Greenland Ecosystem Monitoring

ANNUAL REPORT CARDS 2025

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GREENLAND ECOSYSTEM MONITORING

ANNUAL REPORT CARDS 2025

GEM

Greenland Ecosystem Monitoring

GEM INTRODUCTION

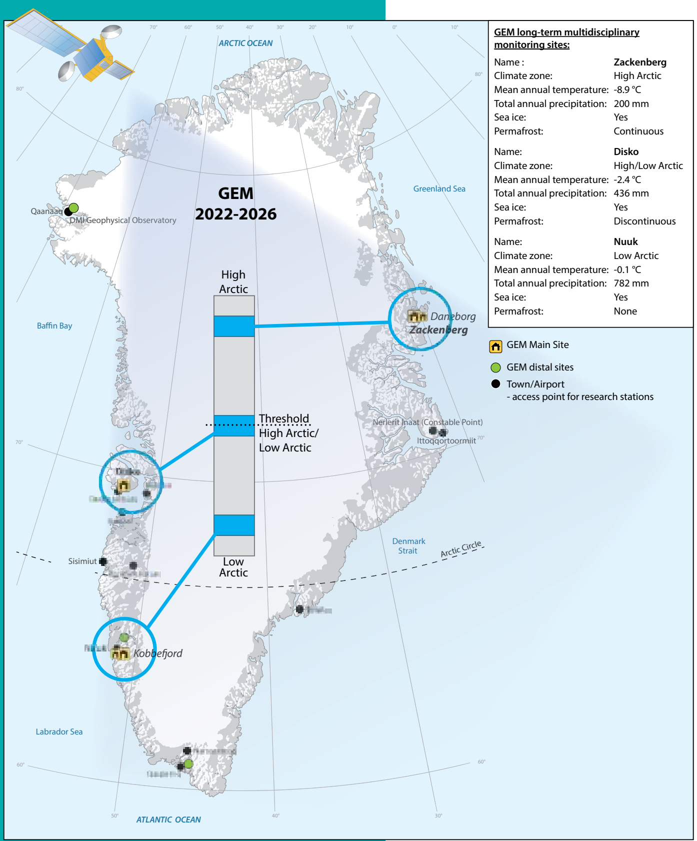

Figure 1. The GEM programme combines intensively studied ecosystems at three main sites (Zackenberg, Disko and Nuuk) with remote sensing and distal sites located along environmental and climatic gradients.

About GEM

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

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

The vision of GEM

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

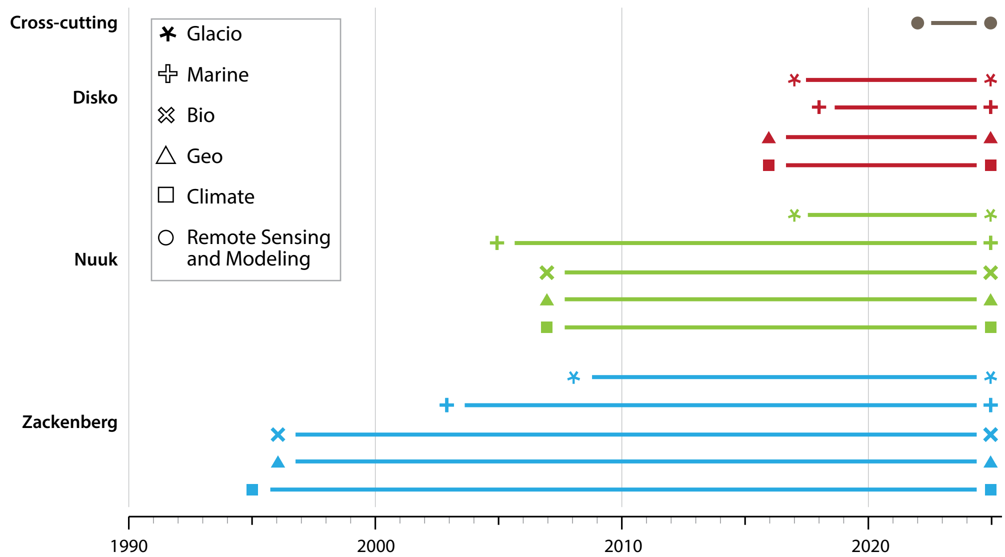

Figure 2. The GEM programme was initiated in 1995 as the Zackenberg Ecological Research Operations (ZERO). In the years 2005-2007 a new main site was established around Nuuk, and in 2016-2018 Disko area was included. All 5 Basisprogrammes are now funded at all three main sites, except for BioBasis at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

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

International cooperation

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

Education and Advice

GEM is making an active effort to help educate the next generation of scientists, with several university courses using GEM data, and associated PhDs and postdocs. GEM scientists work actively reaching out to students in schools and high schools through course and information materials based on GEM knowledge and data. This all combined with international co-operations reach a wide arctic audience. GEM works to create awareness and provide public insight into the changes that occurs in the Arctic climate and ecosystems.

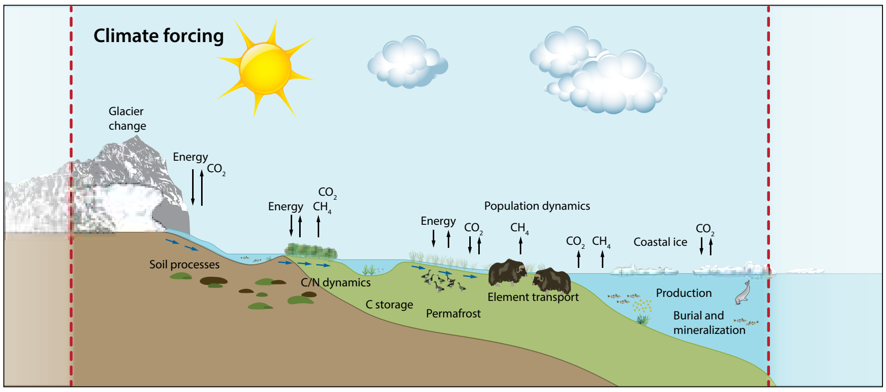

Figure 3. The GEM domain covers the glaciological, terrestrial, limnic and coastal marine compartments of the ecosystem.

Program aims

GEM aims to provide government advice on climate change and impacts, and where relevant GEM knowledge and data are used to address sustainability and adaptation efforts.

Free and open access to data

GEM provides free and open access to all data collected under the programme since the start in 1995. Data collection efforts have grown since the start of the programme and today includes more than 2000 parameters collected at the three main sites Zackenberg, Disko and Nuuk. Additional data are collected through remote sensing and supplementary transects and sites contributing to gradient studies and scaling efforts. All data are made available, quality assured and with DOI assigned to allow citation.

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

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

@GreenlandEcosystemMonitoring

Greenland Ecosystem Monitoring

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

Arctic Station – Disko

Zackenberg Research Station

Kobbefjord Station

ANNUAL REPORT

Results and achievements

News from GEM main sites and outreach

Kobbefjord

In 2025, the Kobbefjord Research Station continued to serve as an important hub for long term ecosystem monitoring, education, and outreach. The master's course Catchment-2Coast was held for the second consecutive year using GEM data from Kobbefjord as input to many of their exercises, though ice in the fjord prevented the course to do field work in Kobbefjord. Students thus collected field data on nutrient transport from terrestrial catchments through freshwater systems to the marine environment in a neighboring fjord.

Educational outreach activities were maintained. BioBasis welcomed four members of the Danish parliamentary Education and Research Committee to Kobbefjord. During the visit, GEM's long term ecosystem monitoring was presented, and the delegation gained insight into how systematic field data underpin understanding of climate change impacts in the Arctic.

The Greenland Ice Sheet Ocean Science (GRISO) network hosted the fourth GRISO Summer School in Nuuk. They visited Kobbefjord on September 11. Aside from the summer school the station hosted a number of masters and PhD students and will hopefully be able to do so in the years to come.

Four members of the Danish parliamentary Education and Research Committee visited Kobbefjord in 2025.

Disko

At Arctic Station in Qeqertarsuaq, monitoring and research activities continued largely unchanged in 2025. The station maintained its role as a platform for Arctic ecosystem research and communication, with regular presentations of GEM activities to visiting groups.

Field excursions and site visits were again used to demonstrate longterm monitoring approaches, and existing collaborations with visiting scientists and students were maintained rather than expanded. Overall, 2025 at Disko was characterised by continuity and consolidation of established activities.

Photo: Charlotte Sigsgaard.

Torben Røjle Christensen,
Scientific leader of GEM

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2025

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Zackenberg and Daneborg

In 2025, energy efficient and sustainable operations at Zackenberg were maintained, building on the successful implementation of renewable energy solutions in previous years. Reduced reliance on diesel continued to contribute to more sustainable logistics during the field season.

Construction of the new main building at Zackenberg progressed as planned as part of the long term infrastructure upgrade toward 2027. At Daneborg, construction of the new boat garage, funded by the Aage V. Jensen Foundations, was completed in 2025 and became fully operational.

Marine monitoring activities at Daneborg continued using the research vessel Arfivik. Following its commissioning in 2024, 2025 represented a year of routine use and consolidation of marine monitoring operations.

Support from the Aage V. Jensen Charity Foundation remained essential to sustaining infrastructure and operational capacity at Zackenberg and Daneborg.

A new boat garage was constructed at Daneborg in 2025 to improve marine monitoring facilities.

Outreach

2025 included several outreach activities highlighting GEM's longterm monitoring:

- Participation in Naturmødet (May 2025)
- Contributions to Greenland Science Week (November)
- Representation at the Danish Climate Symposium in Copenhagen, organised by the National Center for Climate Research (DMI), where Arctic methane emissions were a key theme
- Broadcast of the PBS episode "Tundra Impacts the Planet", featuring Zackenberg and GEM's Scientific Leader Torben Røjle Christensen, illustrating the global significance of Arctic tundra processes

These activities strengthened the visibility of GEM while focusing on communicating established results rather than launching new outreach initiatives.

Education

Educational efforts in 2025 centred on continued use and consolidation of teaching materials developed in earlier years. The project *"Virtuel rejse i arktiske økosystemer - dyk ned i klimaændringerne"* had formally concluded in 2024, but its materials were actively used across Greenland and Denmark in 2025.

The stable uptake of GEM datasets in secondary and higher education reflects the maturation of the educational component of the programme, with limited need for new development during the year.

A polar bear inspecting the weather station at Aucella Slope, Zackenberg. Photo: GeoBasis Zackenberg.

2025

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International collaboration

GEM scientists remained actively engaged in international collaboration throughout 2025. Notably, GEM participated in a workshop on circumpolar ecosystem monitoring in Longyearbyen, Svalbard, hosted by the Norwegian Institute for Nature Research. Here, GEM's integrated ecosystem monitoring approach and recent Greenland results were presented and discussed.

These activities primarily focused on strengthening existing networks and aligning monitoring approaches across the Arctic, consistent with a consolidation year.

GEM database

In 2025, the GEM database registered 3,802 visits, with 1,401 dataset downloads supporting research and education. A total of 475 datasets were available, representing 13 new datasets compared to 2024. The user base increased to 228 registered users, reflecting sustained engagement with the platform.

Following major development efforts in previous years, 2025 focused on stabilization and data curation. Priority was given to data quality, consistency, and accessibility.

Key activities included:

1. Data curation and standardisation, in close collaboration with subprogramme coordinators, including updates to legacy datasets
2. Infrastructure stabilization, ensuring robust and reliable database and website performance
3. Integration of remote sensing and modelling products, significantly expanding access to derived datasets and enhancing cross-site analyses

Overall

Overall, 2025 was a stable "business as usual" year for the GEM programme. Core monitoring activities continued largely as planned across all subprogrammes, while major efforts focused on maintaining data quality, consolidating infrastructure investments, and ensuring continuity in operations, outreach, collaboration, and education.

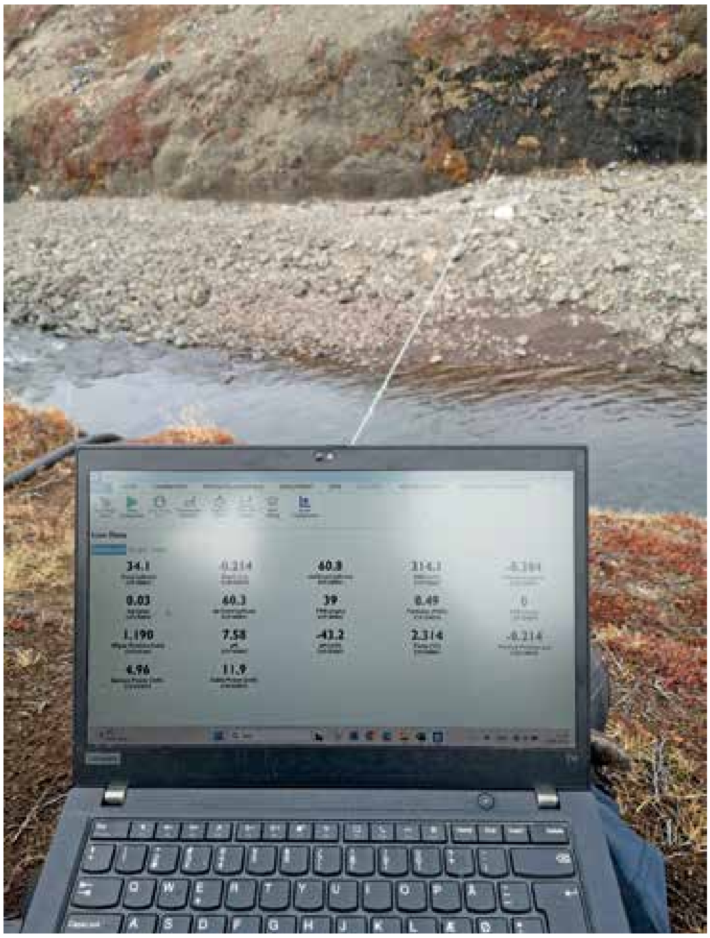

Photo: Charlotte Sigsgaard.

GEM at a glance 2025

- Active Basis Programmes in 2025: 14+remote sensing
- Scientists in the field: 72
- Scientific publications: 39
- Conference with GEM representations: 9
- Conference presentations: 4
- Courses using GEM data: 18

Climate &

Cryos-
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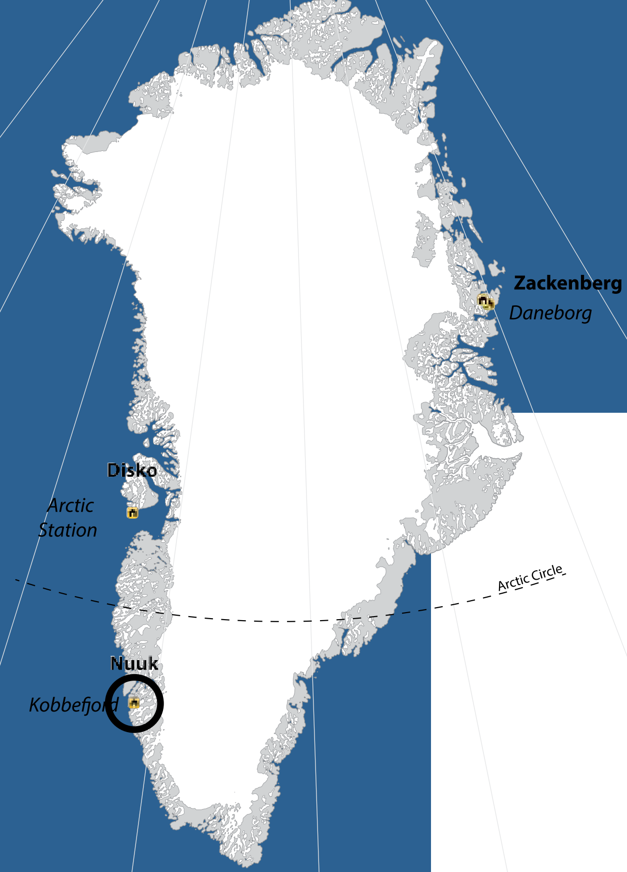
Photo: Thomas Juul-Pedersen.



