temperature in the GEM record was observed at 23.9 °C. It supersedes July 21st, 2006, at 22.9 °C.

Monitored parameter groups

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

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

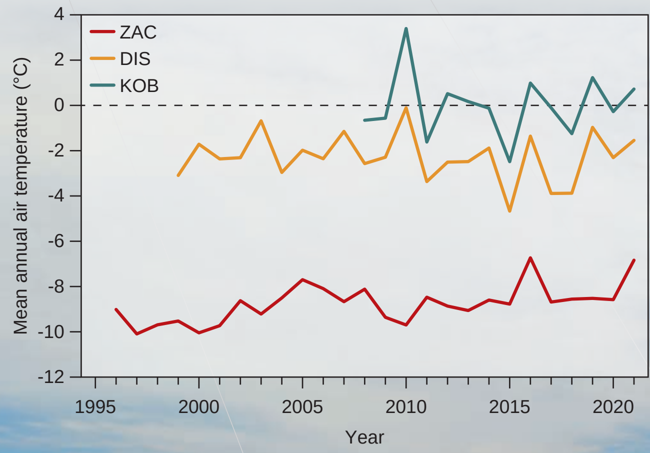

Figure 1. Mean annual air temperature at the three GEM sites Zackenberg (ZAC), Disko (DIS) and Kobbefjord (KOB).

Photo: Asiaq.

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Disko:

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PROGRAMME DESCRIPTION

On the West coast, the winter was warmer and the summer cooler than the 2008-2021 average. Both Kobbefjord and Disko experienced the warmest December days on record (on the 20th and 21st, respectively). In the mean, 2021 brought the 2nd and 3rd warmest Decembers in Kobbefjord and Disko, respectively. At the same time, both locations experienced the coldest Septembers on record.

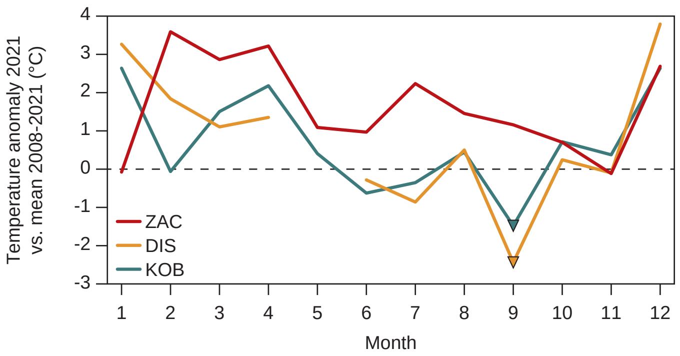


Figure 2. Monthly air temperature anomaly for 2021 compared to the common reference period 2008-2021 for Zackenberg (ZAC), Disko (DIS) and Kobbefjord (KOB). A triangle marks a month whose mean temperature has been more extreme than those of the corresponding month in any other year from 2008-2021. The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

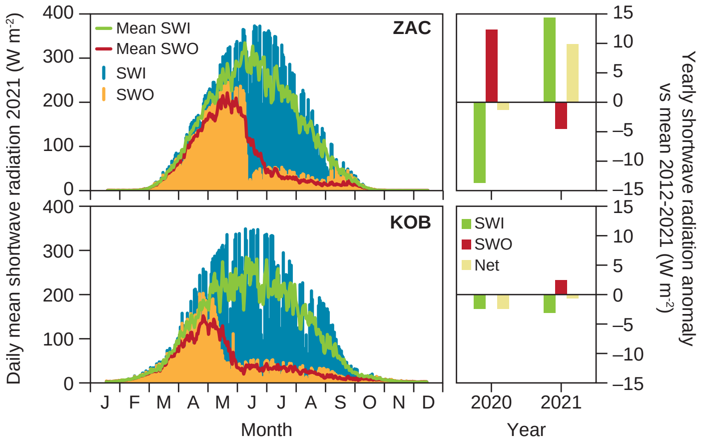
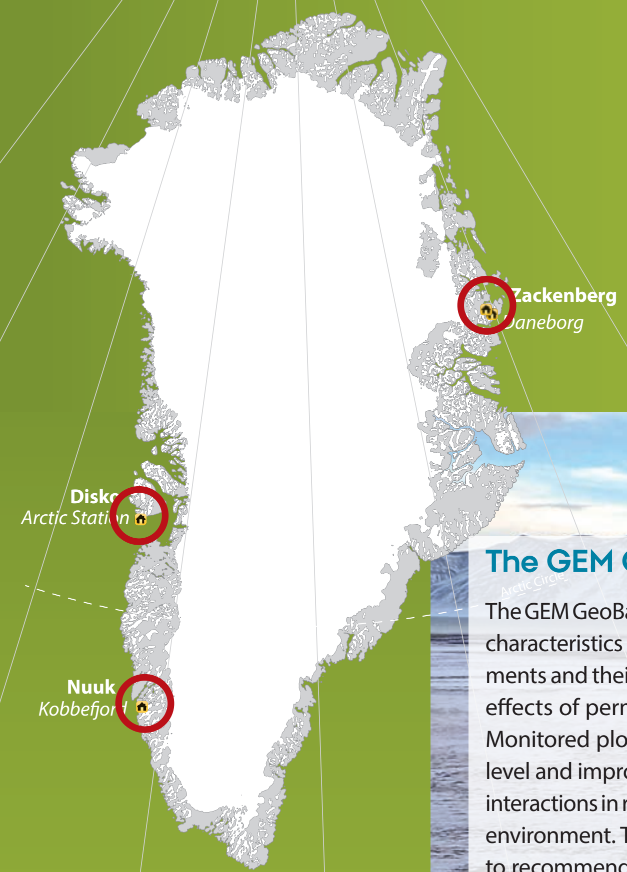


Figure 3. Main plots: Daily mean shortwave incoming radiation (SWI) and shortwave outgoing radiation (SWO) in 2021 with their respective daily means for the period 2012 to 2021 (SWI mean and SWO mean) for Zackenberg (ZAC) and Kobbefjord (KOB). Bar plots (right columns) show yearly mean anomalies for the two most recent years, with outgoing radiation (SWO) taken to be negative, so that the net radiation is simply the sum of SWI and SWO.

While incoming shortwave radiation is reduced when clouds occult the sun, outgoing shortwave radiation is highest if the ground is snow-covered and therefore reflective. Net radiation, the energy retained at the ground, consists of incoming minus outgoing radiation. In Zackenberg, the annual accumulated net radiation was higher in 2021 than in 2020. This was caused by a much larger amount of incoming radiation, whereas outgoing radiation was also higher in 2021 than in 2020 (due to a longer period of snow cover, with earlier snowfall in autumn), diminishing the net difference. In Kobbefjord, there was also slightly more accumulated net radiation in 2021 than in 2020, but here it was due to a reduction in outgoing radiation due to an earlier onset of snow melt in spring. While air temperatures were also higher and they are influenced by local net radiation, they also depend on the transport of energy by larger-scale air flows.



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GEM GEOBASIS

The GEM GeoBasis Programme

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

Monitored parameters

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

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

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

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

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

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

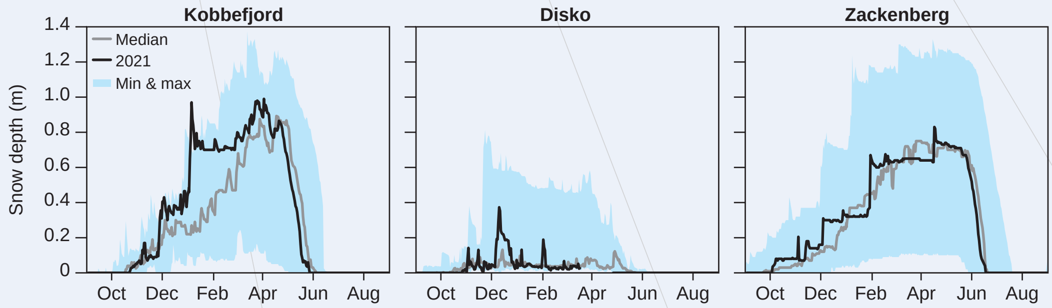

Figure 1. Daily snow depth measurements in 2021 (black lines) compared to min and max for the historical record (shaded area) and the median (grey line). Snow is a key parameter in Arctic ecosystem functioning. Thus, several different monitoring methods are put in place to get information on spatial 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: 2008-2021, Disko: 2012-2021 and Zackenberg: 1997-2021.