GEMS FROM

Cosmic rays from space are constantly hitting Earth, where they interact with molecules in the world around us. We now know that these interactions can be exploited to monitor changes in e.g. climate and ecosystems. Here we present the first installation in GEM of a cosmic ray sensor for soil moisture monitoring.

Soil moisture is important for a range of processes in Arctic ecosystems, such as influencing soil microbial activity, plant growth, permafrost dynamics, and transport of soluble nutrients and carbon. Though soil moisture can vary a lot in a small area due to differences in soil characteristics, vegetation cover and snow distribution, in-situ soil moisture data usually consists of point measurements. Soil moisture is typically measured by sensors permanently installed in the soil, by manual probing at different locations, or via physical soil samples that are weighed and dried to derive water content. Permanently installed sensors produce monitoring data of relative changes in moisture over time and manual samples are relevant to document spatial variability. But none of them offer a feasible method to estimate average soil moisture for an area at hectare-scale over time. Such averages are critical for training and validating not only satellite-based methods to estimate soil moisture, but also models of permafrost, carbon, climate, and biogeochemical processes.

In Kobbefjord, GeoBasis installed a cosmic ray neutron sensor (CRNS) in the summer of 2025, covering an Empetrum-dominated heath, representative for drained heaths in large parts of Greenland and the Arctic. The principle for how this sensor can be used to estimate soil moisture from incoming cosmic rays is condensed in figure 1:

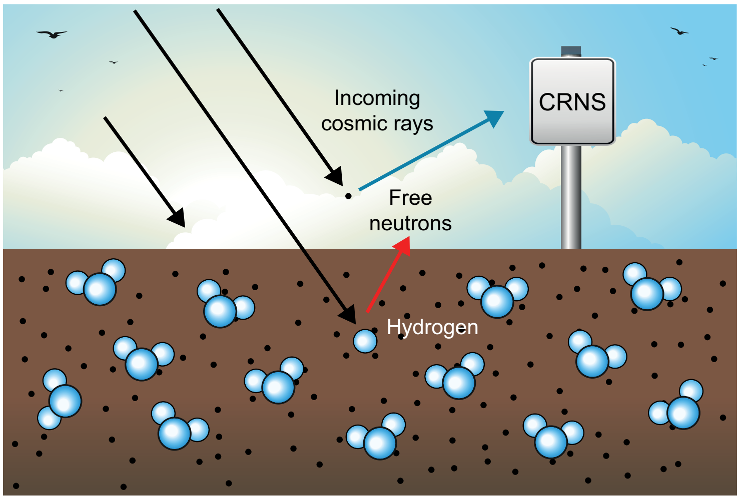


Figure 1. Incoming cosmic rays from space knocks off free neutrons when they interact with particles on Earth. Free neutrons are slowed down by Hydrogen (red arrow) which is often bound in water molecules. Slow neutrons will not reach the Cosmic Ray Neutron Sensor (CRNS). On the contrary, more high-energy neutrons will hit the CRNS when the soil is dry (blue arrow).

Authors:
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[1] University of Copenhagen
[2] Asiaq - Greenland Survey

Data source:
Data will be accessible on GEM database in 2026, http:\\data.g-e-m.d

OUTER SPACE

We have developed a site specific model linking the neutron count to a network of manual soil moisture measurements, by normalizing the neutron count with changes in air humidity and atmospheric pressure (to compensate for changes in atmospheric conditions slowing the free neutrons) as well as with the general level of incoming rays (f_i on Figure 2 that depends on e.g. solar fission activity cycles). Then neutron counts can be converted to an area-averaged soil moisture.

Figure 2 presents the first calibrated dataset, covering the summer and autumn of 2025. Note e.g. the increase in soil moisture in early September caused by a period with rain together with lower evaporation and transpiration from the ecosystem to the atmosphere.

We are now reaching out to the COSMOS network that merge global CRNS data, to increase the visibility of the GEM data. The access to calibrated CRNS data is in high demand among ecosystem and climate modellers and satellite remote sensing researchers as a rare source of training and validation data.

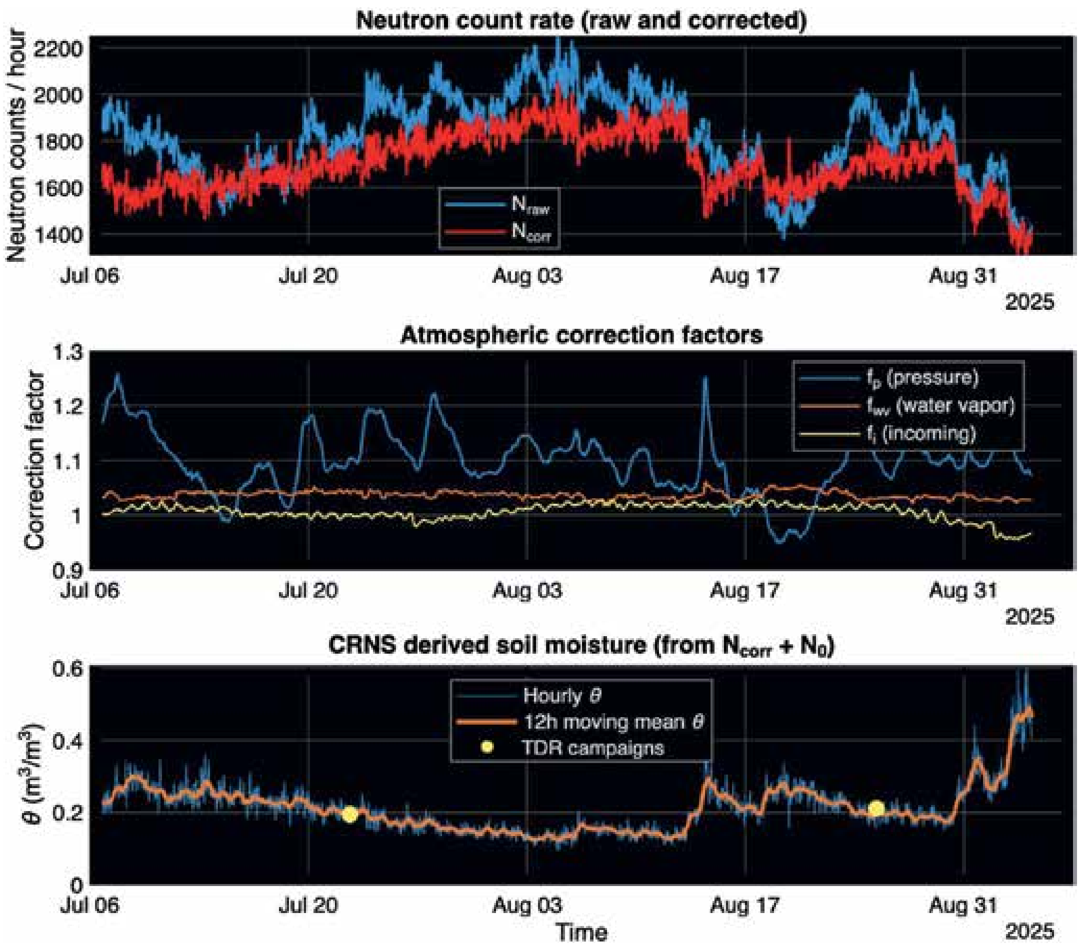


Figure 2. Timeseries of measured neutron count N_{Raw} and atmospherically corrected neutron counts N_{corr} (top), used correction factors for atmospheric pressure f_p, water vapor fwv and incoming cosmic radiation f_i (middle) available from Oulu, Finland, and the calculated resulting soil moisture θ using the corrected neutron counts N_{corr} and N_0 (Bottom). N_0 is a calibrated parameter specific to the study site located at Kobbefjord, Greenland. The yellow dots indicate the manual measurement campaigns of soil moisture (TDR) used for calibration.

ARE WE OVERESTIMATING
WE HAVE LEFT ON EARTH?

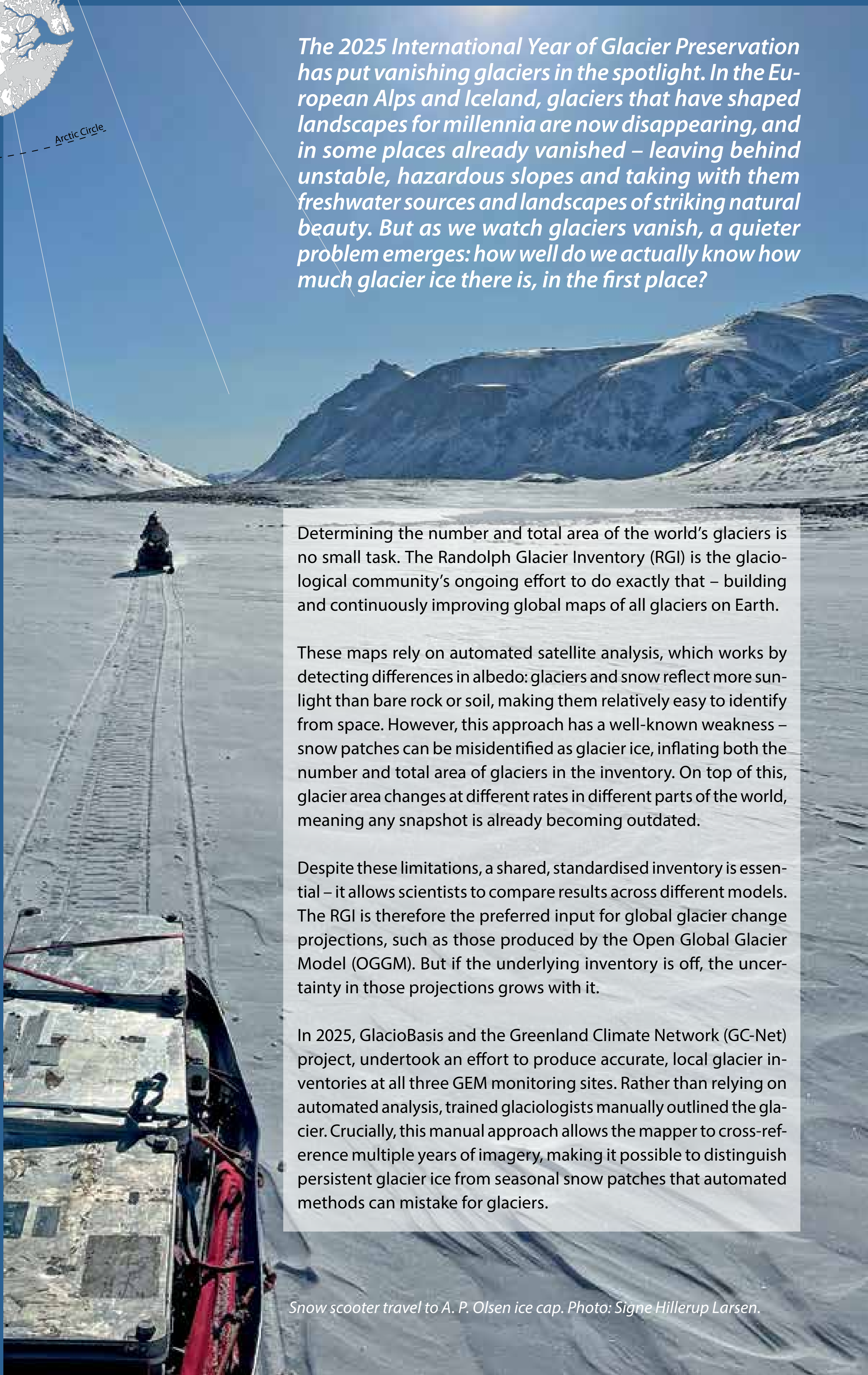
The 2025 International Year of Glacier Preservation has put vanishing glaciers in the spotlight. In the European Alps and Iceland, glaciers that have shaped landscapes for millennia are now disappearing, and in some places already vanished – leaving behind unstable, hazardous slopes and taking with them freshwater sources and landscapes of striking natural beauty. But as we watch glaciers vanish, a quieter problem emerges: how well do we actually know how much glacier ice there is, in the first place?

Determining the number and total area of the world's glaciers is no small task. The Randolph Glacier Inventory (RGI) is the glaciological community's ongoing effort to do exactly that – building and continuously improving global maps of all glaciers on Earth.

These maps rely on automated satellite analysis, which works by detecting differences in albedo: glaciers and snow reflect more sunlight than bare rock or soil, making them relatively easy to identify from space. However, this approach has a well-known weakness – snow patches can be misidentified as glacier ice, inflating both the number and total area of glaciers in the inventory. On top of this, glacier area changes at different rates in different parts of the world, meaning any snapshot is already becoming outdated.

Despite these limitations, a shared, standardised inventory is essential – it allows scientists to compare results across different models. The RGI is therefore the preferred input for global glacier change projections, such as those produced by the Open Global Glacier Model (OGGM). But if the underlying inventory is off, the uncertainty in those projections grows with it.

In 2025, GlacioBasis and the Greenland Climate Network (GC-Net) project, undertook an effort to produce accurate, local glacier inventories at all three GEM monitoring sites. Rather than relying on automated analysis, trained glaciologists manually outlined the glacier. Crucially, this manual approach allows the mapper to cross-reference multiple years of imagery, making it possible to distinguish persistent glacier ice from seasonal snow patches that automated methods can mistake for glaciers.



Snow scooter travel to A. P. Olsen ice cap. Photo: Signe Hillerup Larsen.

Authors:

Signe Hillerup Larsen[1], Alexandra Messerli[2] & Michele Citterio[1]

[1]GEUS

[2]Asiaq

Data source:

Data can be accessed on GEM database, https://data.g-e-m.dk
Glacier inventory:
https://data.g-e-m.dk/datasets/10.17897/TFSM-1S57

HOW MUCH GLACIER ICE

WHY LOCAL GLACIER STUDIES MATTER

GEM
Greenland Ecosystem Monitoring

When these manually produced outlines were compared to the RGI, the differences were striking (Table 1). At the Zackenberg site the total area of the main monitored glacier, the A.P. Olsen ice cap is overestimate by 11% (Fig. 1). Further south on the west coast, the results were even more dramatic: at the Kobbefjord site, Qassinnguit Sermiat is severely overestimated by 178% (Fig. 2), while at the Disko site, Lyngmarksbreen is overestimated by 45% (Fig. 3).

The degree of overestimation is not random – it is closely related to glacier size. Larger glaciers have proportionally smaller edges relative to their total area, so mapping errors around the margins matter less. Smaller glaciers, on the other hand, are far more vulnerable to misclassification, where a fringe of seasonal snow can represent a significant fraction of the mapped area as also seen clearly in our results (Table 1).

When looking at the number of glaciers the issue with misclassification is perhaps bigger. At the Zackenberg site we also made an inventory of all the glaciers in the area, and where the RGI identifies 30 individual ice bodies the manual mapping revealed only 15 (Fig. 4). In the context of the 2025 International Year of Glacier Preservation, having a reliable manual inventory means we can now begin confidently tracking which glaciers are vanishing – something automated inventories cannot yet offer.