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PROGRAMME DESCRIPTION

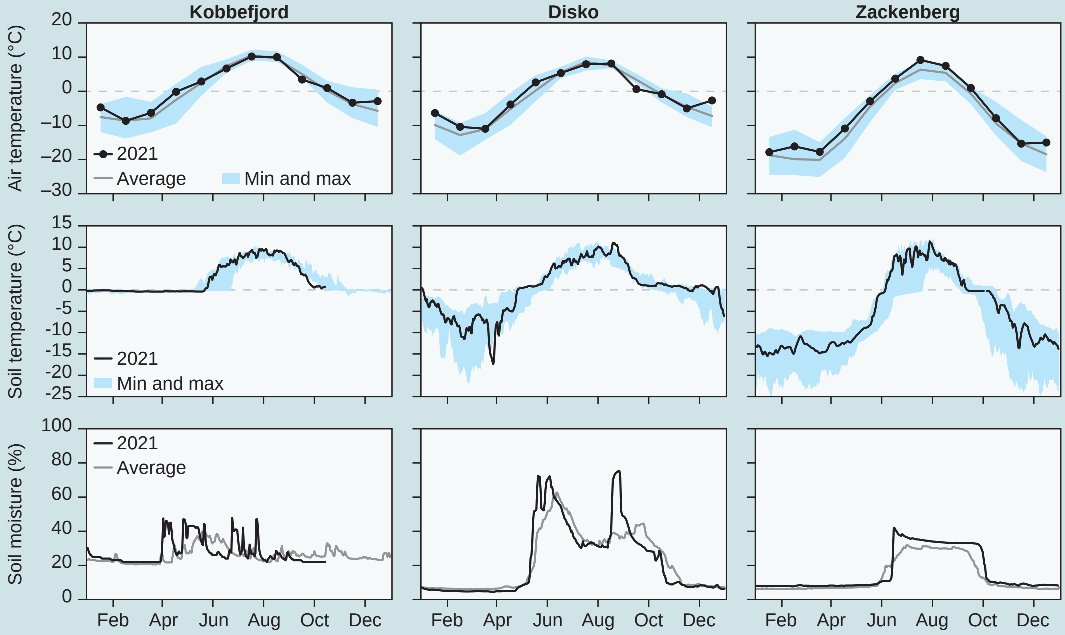

Figure 2. Mean monthly air temperature across sites (top panel) in 2021 compared to average (grey line) and minimum and maximum (shaded area) in historical data. Heath soil temperatures in 10 cm depth (middle panel) in 2021 compared with minimum and maximum (shaded area) and soil moisture within the top 10 cm, shown together with long-term average (grey line). Soil temperature and soil moisture content are important parameters for plant growth, phenology, permafrost, energy fluxes and carbon exchange. Soil temperature and soil moisture are measured under several different vegetation communities and in a wide range of depths, as part of the GeoBasis programme. Data used in the figure: Air temperature: Kobbefjord: 2008-2021, Disko: 2012-2021 and Zackenberg: 1996-2021. Soil temperature: Kobbefjord: 2012-2021, Disko: 2012-2021 and Zackenberg: 1996-2021. Soil moisture: Kobbefjord: 2013-2021, Disko: 2012-2021 and Zackenberg: 2005-2021.

The registered snow depths at the three sites for the winter 2020-2021 shows an average pattern both in the length of the continuous snow cover, and the snow depth (Figure 1). Kobbefjord reached a relatively deep snow depth at an early stage of the winter, impeding cooling of the soil. Around the weather station in Disko it is not unusual that almost snow free conditions are measured during winter due to re-distribution by wind, Føhn-situations, and even rain.

The monthly air temperatures in Zackenberg were above average for almost all months in 2021 while on the west coast both Kobbefjord and Disko had a relatively cold and humid summer, transitioning into the fall with low temperatures in September (Figure 2). This is also reflected in the soil temperature, where Kobbefjord and Disko saw an early cooling in 10 cm depth.

In Zackenberg, the mean maximum thaw depth in ZEROCALM-1 was 89 cm, the deepest registered so far (Figure 3).

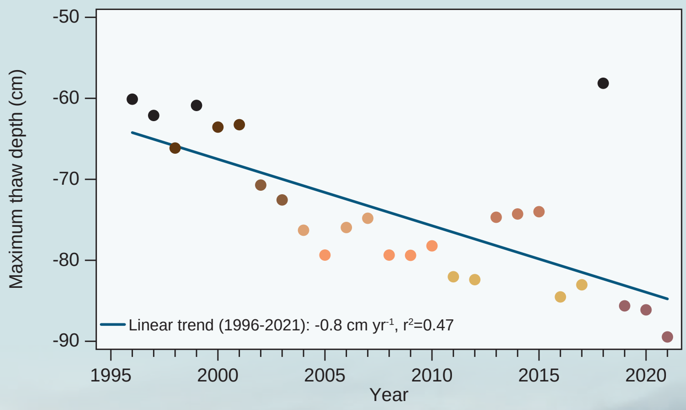

Figure 3. Long-term trend in annual maximum soil thaw depth in Zackenberg Circumpolar Active Layer Monitoring grid # 1 (ZEROCALM-1). Soil thaw and active layer depth are studied under different vegetation types. Monitoring methods include manual probing, as the one shown here, and borehole temperature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

Photo: Daniel A. Rudd.

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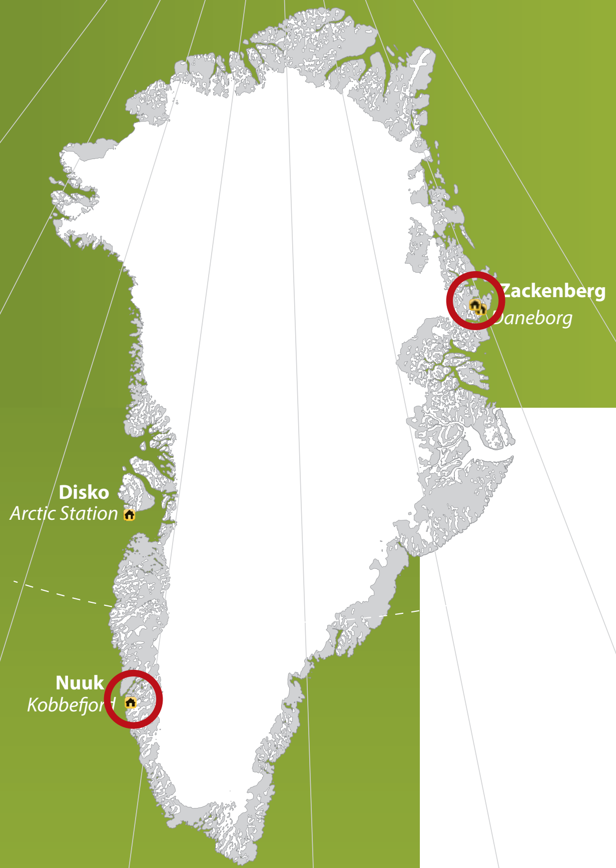
GEM BIOBASIS



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


Photo: Katrine Raundrup.


Photo: Katrine Raundrup.

Monitored parameters

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

Arthropods and microarthropods
- Abundance
- Emergence phenology
- Herbivory rates

Birds
- Abundance
- Reproductive phenology
- Reproduction and predation rates

Mammals
- Abundance
- Spatial distribution
- Reproduction and predation rates

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

General
- Tissue sampling
- Plot-scale abiotic parameters

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Nuuk:

Greenland Institute of Natural Resources

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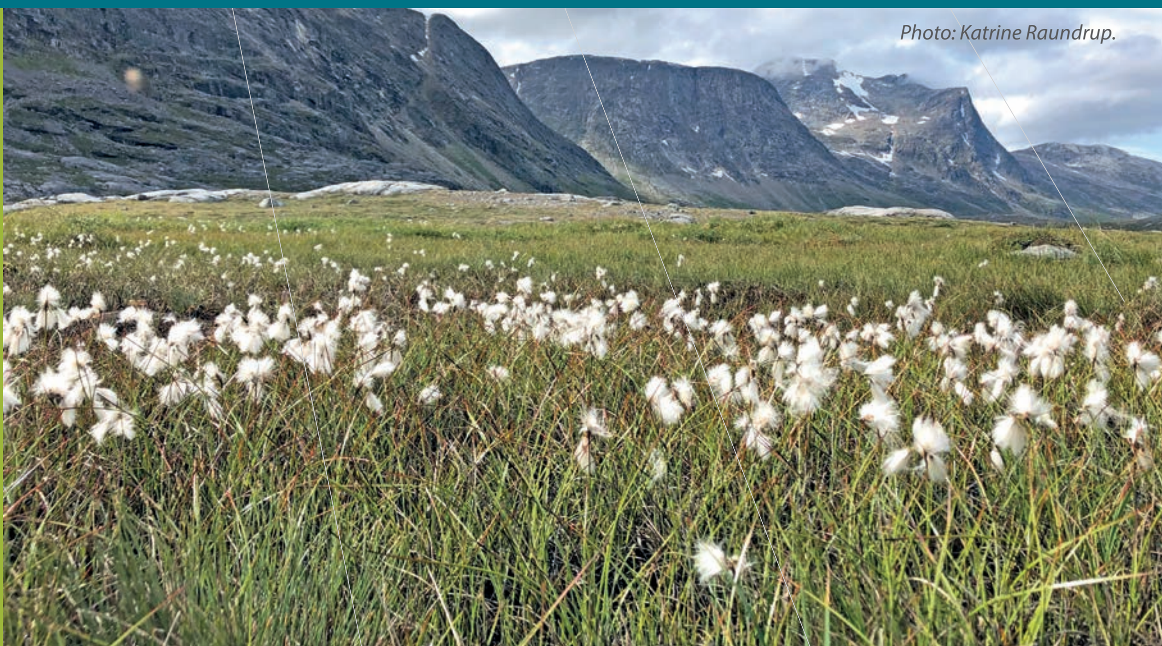


Photo: Katrine Raundrup.

PROGRAMME DESCRIPTION

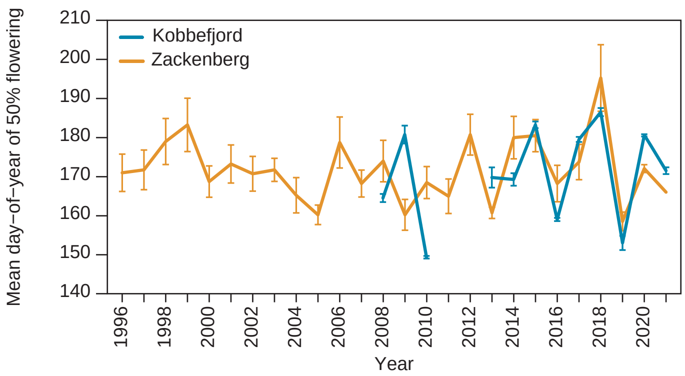


Figure 1. Day of 50 % flowering is indicative of the effect of climate variability on the timing of flowering. The timing of plant growth and flowering is important for e.g. insects and herbivorous animals. The graph shows inter-annual variation in mean Salix *flowering phenology in selected permanent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

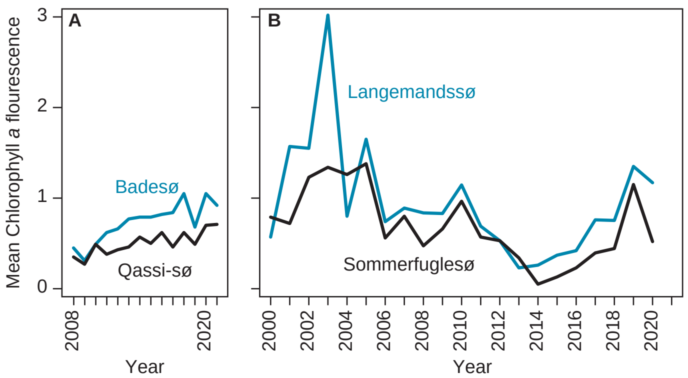


Figure 2. Chlorophyll fluorescence is a measure of productivity in the limnic ecosystem. The graphs show inter-annual variation in chlorophyll fluorescence in lakes at Kobbefjord and Zackenberg 1996-2021. Blue lines indicate lakes with fish, black lines lakes without fish. Note that due to the late onset of the 2020 season at Zackenberg dictated by the covid-situation, only one measurement was conducted in July. Unfortunately, data from 2021 at Zackenberg were not available at deadline.