2025 International Year of Glaciers' Preservation

Table 1. The difference in area over the three monitored glaciers in GEM.

Glacier	Manual area	RGI area	RGI – manual area	RGI overestimation
A. P. Olsen Ice cap	303.1 km² (2024)	337.7 km² (2001)	34.6 km²	11 %
Lyngmarksbreen	20.4 km² (2021)	29.6 km² (2001)	9.2 km²	45 %
Qassinnguit Sermiat	0.609 km² (2025)	1.699 km² (2001)	1.09 km²	178 %

Glacier area is widely used as an indicator of climate change, and on long timescales this is entirely justified. However, on annual to decadal timescales, caution is warranted. Seasonal snow patches can dramatically inflate mapped glacier area from one year to the next, making it difficult to distinguish real ice loss from mapping noise. This is precisely where local, manual mapping efforts like those carried out by GlacioBasis prove their value.

Our findings suggest that global glacier inventories are likely overestimating both the number and total area of glaciers worldwide – and that this has real consequences. Inflated area estimates feed directly into calculations of glacier volume and projections of freshwater flux, at a time when understanding these changes accurately has never been more important.

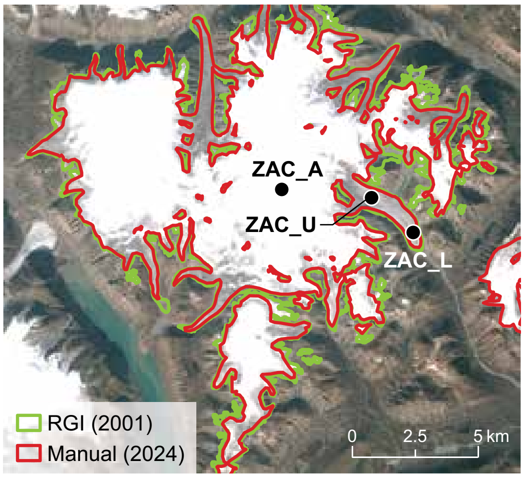


Figure 1. A.P. Olsen Ice Cap at the Zackenberg site, in red is the area detected manually and in green the area from the Randolph Glacier Inventory v7 (RGI).

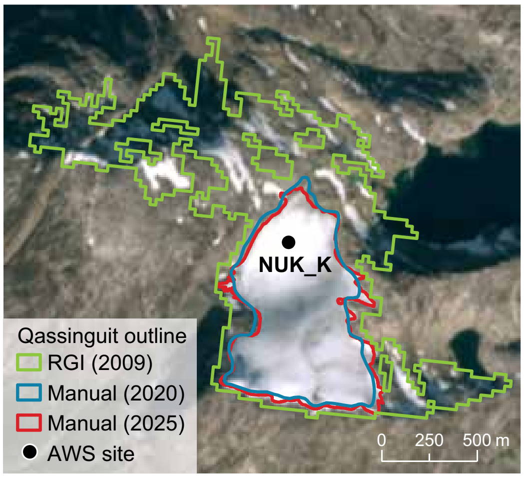


Figure 2. Qassinnguit Sermiat at the Kobbefjord site. The manually detected area is in red for 2025 and blue for 2020 and in green Randolph Glacier Inventory v7 (RGI).

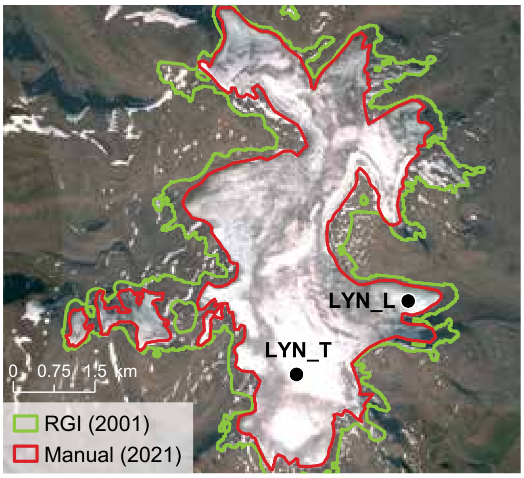


Figure 3. Lyngmarksbreen at the Disko site. Red marks the manually detected area in 2021 and in green the Randolph Glacier Inventory v7 (RGI).

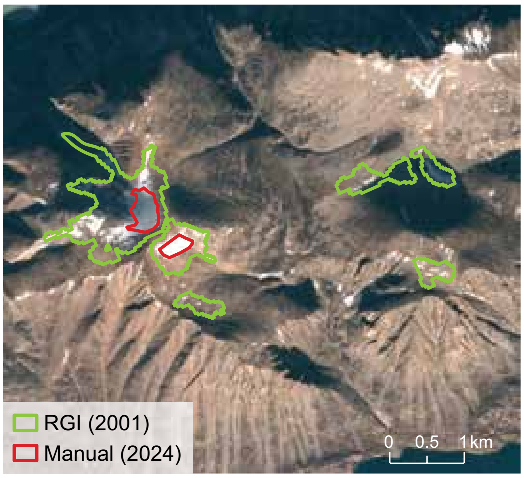


Figure 4. The top of Zackenberg mountain, where the Randolph Glacier Inventory v7 in green shows 6 distinct glacier bodies and the manually detected glacier area in red shows only 2.

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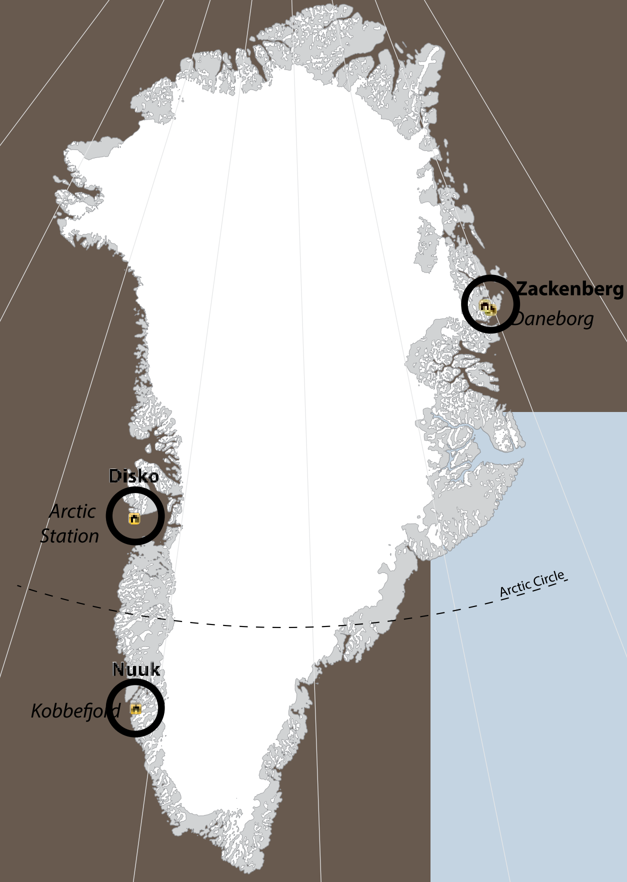
Photo: Charlotte Sigsgaard

WINTER FLUX DATA

NEW LIGHT ON ARCTIC ECOSYSTEM



Flux monitoring has taken place at the three GEM locations for many years, providing important insight into Arctic ecosystems and their responses to a changing climate. However, challenging conditions have led to a critical lack of measurements in the winter and shoulder seasons. Recent developments in offgrid power systems now provide opportunities for measurements when stations are not manned. All three GEM flux sites are currently operating into the wintertime, providing crucial data that help close the knowledge gap on the role of winter and shoulder season processes in the Arctic carbon budget.

The GEM locations Nuuk, Disko and Zackenberg represent a climate gradient from Low Arctic to High Arctic. Nuuk has no permafrost, Disko has discontinuous permafrost, and Zackenberg, with a mean annual temperature of –8.9 °C, has continuous permafrost. CO_2 flux and sensible and latent heat fluxes are currently measured at heath and fen sites in Nuuk and Zackenberg, and at a heath site in Disko. The fen sites in Nuuk and Zackenberg were established in 2007, while the Disko heath site was established in 2012; the Zackenberg heath tower has operated since 2000. These four sites are also part of the Integrated Carbon Observation System (ICOS), a European research infrastructure providing high-quality, standardized long-term measurements from a wide network of eddy covariance towers. All GEM eddy covariance stations use similar instrumentation, setup and data processing to ensure highquality, comparable data across sites.

Recent research conducted at other Arctic field sites has shown that wintertime and shoulder season processes play a larger role in the annual carbon budget of Arctic ecosystems than previously estimated (Natali et al., 2019; See et al., 2024). Observations in the winter and shoulder seasons are generally more scarce than growing season observations, but existing data do show that respiration occurring in this period potentially can offset large amounts of the carbon that is taken up during the growing season. Furthermore, this role may be amplified in the future, as increasing temperatures will drive a higher ecosystem respiration. Winter and shoulder season flux data from the GEM sites are therefore extremely valuable for strengthening our understanding of Arctic ecosystems and their feedbacks.

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Data source:

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

GeoBasis – Flux monitoring and the ICOS data portal

FROM GEM SITES SHEDS

FUNCTIONING AND FEEDBACKS

Measurements in the wintertime have taken place at the heath site in Disko for almost as long as the eddy covariance tower has existed, with only short gaps due to instrument failure or power shortages. This high data coverage is possible because the station is manned yearround and has access to direct power. The stations in Nuuk and Zackenberg are inaccessible for large parts of the year, and winter conditions are very harsh, so flux measurements have long been limited to periods when stations were physically manned. With the development of robust offgrid power systems based on solar, wind and fuel cells, it is now possible to keep these stations operating into the winter. This was first achieved at the Zackenberg fen in winter 2021/2022, and varying setups have been tested since. Another winter setup was tested for the first time in Nuuk in winter 2024/2025. Thus, 2024/2025 was the first winter season with partial winter flux data at all three GEM locations.

Figure 1 shows the measured CO_2 flux at the fen sites in Nuuk and Zackenberg and the heath site in Disko in 2024 and 2025. In 2024, Zackenberg Fen had very high data coverage; 2025 had more gaps, though even fewer observations can still support later gapfilling. An offgrid solar and windbased power system was installed at Nuuk Fen in autumn 2024. It unfortunately shut off in early November but powered back on in February when more solar energy became available. Since the station was not physically manned until June because of ice in Kobbefjord, all spring data would have been lost without the offgrid system. Winter fluxes at Zackenberg Fen and Nuuk Fen are generally low but still influence the annual carbon budget because the winter period is so long compared to the short growing season. In the shoulder seasons, during spring thaw and autumn freeze, larger respiration bursts sometimes occur, as seen at Zackenberg Fen in spring 2024. These events are also important to capture. Winter fluxes at Disko are more variable, which is expected given the generally lower snow cover compared to Zackenberg and Nuuk. Continuous winter and shoulderseason measurements at all three sites will only grow in importance as climate change affects ecosystems in different and sometimes unpredictable ways.

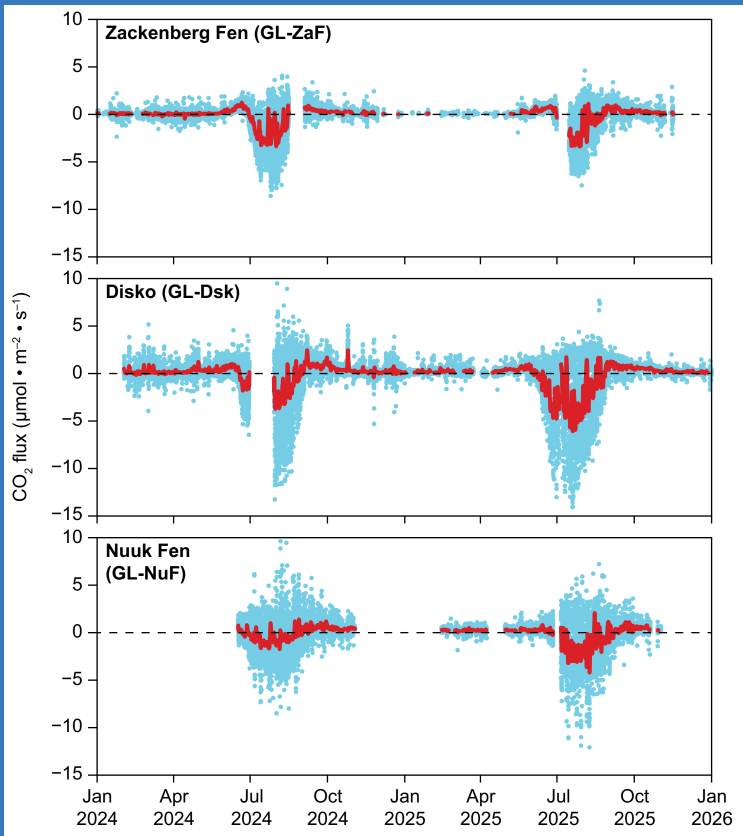

Figure 1. CO_2 flux measured at the eddy covariance sites Zackenberg fen, Disko, and Nuuk Fen. The blue dots are measured data (30-minute averages), and the red lines are daily averages.

All in all, challenges to measuring flux data in harsh Arctic winter conditions remain, but continued improvements in offgrid power systems will hopefully enable even greater temporal coverage at the GEM flux sites in the years to come. This will allow researchers to monitor how the different ecosystems respond to a changing climate throughout the year and help close the knowledge gap on winter and shoulderseason processes.

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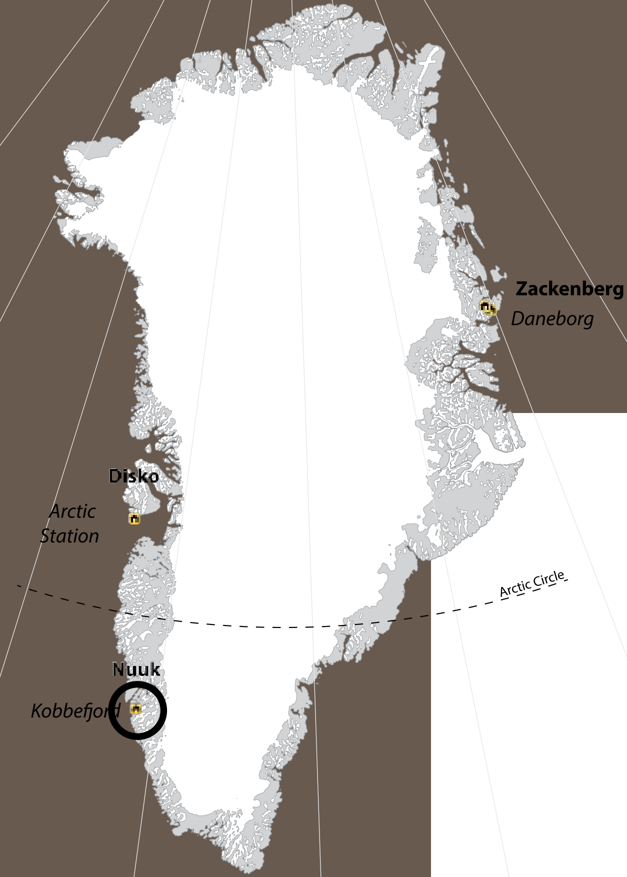

Annual Report Card 2025

IN SITU TO SATELLITE

WHY WE NEED BOTH

Greening phenology is monitored in 20 permanent plant plots in Kangerluarsunnguaq (Kobbefjord) using a handheld RapidScan. Comparing these measurements to satellite-derived NDVI from Sentinel-2 imagery revealed systematic difference, with Sentinel-2 overestimating greenness at low RapidScan values and under-estimating it at high values. When analysed separately, satellite NDVI showed higher baseline greenness and a stronger positive temporal trend than RapidScan NDVI. In other words, when estimating Arctic greening both level and rate of any change depends on the method used.

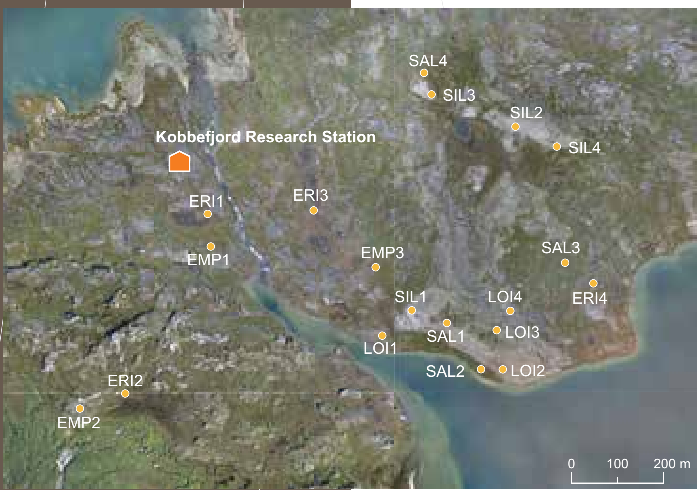

Figure 1. BioBasis Nuuk plots where NDVI is measured. Plots represent a variety of widely distributed habitats (from high to low NDVI) with focus on the plant species Loiseleuria procumbens, Silene acaulis, Empetrum nigrum, Salix glauca, *and* Eriophorum angistifolium.

Authors:

Ida Bomholt Dyrholm Jacobsen[1,2], Niels Martin Schmidt[2] & Katrine Raundrup[1]

[1]Greenland Institute of Natural Resources

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Data source:

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

BioBasis Nuuk Plot NDVI: https://doi.org/10.17897/TQTT-EV69

Main

The BioBasis Nuuk program monitors greening (vegetative) and reproductive phenology in 20 plots in Kangerluarsunnguaq (Kobbefjord, Fig. 1 MAP). Monitoring is done weekly in the snow free season between May and October. Since 2018, the Normalized Difference Vegetation Index (NDVI) monitoring has been done using a handheld RapidScan CS-45 sensor. While the RapidScan sensor measures at a spatial scale able to account for landscape heterogeneity, these measurements are limited by accessibility. Free satellite imagery provides coverage of much larger spatial extend but at the expense of capturing fine scale heterogeneity.

We compared NDVI derived from a handheld RapidScan sensor with NDVI extracted from Sentinel-2 imagery across 20 plots during five months, and seven years from the BioBasis program in Kangerluarsunnguaq. To quantify the relationship between the two types of NDVI-measurements, we fitted linear mixed-effects models that accounted for the structure of the sampling: plots, months, and years.

RapidScan measurements capture reflectance at very fine spatial (app. 20 cm × 80 cm or 0.16 m^2 footprint) while Sentinel-2 pixels (10 m resolution) integrate heterogeneous tundra surfaces. Because vegetation in Arctic systems is structured at small spatial scales and strongly influenced by microtopography and moisture gradients, differences in measurement scale are expected to influence both NDVI magnitude and inferred change. Our comparison aimed to quantify the relationship between in-situ and satellite observations rather than to validate one against the other. Sentinel 2 NDVI data was extracted with Google Earth Engine and limited to images within +/- 2 days of an in-situ measurement.

The mixed-effects model revealed a systematic deviation between the sensors (Fig. 2). The slope of the relationship between RapidScan and Sentinel NDVI was substantially lower than 1, indicating range compression at the satellite scale relative to the. Specifically, satellite NDVI tends to overestimate greenness at low RapidScan values and underestimate greenness at high RapidScan values.

NDVI:

The observed compression of Sentinel NDVI range is consistent with known effects of pixel-mixing in heterogeneous tundra landscapes. A single Sentinel 2 pixel might integrate a variety of, oftentimes very different, habitats. In sparsely vegetated areas (Fig. 4), small, vegetated patches can disproportionately influence pixel reflectance, leading to higher satellite NDVI relative to on the ground measurements. In densely vegetated habitats (Fig. 5), canopy complexity and NDVI saturation reduce sensitivity at high biomass levels, resulting in underestimation. Soil and background reflectance effects are particularly influential in discontinuous Arctic vegetation and likely contribute to the observed deviations.

Satellite-derived NDVI exhibited a statistically significant higher overall baseline level (intercept ≈ 0.47) and a stronger positive temporal trend (≈ 0.0063 NDVI units per year) than the RapidScan measurements (Fig. 3). RapidScan NDVI showed a lower baseline level (≈ 0.40) and a more moderate rate of increase (≈ 0.0029 NDVI units per year). Thus, the large-scale satellite data suggest both higher average greenness and more pronounced greening over time compared to the local-scale RapidScan measurements.

These results demonstrate that differently scaled NDVI measurements yield systematically different representations of Arctic vegetation dynamics. Satellite platforms such as Sentinel 2 and Landsat provide essential spatial continuity coverage necessary for detecting regional greening trends but potentially on a compressed scale. RapidScan measurements offer high-resolution insight into vegetation structure and microscale variation. Neither should be considered inherently more accurate; each captures a distinct projection of ecosystem state. Robust long-term monitoring in the Arctic regions require integration of both satellite and in situ data to constrain interpretation and fully characterise vegetation change across scales.

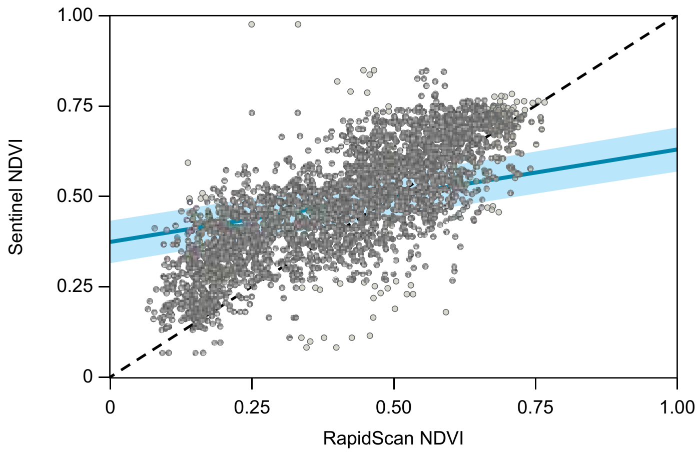

Figure 2. Comparison of the Sentinel2 NDVI and RapidScan NDVI. Blue line represents an estimate of mixed linear modelling accounting for both plot, month/phenology and year.

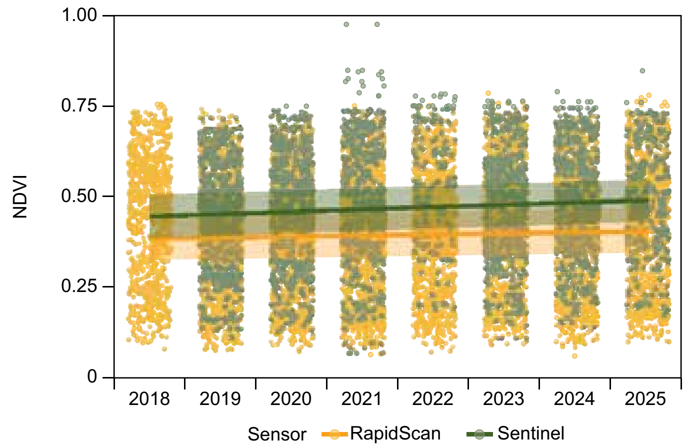

Figure 3. Mixed linear model of Sentinel2 and RapidScan data respectively. Accounting for plot and phenology in both, data from the two sensors yild different levels of NDVI and different rates of change from 2018/2019–2025.

Figure 4. Example of NDVI plot with low level of NDVI: Silene acaulis *(SIL1). Photo: BioBasis August 15th, 2025.*

Figure 5. Example of NDVI plot with high level of NDVI: Salix glauca *(SAL4). Photo: BioBasis August 15th, 2025.*

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CLIMATE CHANGE

OLIGOTROPHICATION IN A

Two decades of ecosystem monitoring in Northeast Greenland reveal a strong decline in nutrients and phytoplankton in Young Sound. Long-term GEM data show how tundra greening and fresher, nitrate-poor coastal waters are reducing nutrient availability and phytoplankton biomass, with potential consequences for Arctic food webs and carbon cycling. Our findings underscore the importance of sustained, integrated monitoring across land, rivers, and coastal seas for detecting emerging ecosystem feedbacks.

Arctic fjords are the downstream endpoint of terrestrial and riverine processes, while at the same time being shaped by exchanges with the adjacent coastal ocean. As the Arctic warms, tundra vegetation is greening and freshwater influence from glaciers and rivers is increasing, altering land–sea nutrient pathways and, in turn, coastal productivity and ecosystem functioning.

Using more than 20 years of coordinated ecosystem-wide monitoring across the terrestrial-river-fjord continuum in Young Sound in Northeast Greenland, we quantified long-term changes in nutrient supply and ecosystem response. We found a pronounced decline in summer nitrate concentrations (~49%) and phytoplankton biomass (~60%) in the fjord (Fig. 1A,B). Over the same period, tundra vegetation greenness increased by ~12%. This likely reflects greater nitrogen retention on land, leading to an apparent ~65% reduction in riverine nitrate input to the fjord (Fig. 1C,D). Together with inflow of fresher, nitrate-poor coastal waters, these processes help to explain the sustained observed decline in phytoplankton biomass.

Authors:

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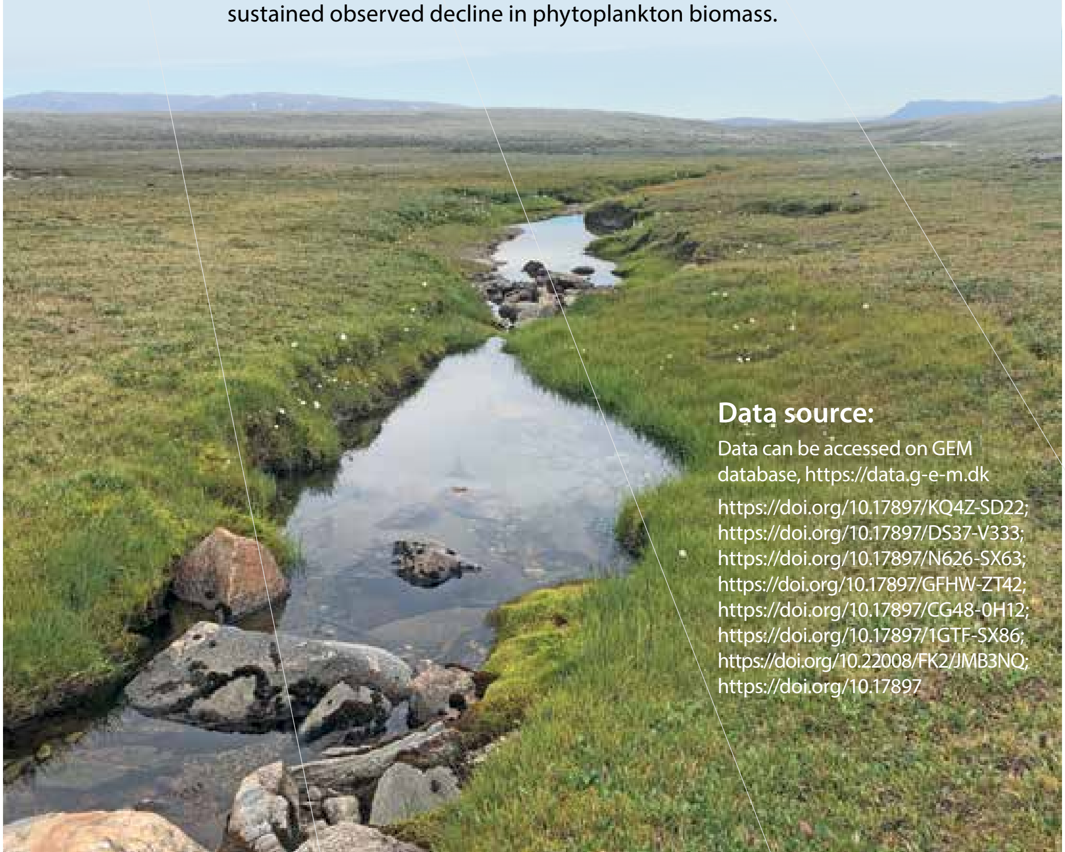
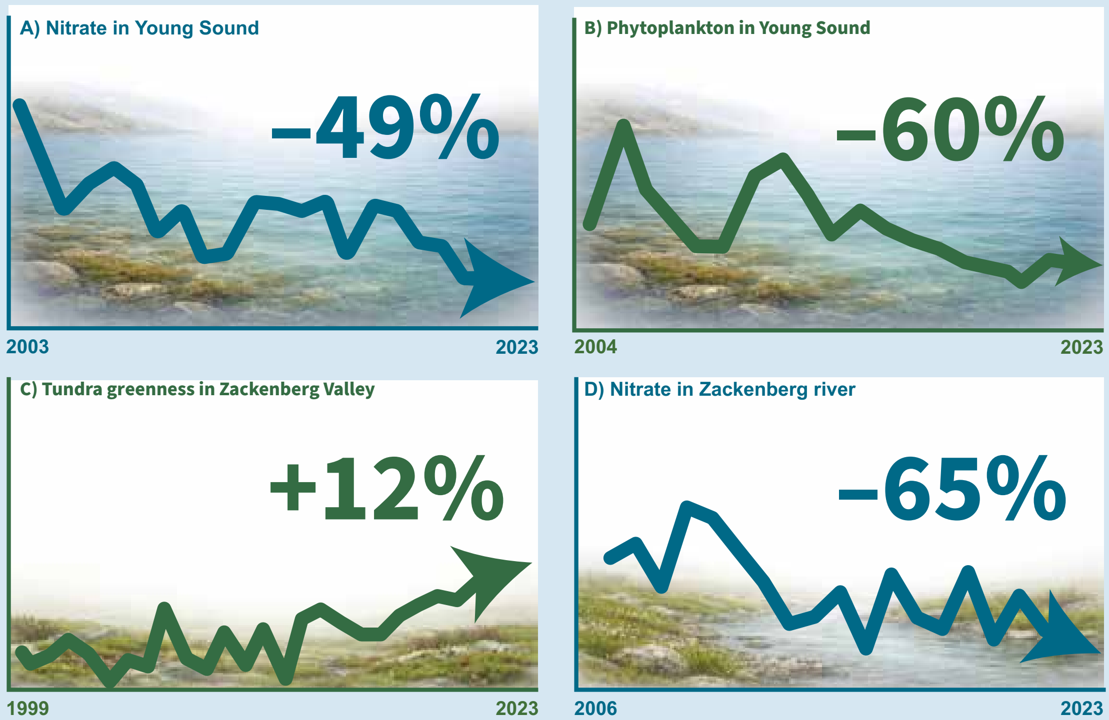


Data source:

Data can be accessed on GEM database, https://data.g-e-m.dk
https://doi.org/10.17897/KQ4Z-SD22; https://doi.org/10.17897/DS37-V333; https://doi.org/10.17897/N626-SX63; https://doi.org/10.17897/GFHW-ZT42; https://doi.org/10.17897/CG48-0H12; https://doi.org/10.17897/1GTF-SX86; https://doi.org/10.22008/FK2/JMB3NQ; https://doi.org/10.17897

DRIVES COASTAL
HIGH-ARCTIC FJORD

Greenland Ecosystem Monitoring



Why this matters

Understanding how climate change propagates across connected ecosystems is essential for predicting future Arctic productivity. Locally, reduced nutrient supply can lower primary production and cascade through fjord food webs that support plankton, fish, seabirds, and marine mammals. Similar land-sea interactions may also influence other Greenland catchments and fjords and Arctic shelf seas. At a larger scale, and because coastal primary production influences carbon uptake and export, nutrient-driven changes in fjords also matter for the Arctic carbon cycling and climate feedbacks.