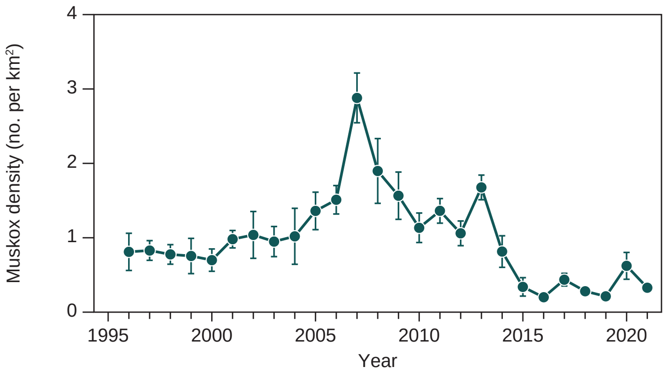
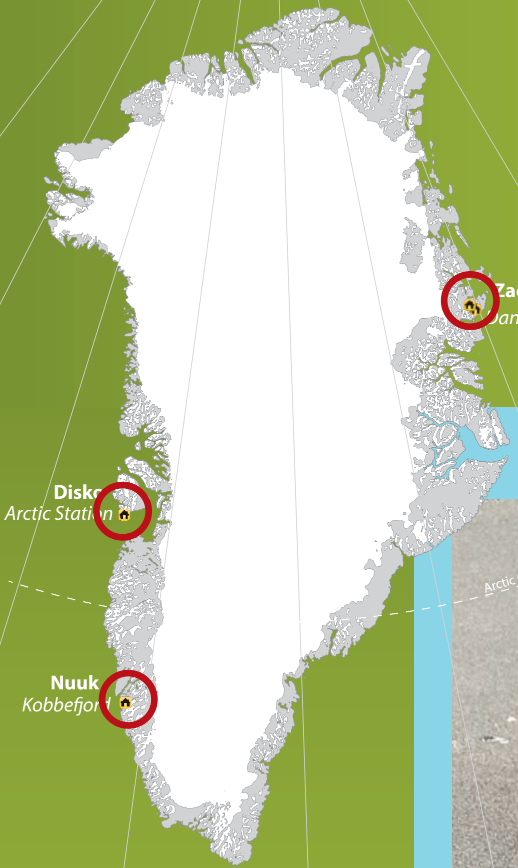


Figure 3. Inter-annual variation in muskox population dynamics (July and August) at Zackenberg 1996-2021.



Annual Report Card 2021

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).

Photo: Mie Winding.

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

Lead Institutions:

Zackenberg:

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Mie H.S. Winding, Greenland Institute of Natural Resources, miwi@natur.gl

Nuuk:

Thomas Juul-Pedersen, Greenland Institute of Natural Resources, thpe@natur.gl

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Torkel Gissel Nielsen, Technical University of Denmark, tgin@aqua.dtu.dk

Sandøen. Photo: Carl Isaksen.