New insight

This cross-cutting study provides rare long-term, observational evidence from the High Arctic that warming and concomitant terrestrial greening can reduce coastal productivity when terrestrial greening and changing coastal water masses jointly limit nutrient supply. Our findings challenge the common expectation that longer ice-free conditions will necessarily increase Arctic marine productivity and highlight the importance of sustained, integrated monitoring that captures linkages across the terrestrial-river-fjord continuum for detecting emerging ecosystem feedbacks.

Biodiver
Populati

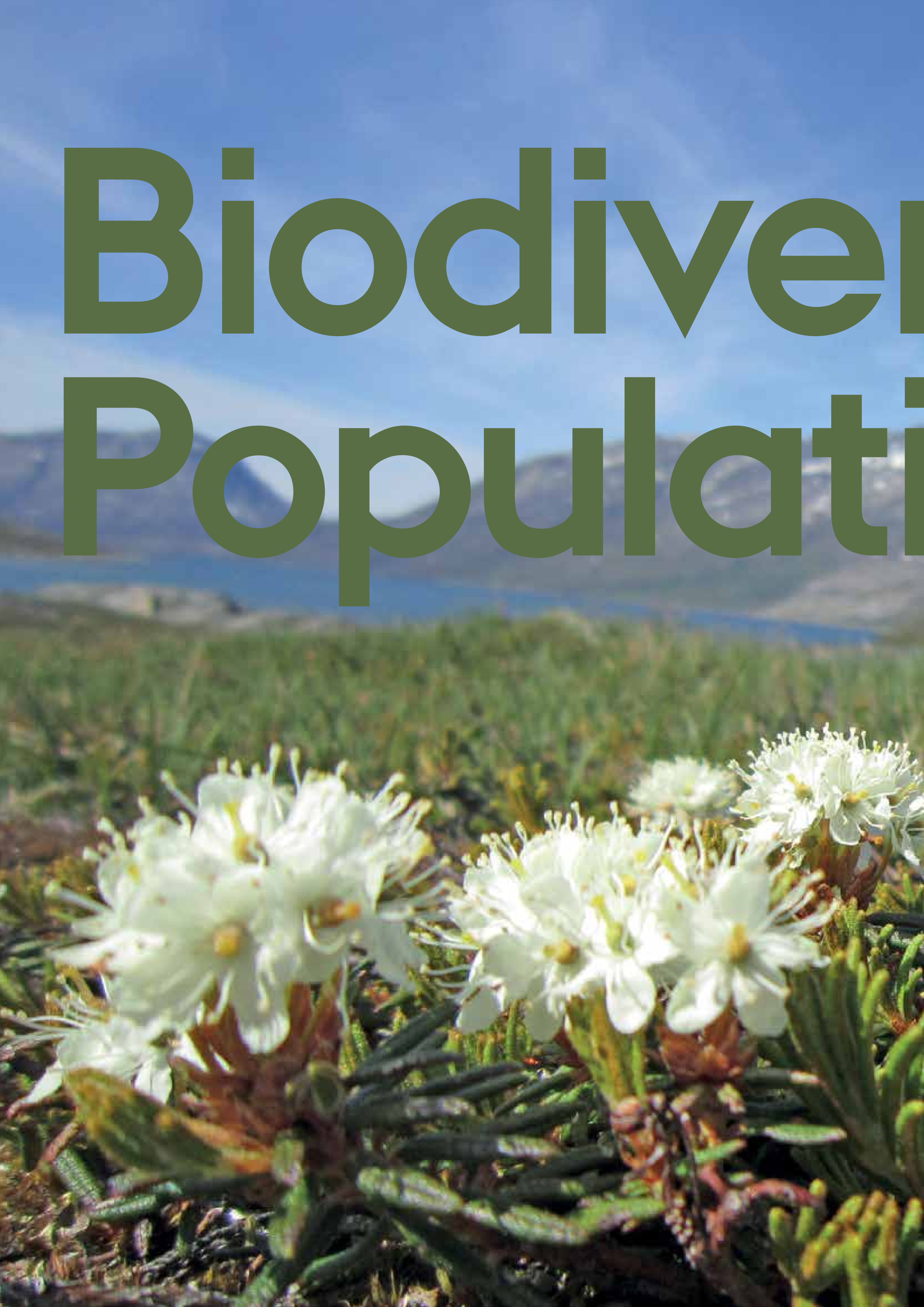


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Photo: Katrine Raundrup.

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REDUCED GROWTH

IN AN EARLY ARCTIC SUMMER CANNOT

In northeast Greenland, an exceptionally early summer created the largest recorded mismatch between Sanderling hatch dates and arthropod phenology, potentially causing reduced chick growth due to food shortage. Indeed, chicks grew markedly worse in this extreme year, especially in the first week of life, and they did not compensate later. However, poor growth was not explained by food shortage alone: growth reflected the combined effects of prey biomass, temperature, wind and likely intrinsic or early-life constraints. As extreme seasons become more frequent, multi-causal, spatially explicit monitoring is essential for predicting climate impacts on Arctic wildlife.

Sticky trap.
Photo: Jeroen Reneerkens

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[1]Aarhus University, Department of Ecoscience, Denmark

[2]Netherlands Institute for Sea Research, Texel, the Netherlands

Data source:

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

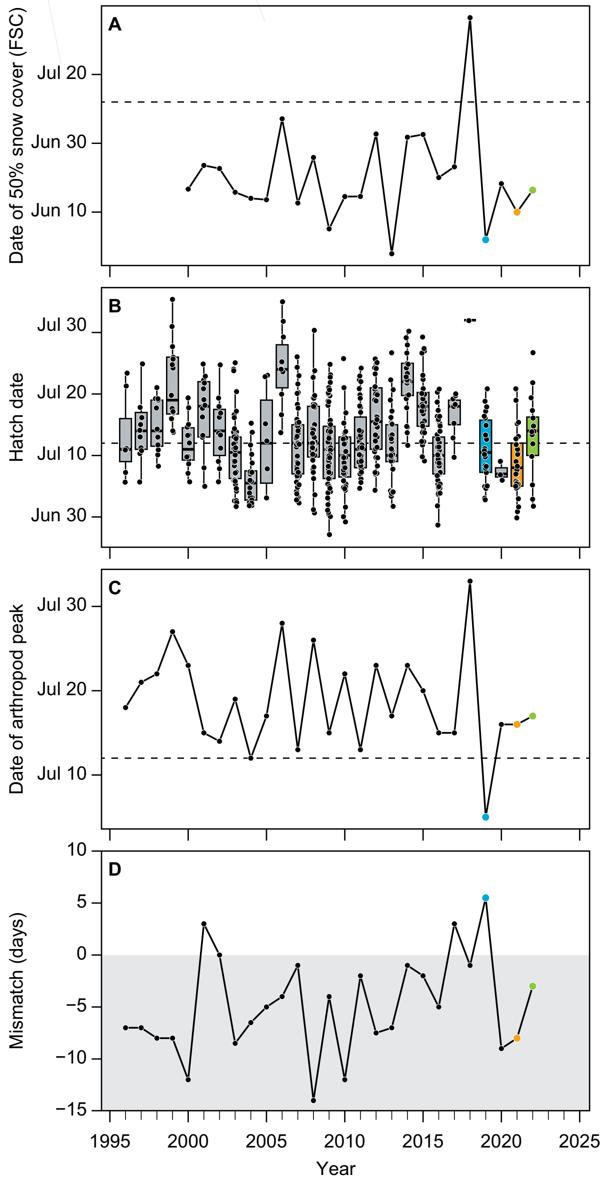
Bird breeding phenology: https://data.g-e-m.dk/datasets/10.17897/5S51-HE52

Arthropods: https://data.g-e-m.dk/datasets/10.17897/KBN7-WP73

GEM ClimateBasis:

Air temperature: https://data.g-e-m.dk/datasets/10.17897/9V7J-Z845

Wind speed: https://data.g-e-m.dk/datasets/10.17897/M0Q9-S706



Arctic-breeding shorebirds depend on a short summer season in which snowmelt, insect emergence and chick development must align closely. Climate change is expected to increase the frequency of extreme years, making it essential to understand how such events affect trophic interactions and offspring development. Long-term monitoring at Zackenberg, northeast Greenland, provides a unique opportunity to place extreme seasons in the context of decades of environmental and biological data.

Using 27 years of monitoring data (1996–2022), combined with detailed field studies of Sanderling *Calidris alba* chicks in 2019, 2021 and 2022, we investigated how variation in arthropod availability, weather conditions and breeding phenology affects chick growth. In Zackenberg, we observe no strong long-term directional trends in summer temperature, snowmelt timing or arthropod phenology. However, 2019 stood out as an exceptionally early year, with the second earliest snowmelt and the earliest arthropod phenology recorded.

Figure 1. Timing of snowmelt, arthropod phenology and Sanderling hatch dates at Zackenberg (1996–2022), highlighting the extreme mismatch in 2019.

OF SHOREBIRD CHICKS

BE EXPLAINED BY FOOD SHORTAGE ALONE

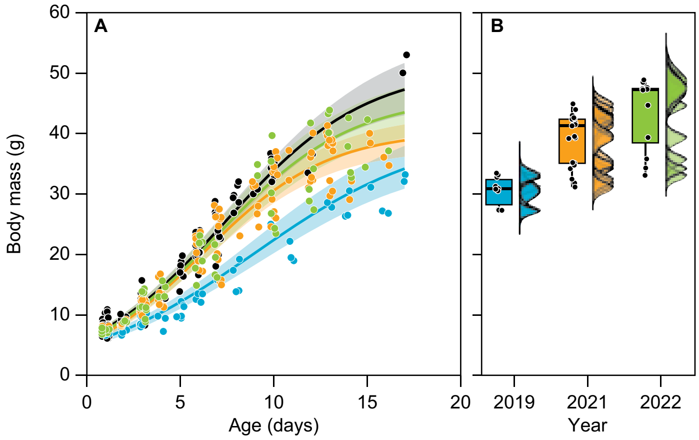


Figure 2. (A) Annual growth curves and fledging weights of Sanderling chicks in 2019 (blue), 2021 (orange) and 2022 (green), compared with data from 1996-2017 (black) indicate strongly reduced growth and fledging mass (B) in the extreme early year 2019.

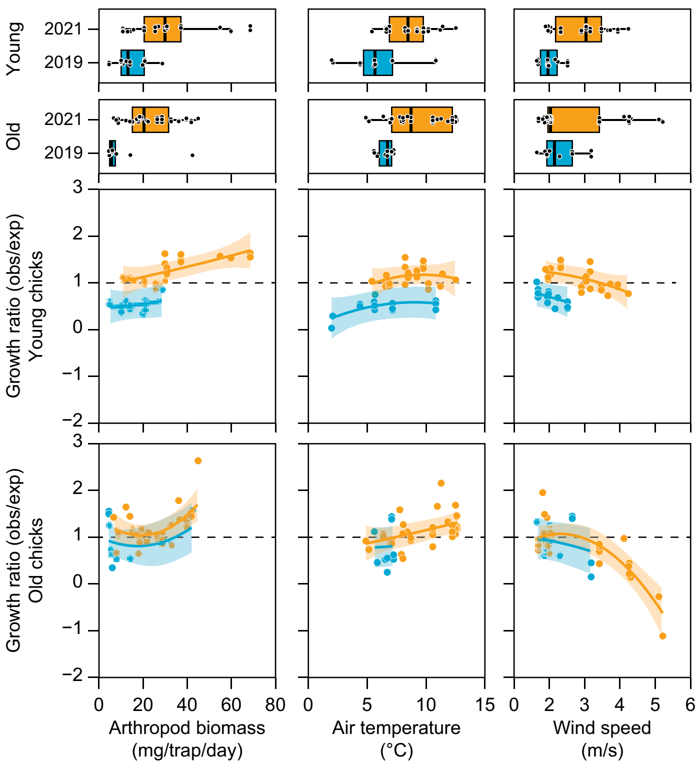


Figure 3. Relationships between short-term chick growth rates and arthropod biomass, air temperature and wind speed, illustrating the combined effects of food and weather. The data are shown separately for chicks in their first week of life (Young chicks) and in their second week of life until fledging (Old chicks).

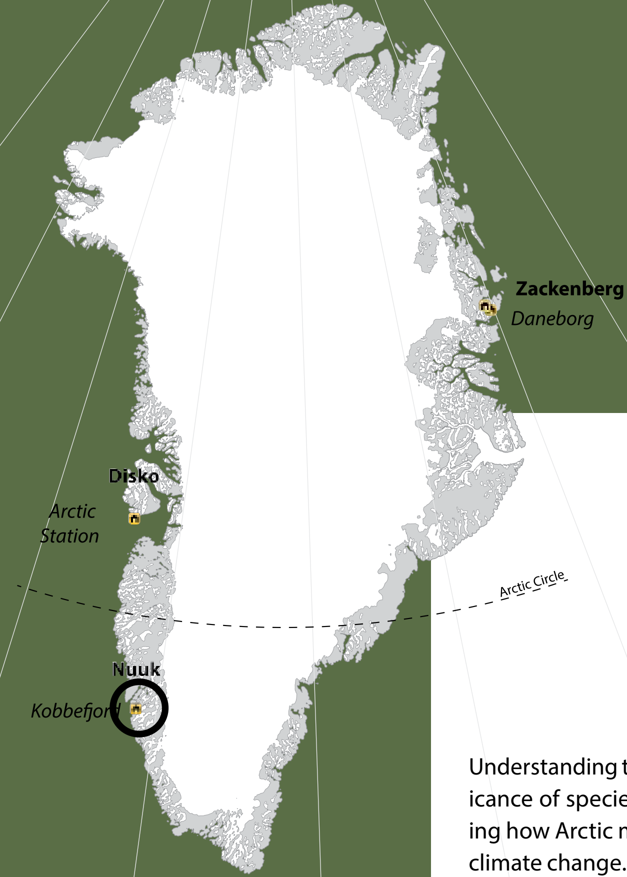
In that early year 2019, Sanderling chicks hatched well after the peak in arthropod biomass, creating the largest trophic mismatch observed since monitoring began. Chick growth in this year was markedly poorer than in 2021 and 2022, and also poorer than the long-term average. This reduction in growth was driven almost entirely by young chicks in their first week of life. Importantly, chicks that grew slowly early on did not show compensatory growth later, resulting in substantially lower fledging weights.

Despite this strong mismatch, poor growth in 2019 could not be explained by food shortage alone. Mean arthropod biomass during the chick period was not exceptionally low compared to the long-term record, and variation in fledging weight among broods was not explained by average prey abundance, temperature or wind speed. Short-term growth rates were best explained by the combined effects of prey availability, air temperature and wind speed, highlighting that chick growth is shaped by multiple interacting factors rather than a single limiting resource.