PROGRAMME DESCRIPTION

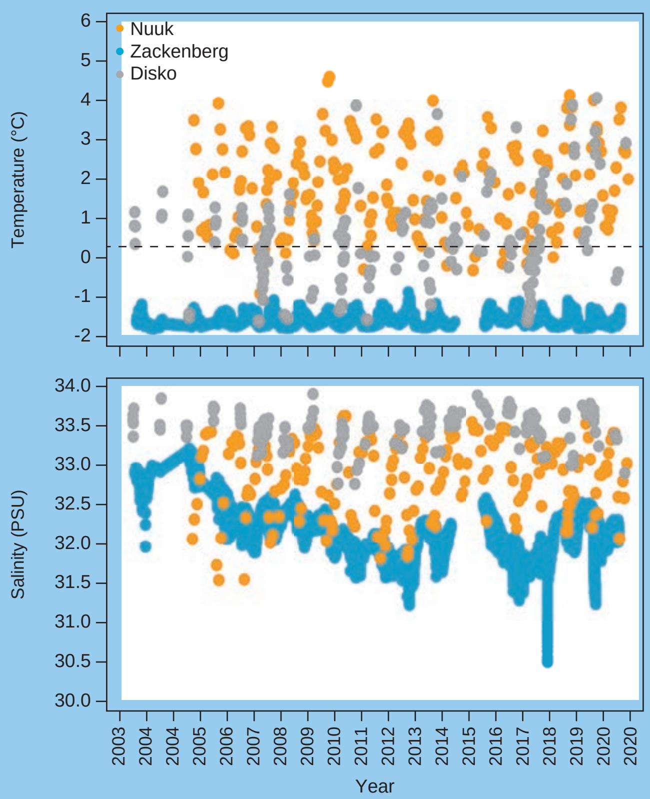


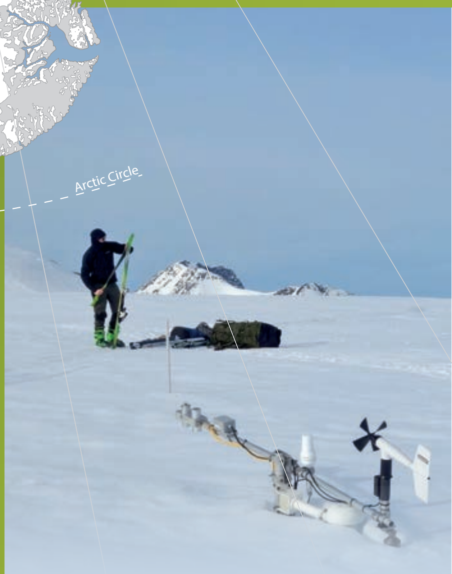
Figure 1. Water temperature and salinity at the permanent monitoring stations in Nuuk, Disko and Zackenberg. The time series from Nuuk and Disko represents one depth (63 m) selected from a monthly profile covering the entire water column. The time series from Zackenberg represents an autonomous mooring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

Photo: Mie Winding.

Annual monitoring of macroalgae in Daneborg, Zackenberg. Photo: Mie Winding.

Annual Report Card 2021

GEM GLACIOBASIS



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

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

Monitored parameters:

Near surface climate:

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

Surface mass balance

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

Lead institutions:

Zackenberg:

Geological Survey of Denmark and Greenland

Manager: Signe Hillerup Larsen, shl@geus.dk

Disko:

Geological Survey of Denmark and Greenland

Manager: Michele Citterio, mcit@geus.dk

Nuuk:

Asiaq – Greenland Survey

Manager: Kirsty Langley, kal@asiaq.gl

Contributing authors:

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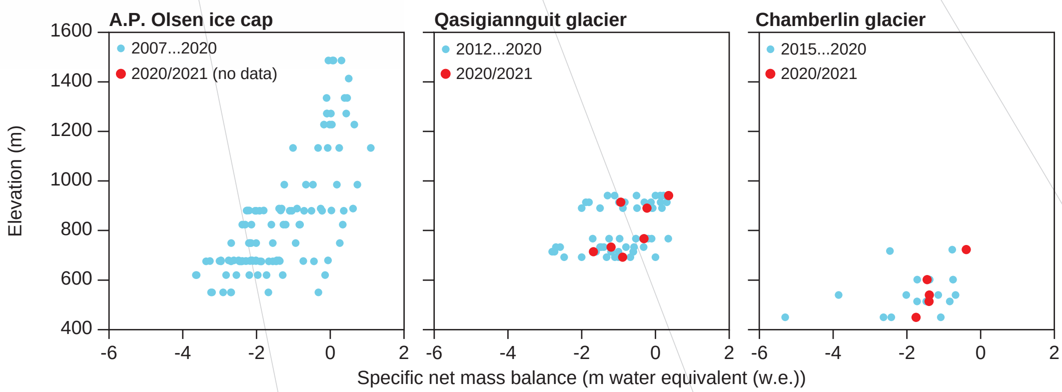


Figure 1. Glacier surface mass balance vs. elevation at the stakes on A.P. Olsen ice cap (Zackenberg, 14 stakes), Qasigiannguit glacier (Kobbefjord, 9 stakes) and Chamberlin Glacier (Disko, 7 stakes).