A key insight from our study is the importance of spatial heterogeneity in food availability. Arthropod biomass varied strongly among locations were families foraged, even on the same day. By measuring prey availability directly at the locations used by individual broods, we uniquely measured food conditions as experienced by chicks as good as possible.

Importantly, even when young chicks in 2019 experienced similar prey availability and weather conditions as chicks in 2021, their growth remained poorer. This suggests that additional constraints played a role, such as early-life conditions or maternal effects acting through incubation behaviour, egg characteristics or hormonal pathways. These factors are rarely included in studies of trophic mismatches yet may be critical for understanding growth responses in extreme years.

Our findings demonstrate that extreme phenological years can produce strong trophic mismatches, but that their biological consequences do not follow a simple food-limitation pathway. Instead, chick growth reflects the combined influence of food, weather and intrinsic factors. As extreme summers are expected to become more frequent in the Arctic, understanding these multi-causal pathways is essential for predicting how climate variability will affect Arctic food webs and migratory bird populations.



ABRUPT LOSS IN DIVERSITY SIGNALS REGIME

MarinBasis-Nuuk detected an abrupt decrease in microplankton species richness in Nuup Kangerlua, signalling how changes in ocean inflow may reshape Arctic fjord ecosystems. This regime shift, linked to coastal water dynamics, offers critical insight into the potential future of Arctic marine biodiversity under warming scenarios.

Understanding the dynamics and ecological significance of species richness is essential for predicting how Arctic marine ecosystems will respond to climate change. In this study, a 15-year time series from Nuup Kangerlua revealed that microplankton species richness (taxa >20 µm) dropped abruptly from an average of 37 species per sample (2009–2012) to just 17 species from 2013 onwards.

This ecological shift followed changes in the inflow of Atlantic-type water (ATW) from the coastal shelf into the fjord. During the high-richness period (2009–2013), substantial ATW inflow was associated with elevated surface temperatures and significantly higher nitrate concentrations. Nitrate is typically a limiting nutrient in Arctic fjords; its increased availability likely supported higher species richness, consistent with Species-Energy theory. Interestingly, the ATW did not appear to directly introduce temperate species but rather created environmental conditions such as higher temperatures and nutrients, that supported a more diverse local community. The study demonstrates that these changes represent a true regime shift, characterized by altered correlations between species richness and environmental drivers like salinity and nutrients.

The findings demonstrate that even short-term climatic events can trigger lasting ecological regime shifts, with potential consequences for food web stability, fisheries productivity, and biogeochemical cycling. These insights serve as critical evidence of ecosystem tipping points and constitute important indicators in the ongoing climate impact monitoring by the Greenland Ecosystem Monitoring (GEM) programme. They also provide valuable knowledge for national and regional ecosystem assessments. Despite the time series being rather short in a climate change perspective, it also shows how even shorter time series can reveal how ecosystem changes can affect biodiversity. This knowledge of shorter-term dynamics can help to predict effects of long-term changes, such as climate warming, on biodiversity.

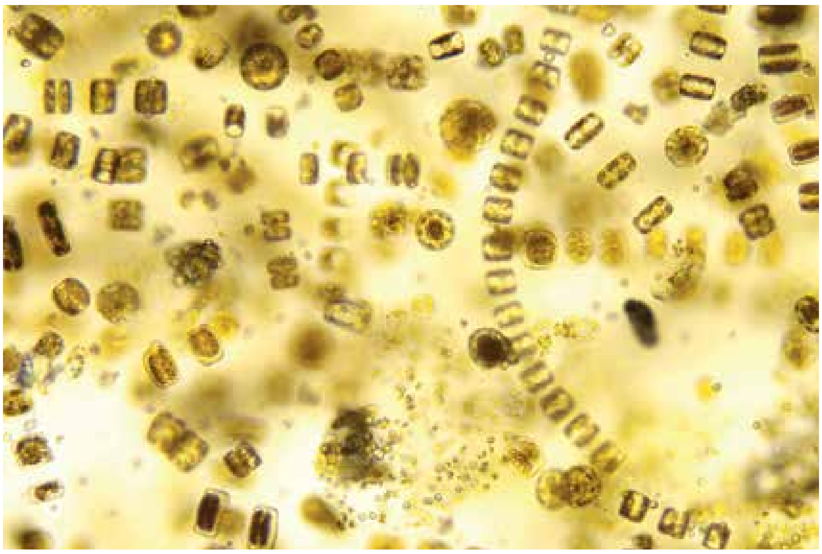


Figure 1. Typical phytoplankton community during the spring bloom in Nuup Kangerlua with abundant Thalassiosira *spp. and* Phaeocystis *sp. colonies*

Authors:

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Data source:

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

Protist composition data: https://doi.org/10.17897/Y3A4-9D86

Nutrients: https://doi.org/10.17897/3NQX-FA50

CTD data: https://doi.org/10.17897/KMEK-TK21

MICROPLANKTON
SHIFT IN ARCTIC FJORD

Figure 2. Phytoplankton net sampling in Nuup Kangerlua during the monthly monitoring.

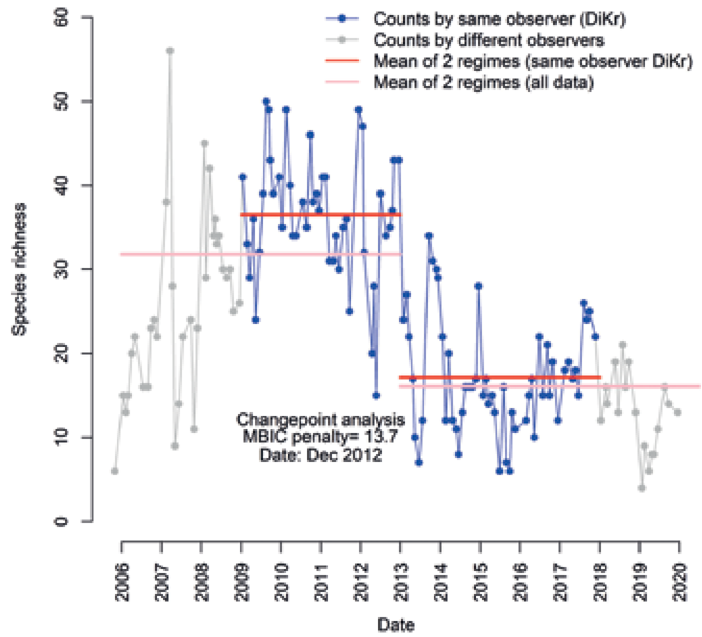

Figure 3. Changes in protist species richness (number of different species) over the time serios of MBN. Statistical changepoint analyses found a significant changepoint in 2012. (Vonnahme et al., 2025).

These results highlight the sensitivity of Arctic ecosystems to Atlantification, offering a window into how similar patterns may unfold elsewhere under climate change. For stakeholders and policymakers, monitoring such biodiversity tipping points is vital to inform conservation efforts and adaptation strategies.

This study was conducted in close collaboration between MarinBasis-Nuuk and FACE-IT – The Future of Arctic Coastal Ecosystems (EU Grant: 869154).

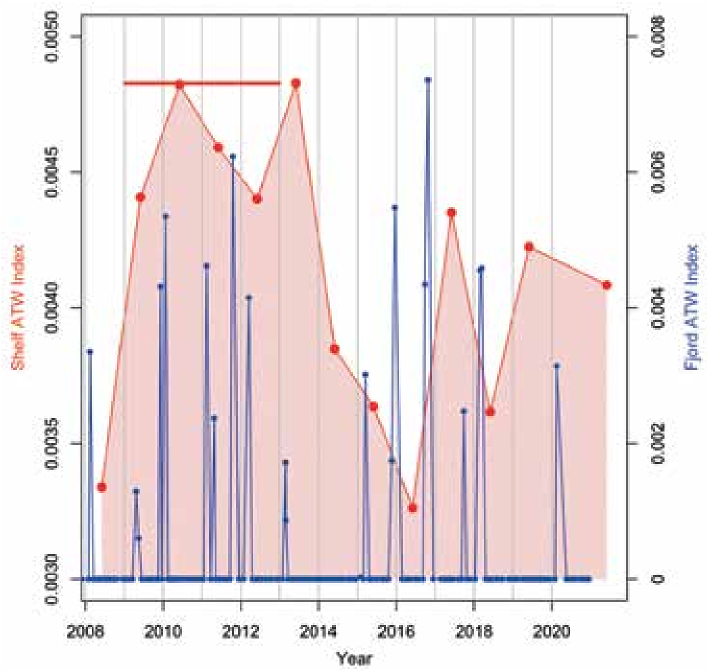

Figure 4. Changes in Atlantic type water index (modified after Skogseth et al., 2020) which takes the volume and temperature of coastal subpolar mode water into account. Annual data for the shelf break outside Nuuk are given in red, and monthly data for the mouth of Nuup Kangerlua (main MBN monitoring station) are given in blue. (Vonnahme et al., 2025).

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Skogseth, R., Olivier, L. L., Nilsen, F., Falck, E., Fraser, N., Tverberg, V., ... & Falk-Petersen, S. (2020). Variability and decadal trends in the Isfjorden (Svalbard) ocean climate and circulation–An indicator for climate change in the European Arctic. Progress in Oceanography, 187, 102394.

NEWCOMERS ON – THE SPREAD OF WASPS

The consequences of climate change coupled with increased international trade and tourism are paving the way for new species to arrive in Greenland. The findings of social wasps (Vespinae) in window traps and pitfall traps monitored by BioBasis in Kobbefjord sparked an investigation into the spread of wasps in Greenland, revealing two new species for the country with rapid range expansions during the last years. Social wasps are ferocious predators of other invertebrates and will settle as top predators in terrestrial arthropod communities in Greenland. As such, their introduction could potentially rewire or weaken terrestrial interaction networks such as food webs and pollinator networks.

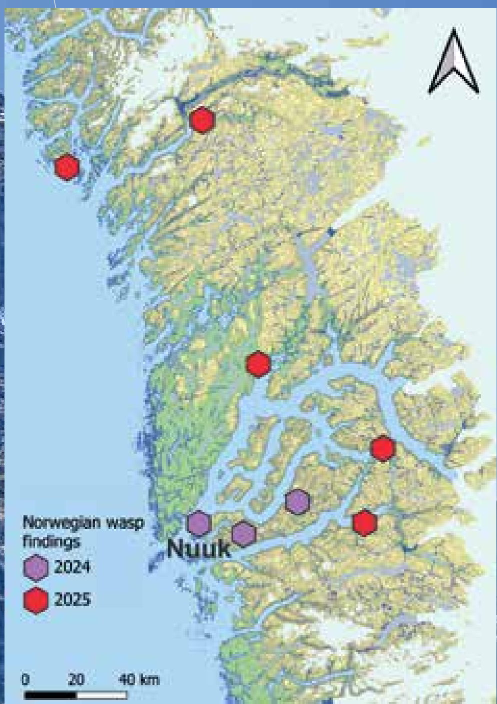

Figure 1. The distribution of the Norwegian wasp Dolichovespula norwegica *in Greenland during 2024 and 2025.*

Social wasps (Vespinae) have historically been absent from Greenland. However, in 2024 several Red wasps (*Vespula rufa* (Linnaeus)) and Norwegian wasps (*Doliochovespula norwegica* (Fabricius)) were found in pitfall and window pitfall traps monitored by BioBasis in Kobbefjord in Kobbefjord. While both are Holarctic species, their coloration patterns suggest the populations in Greenland are of European origin. Due to the detrimental ecological effects of their close relatives in other parts of the world, it is of high importance that the effect of these introductions is monitored and evaluated. Using reports of wasps with pictures sent to Greenland Institute of Natural Resources, active search, and iNaturalist observations, coupled with a public call to report on wasp sightings in the country during 2025, the spread and distribution of these newcomers to Greenland was mapped.

Authors:

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Swedish University of Agricultural Sciences

Data source:

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

BioBasis Nuuk Kobbefjord

Arthropod data: https://doi.org/10.17897/KBN7-WP73

THE MOVE
IN GREENLAND

GEM
Greenland Ecosystem Monitoring

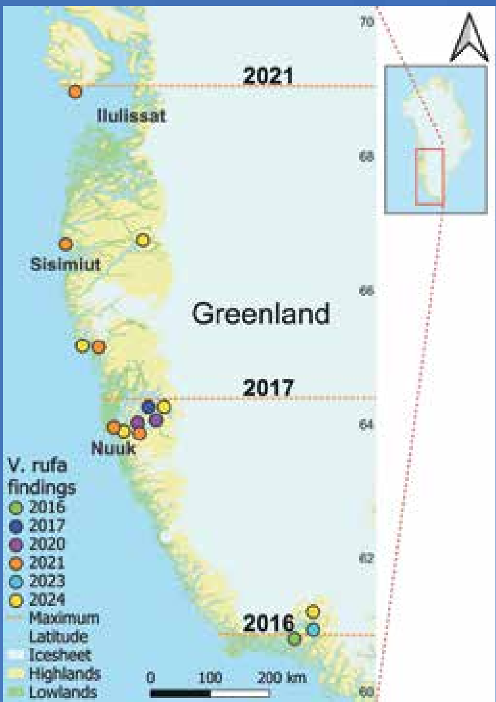

Figure 2. The distribution and spread of the Red wasp Vespula rufa *in Greenland between 2016 and 2024. No sightings were reported in 2025. Note that the findings from Narsarsuaq in 2014 are not included, as they have not been fully verified yet. Dashed lines marks the northernmost finding for each given year.*

The Red wasp was first sighted in 2014 in Narsarsuaq (south Greenland) and has since spread northwards, with sightings all the way north to Qeqertarsuaq in 2021. Its strongholds with queens and nests sighted seem to be in south Greenland and around Nuuk. Strangely, there were no reports of the Red wasp in 2025 from anywhere in the country. It is noteworthy that all records of the Red wasp are close to major settlements and/or main airports. This spotty distribution could reflect an association with inhabited areas, suggesting that the Red wasp cannot survive in uninhabited parts of Greenland.

The Norwegian wasp was first discovered in discovered in BioBasis' pitfall and window traps around Kobbefjord Research Station in 2024. Citizen reports and active search during the same year revealed a broader distribution within the Nuuk fjord area. In 2025, the species was again spotted in Kobbefjord and around Nuuk. In addition, it was reported from Kapisillit (~ 40 km east of nearest 2024 sightings), Maniitsoq (~ 150 km north of Nuuk), and even at the end of Isortoq fjord (~ 60 km from the nearest town Maniitsoq). This suggest that the Norwegian wasp is on a quick expansion and might be able to survive the Greenlandic winters outside of towns and settlements, potentially spreading further into the uninhabited parts of the country compared to the Red wasp.

The historical lack of wasps in Greenland should raise concerns about their potential effects on native species, especially considering the detrimental effects that vespid introductions have had on food webs in other parts of the world. Importantly, Greenland lacks generalist arthropod predators. While spiders partly fill this niche, social wasps are locally often more numerous and more voracious than the spiders and consume the spiders themselves. This will likely result in them settling as top predators within arthropod communities in Greenland. However, no studies have examined the effects of social wasp introductions in novel Arctic environments. As such, it remains unknown what effects the Red and Norwegian wasp will have on local interaction networks in Greenland.

*Figure 3. Lateral view of a Norwegian wasp (*Dolichovespula norwegica*) worker.*

*Figure 4. Lateral view of a Red wasp (*Vespula rufa*) worker.*

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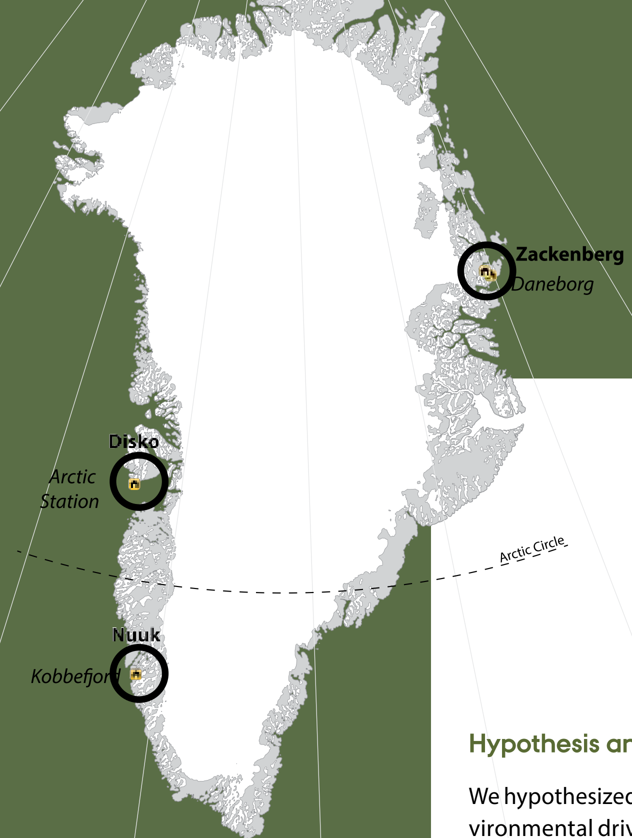

TRENDS IN CLIMATE AND MARINE BIOTA ACROSS

We assessed cumulative change in climate-related environmental drivers across Greenland's marine ecosystems and found that West, East, and Southeast Greenland are hot spots of environmental change. Responses of Greenland marine biota reflected the spatial variation in cumulative environmental change by showing the largest proportion of significant trends in those hotspot regions.

Hypothesis and approach

We hypothesized that trends of climate-related environmental drivers vary regionally across Greenland and are reflected in responses of marine biota. To test this hypothesis, we quantified the rate of change in key climate-related environmental variables across Greenland and compared it with trends in marine biota. The targeted environmental drivers were sea ice concentration, sea ice seasonality, sea surface temperature, salinity, freshwater inputs from solid ice discharge and freshwater input from liquid runoff from land. Data were obtained from satellite and modelled information, and most trends were computed over 4 decades. In order to understand regional variability, we compared the trends across six regions (Northwest-NW, west-W, southwest-SW, northeast-NE, east-E, southeast-SE) covering Greenland's coastal and shelf marine ecosystems. We also combined the trends through their Z-scores (units of standard deviation per year) to express the cumulative trends and identify regional hotspots of change. For the same Greenland regions, we also reviewed the literature for trends in marine biota to understand regional variability in relation to changes in the environment, and to pinpoint knowledge gaps. The groups of marine biota were: benthic flora, benthic fauna, plankton, fish, seabirds, and marine mammals.

Trends in key climate-related variables

The Greenland regions W, E and SE were most impacted by climate change, driven by increasing sea surface temperatures (0.22–0.5 °C decade^{-1}), freshwater inputs (10.14–24.93 Gt yr^{-1} decade^{-1}), declining sea ice concentrations (3–5.3 % decade^{-1}), and more open water days (10.92–23.9 days decade^{-1}). The regions N and NE appeared more resilient due to lower sea surface temperature increases (0.01–0.03 °C decade^{-1}) and sea ice declines (0.5–2.1 % decade^{-1}). Changes in SW Greenland were limited to sea surface temperature (0.27 °C decade^{-1}) and freshwater runoff (7.66 Gt yr^{-1} decade^{-1}) increases since the 1990s. The cumulated trends assessed as Z-scores clearly showed the regional differences and the hotspots of changes (Fig. 1).

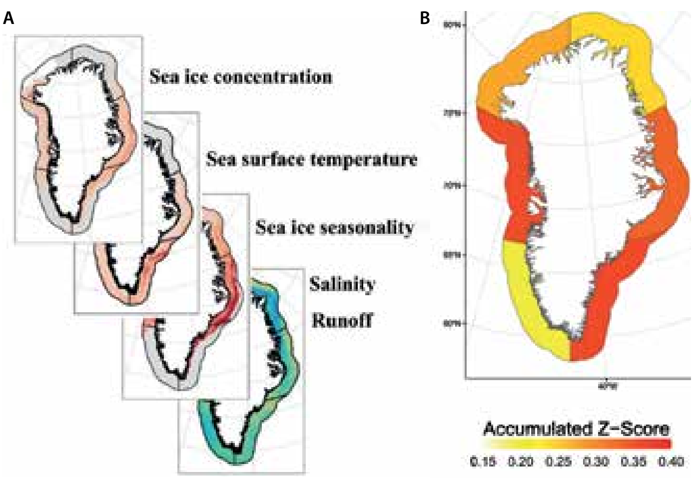

Figure 1. A: Layers of decadal linear trends of various climate change related environmental variables (sea ice concentration, sea surface temperature, sea ice seasonality, salinity and runoff) over the period 1979–2021 (salinity 1991-2021) illustrated for six Greenland regions Northwest (NW), Northeast (NE), West (W), East (E), Southwest (SW), and Southeast (SE) Greenland. B: Sum of the absolute values of the z-score trends (units of standard deviation per year) for the environmental drivers across different regions, considering only significant trends. This metric represents the cumulative strength of environmental change, irrespective of the direction of individual trends. Based on Ager et al. 2025.

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Data source:

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

GEM MarinBasis – crosscutting. The report card is based on Ager et al. 2025 (https://doi.org/10.1016/j.scitotenv.2025.179443), which synthesizes data from published sources, including publications based on GEM data (see supplementary data on biota trends https://zenodo.org/records/11352999).

Indeed several of the cited sources of biota trends are based on GEM data and acknowledge GEM.

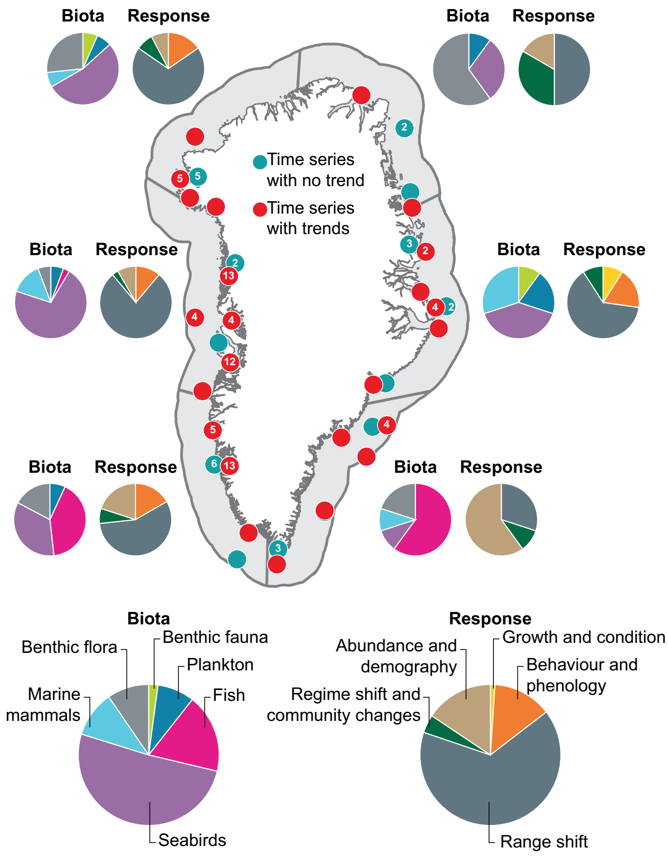

Figure 2. Distribution of biological time series compiled from the literature grouped by biota and type of response. The pie charts below the map represent the total distribution, while region-specific charts are shown adjacent to the respective region. The left sets of pie charts are grouped by biota and the sets right by response type. Red circles represent time series with trends; purple circles represent those without. Numbers within the circles represent the number of trends in case they overlap geographically. Based on Ager et al. 2025.

Figure 3. Distribution of environmental drivers related to changes in biota around Greenland, based on literature review. Yellow symbols represent changes in sea ice (incl. Concentration, open water period, coverage), teal/yellow symbols represent changes in both sea ice and runoff, red/yellow symbols represent changes in sea ice and air temperature, teal symbols represent changes in runoff, and purple symbols represent changes in sea temperature. Based on Ager et al. 2025.

Trends in marine biota

Based on the literature, we identified a total of 43 studies reporting overall 94 time series of marine biota (Fig. 2). Of these 73 exhibited significant changes. The biota time series were unevenly distributed among regions with the highest frequency in W (n = 37) and SW (n = 30) and fewer in E (n = 15), NW (n = 13), SE (n = 12), and NE (n = 5). Accordingly, many of the studies were clustered around specific regions characterized by easy accessibility (i.e. around villages, and monitoring stations). Along the west coast, this included Nuuk (n = 19), Qeqertarsuup Tunua (n = 12), Nuussuaq (n = 15), and Qaanaaq (n = 10). On the east coast, the area near Ittoqqortoormiit (n = 5) and Daneborg (n = 5) were the most studied.

Seabirds were the most studied group (n = 48) followed by fish (n = 17), marine mammals (n = 10), benthic flora (n = 9), plankton (phytoplankton and zooplankton) (n =8), and benthic fauna (n = 2) (Fig. 2). The most common type of ecological response was changes in abundance and demography (n = 64), of which seabird observations constituted the majority (n = 45), followed by growth and condition (n = 13), regime shifts and community changes (n = 15), range shifts (n = 4), and behaviour and phenology (n = 1) (Fig. 2).

The proportion of significant biota trends largely mirrored the intensity of regional environmental changes. Hence, the largest percentage (78%) of significant biota trends was linked to the W, E and SE regions combined, 73 % of time series showed significant trends in SW, and 56 % in the NW and NE. Fish, benthic flora, and benthic fauna responses remained unclear due to data gaps, underscoring the need for further research.

Of the marine biota timeseries, 37 identified an environmental driver of change: sea ice (20), temperature (19), and runoff (2) (Fig. 3). Only four time series considered multiple drivers.

For more detail, please consult Ager et al. (2025).

Conclusion

The study reveals widespread biological change linked to the changing climate but with distinct regional patterns in environmental drivers and associated responses across Greenland, highlighting the need for regional coverage to understand climate-driven changes at Greenland scale. The study also underscores the need for better knowledge on impacts of multiple drivers on marine biota and their interaction for improved understanding of effects of climate change on Greenland's marine ecosystems.

Reference

Ager, T.G., Sejr, M.K., Duarte, C.M., Mankoff, K.D., Schourup-Kristensen, V., Boertmann, D., Møller, E.F., Thyrring, J. & Krause-Jensen, D. (2025). Climate change and its diverse regional impacts on Greenland's marine biota. Science of the Total Environment, 979, 179443.

PROGR
DESCR

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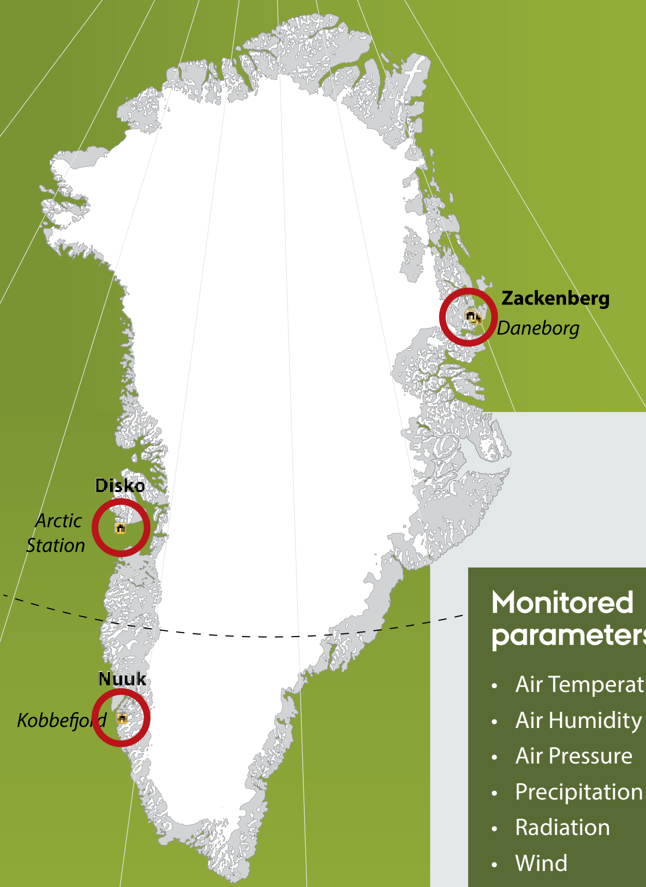
The program descriptions are restricted to the five data-gathering observational programmes. In addition the Remote Sensing and Modelling programme is using the observational data from these five programmes for integration.



Annual Report Card 2025

GEM
CLIMATEBASIS

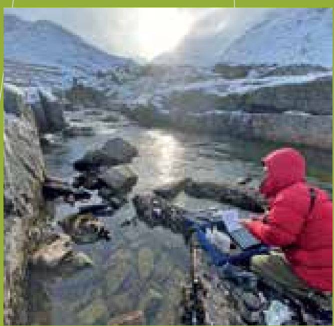
The ClimateBasis programme monitors climate and hydrology in Zackenberg, Kobbefjord and Disko and is run by Asiaq – Greenland Survey. The collected data build base-line information on climate variability and trends for all the other sub-programmes within GEM and serve as a trustworthy foundation for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

Monitored parameters

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

In 2025, all three GEM sites experienced warmer mean annual temperatures than in 2024 (Fig. 4). Zackenberg experienced two pronounced warm episodes with temperatures above the background for the time of year (Fig. 1). The second of these episodes produced the warmest temperatures ever recorded at Zackenberg, an hourly average of 24.6 °C on July 16, 2025. These warm episodes occurred against a background of below-average temperatures during spring and summer. The west coast stations of Disko (Fig. 2) and Kobbefjord (Fig. 3) experienced average or below-average summers and warmer winters. Disko stands out with a late summer and autumn close to the coldest records for this period, followed by an unusually warm November and December. The Disko record, which starts towards the end of 1993, also shows how winter temperatures there were considerably colder in the early 1990s than they are now. Around the middle of that decade, sea ice ceased to cover the whole of Disko Bay in winter, owing to a major oceanic regime shift toward warmer waters (Hansen et al., 2012).

At all GEM locations, the total yearly precipitation shows characteristic patterns of interannual variability (Fig. 4). It is particularly pronounced at Kobbefjord, the location with the highest mean accumulation. All three locations have registered some years of very high precipitation in the period since 2020, followed more recently by dryer years.



Discharge measurements using salt dilution at Kobbefjord, with the destroyed foot bridge in the background.

Preparing for discharge measurements using velocimetry at Kobbefjord.