PROGRAMME DESCRIPTION

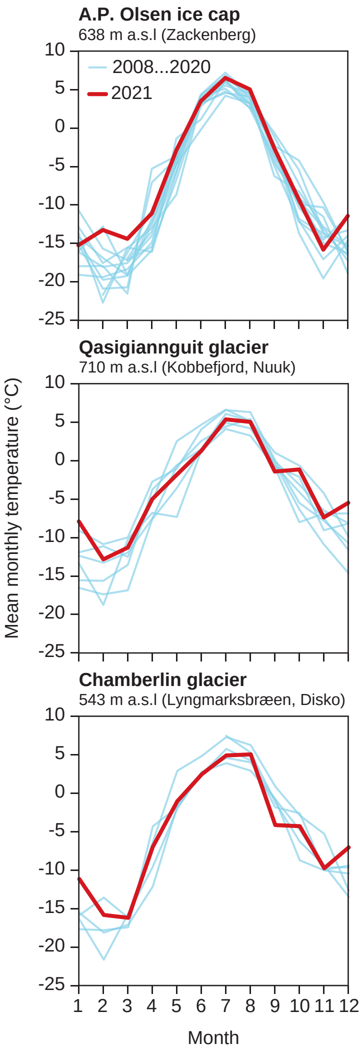


Figure 2. Mean monthly air temperatures from automatic weather stations in the ablation zone of the monitored glaciers at the three GEM sites in 2021 (red) vs. earlier years (light blue).

The travel limitations during 2020 and 2021 due to the Covid-19 pandemics resulted in the loss of several manual measurements at Zackenberg and Disko. As a consequence there is no direct measurement of glacier surface mass balance at Zackenberg in 2021. The winter 2020/2021 was among the warmest recorded at all sites (Figure 2) and melt conditions have been above average throughout the season at Zackenberg, whereas melt conditions at Qasigiannguit near Nuuk and Chamberlin at Disko were closer to average (Figure 3).

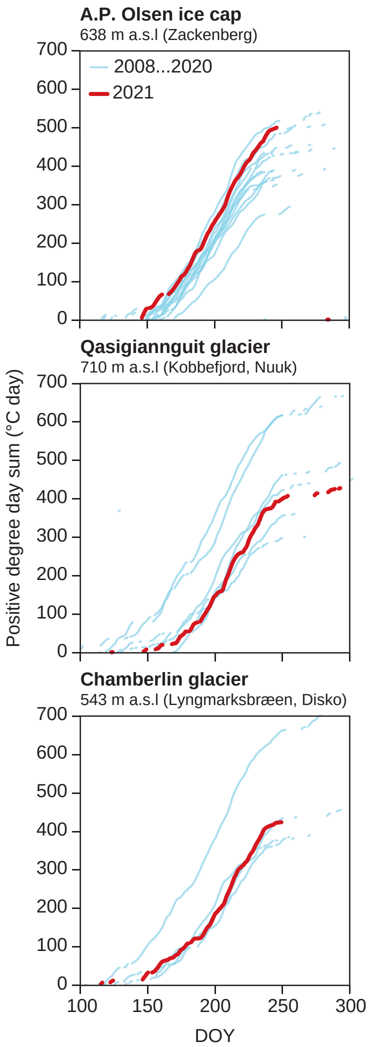


Figure 3. Positive degree day (PDD) sums, indicating melting conditions, from GlacioBasis automatic weather stations in the ablation zone of the monitored glaciers at the three GEM sites in 2021 (red) vs. earlier years (light blue). Gaps visible in the curves indicate sub-freezing daily mean temperatures.

Greenland Ecosystem Monitoring

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

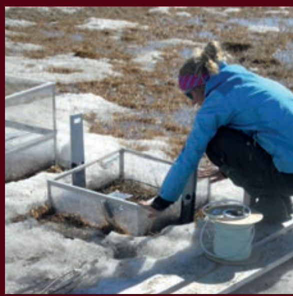
www.g-e-m.dk

ClimateBasis Programme

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

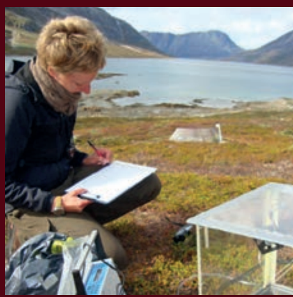
GeoBasis Programme

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



BioBasis Programme

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



MarineBasis Programme

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

GlacioBasis Programme

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

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Grønlands Naturinstitut
Pinngortitaleriffik • Greenland Institute of Natural Resources

DTU Technical University of Denmark

UNIVERSITY OF COPENHAGEN