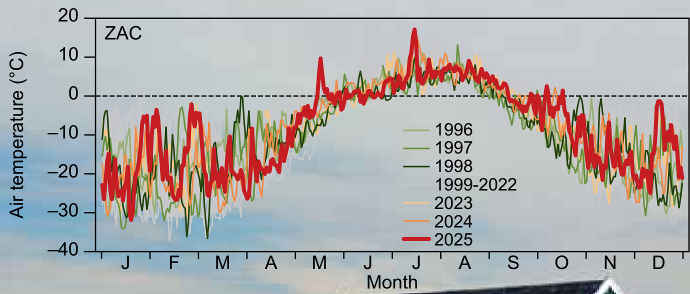


Figure 1. Daily mean temperatures at Zackenberg for all years on record, with 2025 shown in red. The first and last three years on record are colored in order to illustrate long-term changes in the annual cycle.

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PROGRAMME DESCRIPTION

In Disko, precipitation in 2025 (440 mm) was very close to average (435 mm) and in Kobbefjord slightly below (846 mm in 2025 and 891 mm on average). Zackenberg experienced a very dry year with 164 mm compared to the average of 243 mm. Only 3 years in our record have been drier: 1999, 2012 (the driest, with 93 mm) and 2019.

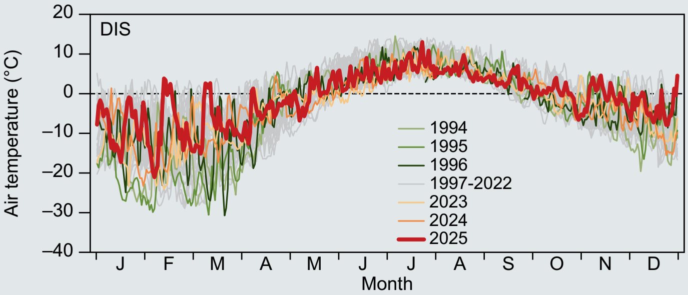

Figure 2. Daily mean temperatures at Disko for all years on record, with 2025 shown in red. The first and last three years on record are colored in order to illustrate long-term changes in the annual cycle.

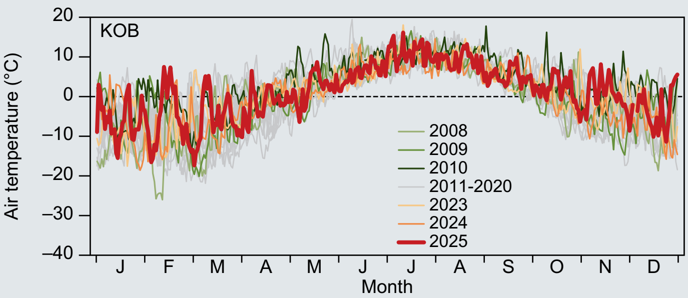

Figure 3. Daily mean temperatures in Kobbefjord for all years on record, with 2025 shown in red. The first and last three years on record are colored in order to illustrate long-term changes in the annual cycle.

The long timeseries from Zackenberg illustrates some of the difficulties of measuring precipitation: While a almost step-like increase in precipitation appears to be discernible to the human eye in 2014, it also happens that the rain gauge was changed to a different model in that year. The old gauge, a Belfort Universal Weighing Gauge model 5915, had started showing signs of ageing and problems with data quality, making comparative analysis of the two gauges in the period while both were still operating concurrently more difficult. Nonetheless, it is clear that the new gauge, an Ott Pluvio2 Weighing Gauge, catches more of the occurring precipitation, especially when it falls as snow. Snow is generally hard to measure under windy conditions. Therefore, the timeseries displayed for Zackenberg in Figure 4 also shows an attempt to correct the data from the older Belfort gauge. The left half of the bars up to the year 2014 shows the original data while the right half shows the corrected data. First, the proportion of snow to rain is adjusted because the gauge had a propensity to freeze in cold conditions and then register the weight of all accumulated snow in a sudden 'thawing' event. Therefore, big precipitation events registered as rain at a time when temperatures crossed from below to above 0° C are re-assigned to the snow proportion. Second, the annual total precipitation is adjusted by calculating the average ratios between annual totals for both gauges and data from the Copernicus Arctic Regional Reanalysis (Schyberg et al., 2020) for Zackenberg. The result indicates that on average, the Ott gauge captures 1.28 times more precipitation than the Belfort gauge, and precipitation amounts before June 2014 were multiplied by this factor. Note that model data is only used as a comparison benchmark here and does not enter the data preparation directly. The same procedure applied to observational data from Danmarkshavn (Drost Jensen et al., 2025), some 260 km to the north of Zackenberg, results in a very similar adjustment ratio of 1.31.

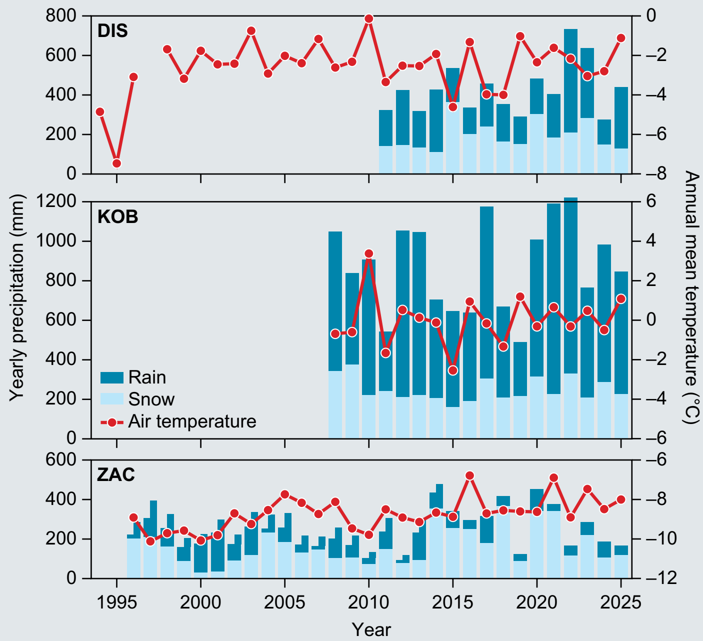

Figure 4. Annual Precipitation totals and mean annual temperatures for the three GEM sites in Disko (DIS), Kobbefjord (KOB) and Zackenberg (ZAC). The precipitation total is partitioned into rain and snow according to a temperature threshold of 1° C (Jennings et al., 2018); if the hourly mean temperature is above the threshold, the precipitation within this hour is counted as rain, otherwise as snow. In Zackenberg, the rain model of rain gauge used was changed in June 2014. The newer model catches more of the actual precipitation, and an attempt to correct for the deficiencies of the older model is displayed by the right halves of each yearly bar (the left half corresponding to the data as is). The main text gives more details.

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GEM
GEOBASIS

Polar bear. Photo: GeoBasis ZAC.

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The GEM GeoBasis Programme

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

The four GEM eddy covariance stations are operated as Integrated Carbon Observation System (ICOS) labeled ecosystem stations. The stations have been standardized to be aligned with ICOS standards, which must be regarded as the eddy covariance community state-of-the-art standards. Zackenberg Fen is labelled as a Class 2 station, which sets some strict requirements on how the station operates. The other three stations are labelled as Associated Stations, which has a less strict protocol.

Across all stations, the growing season, defined by sustained net CO_2 uptake, again begins in late June to early July. As observed in previous years, the transition back to net CO_2 release occurs earlier at the high-Arctic sites, particularly at Zackenberg. The magnitude and seasonal dynamics of fluxes continue to vary substantially among ecosystems, with the smallest net CO_2 sink observed at the dry heath ecosystem at Zackenberg Heath (Fig. 1).

Monitored parameters

Snow properties
- Snow cover
- Snow depth
- Snow density

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

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

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

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

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

Disko Østerlien remains the only station connected to grid power, enabling continuous year-round operation. Zackenberg Fen operates on an autonomous off-grid power system during winter, which has now been further tested under extended seasonal conditions. Kobbefjord Fen has for the first year operated year round on a similar off-grid system with success. Zackenberg Heath are restricted to operation during periods of site accessibility, influencing annual data coverage (see figure for specific start and end dates of operation in 2025).

Autumn morning at the fen in Kobbefjord, September 2025. Photo: Karoline Nordberg Nilsson.

PROGRAMME DESCRIPTION

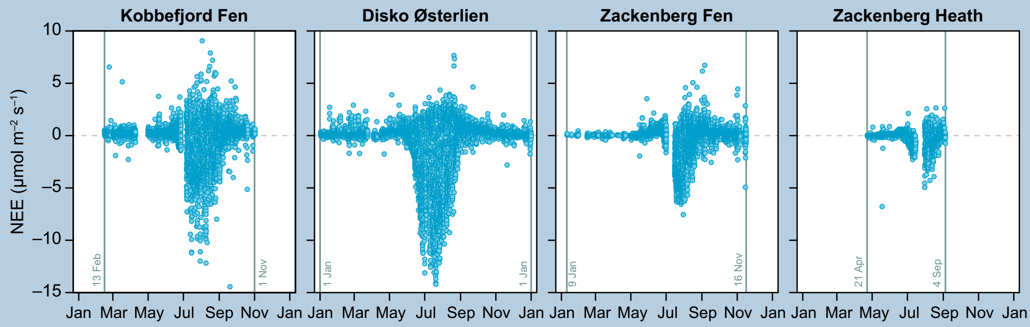

Figure 1. The half-hourly Net Ecosystem CO_2 Exchange (NEE) is measured at the GEM/ICOS eddy covariance (EC) stations located at Kobbefjord Fen, Disko Østerlien, Zackenberg Fen, and Zackenberg Heath. Negative values indicate a net ecosystem sink of CO_2, while positive values indicate a CO_2 source.

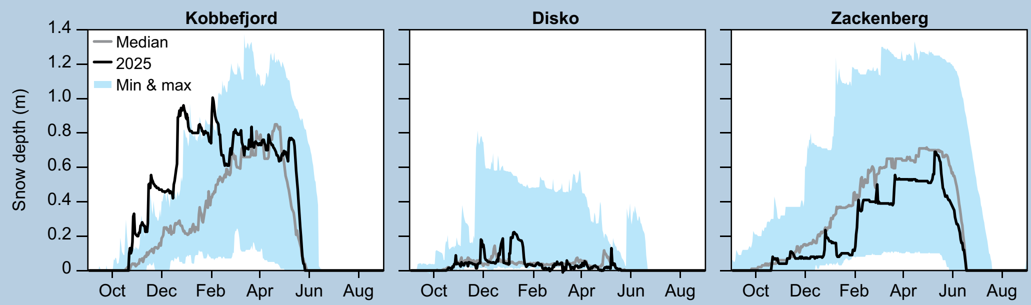

Figure 2. Snow depth measurements in 2024-2025 (black lines) compared to min and max for the historical record (shaded area) and the median (grey line). Snow is a key parameter in Arctic ecosystem functioning. Several different methods are in use to get information on spatial distribution and temporal patterns in snow cover, across the three GEM sites. Methods include time-lapse photography, transect surveys, snow density measurements and, as shown here, long-term point-based monitoring of snow depth. Data used in the figure: Kobbefjord: 2008-2025, Disko: 2012-2025 and Zackenberg: 1997-2025.

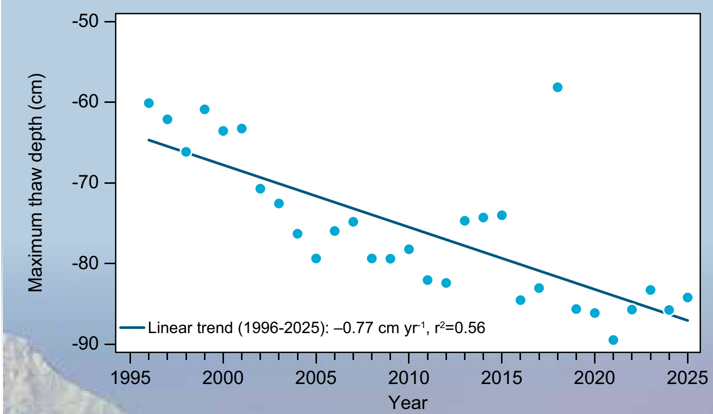

Figure 3. Long-term trend in annual maximum soil thaw depth in Zackenberg Circumpolar Active Layer Monitoring grid #1 (ZEROCALM-1). Soil thaw and active layer depth are studied under different vegetation types. Monitoring methods include manual probing, as the one shown here, and borehole temperature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

Zackenberg showed a slower-than-usual snow accumulation through the autumn and early winter, with the snow depth remaining well below the long-term median (Fig. 2). A maximum of 0.70 m was reached in a relatively late-season snowfall in May, which momentarily interrupted the spring melt. In contrast to Zackenberg, snow in Kobbefjord accumulated more rapidly than in previous years following the onset of snowfall in late October. The maximum snow depth reached 1.04m and peaked earlier than usual. The snow depth was well above the median in the first half of winter, while the latter half of winter featured several warming spells and additional snowfall events before the spring melt in May. In Disko, snow depth reached a maximum in the first half of January, before being redistributed or swept away by strong winds. Several times after that, the site became completely snow-free due to intense warm spells lasting several days, with temperatures reaching up to 8–10 °C.

The mean maximum thaw depth of the 110 grid nodes in ZEROCALM-1 reached 84 cm at the end of the summer (Fig. 3).

Snow covered riverbed, January 2025.
Photo: Kisser Thorsøe.

GEM BIOBASIS

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

Monitored parameters

Vegetation
- Flowering phenology
- Plant community composition
- Plant community distribution and zonation
- ITEX and 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

Photos: Katrine Raundrup

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Greenland Ecosystem Monitoring

PROGRAMME DESCRIPTION

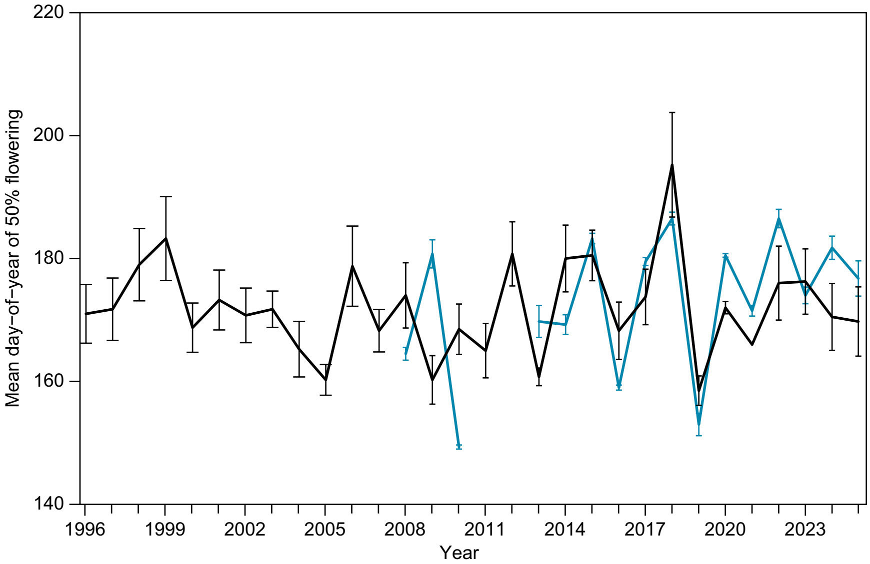

Figure 1. Day of 50 % flowering is indicative of the effect of climate variability on the timing of flowering. The timing of plant growth and flowering is important for e.g. insects and herbivorous animals. The graph shows inter-annual variation in mean Salix *flowering phenology during the period 1996 to 2025 in selected permanent plots in Kobbefjord (blue) and Zackenberg (black). Note that no flowering was observed in Kobbefjord in the years 2011 and 2012 due to insect outbreak, 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.*

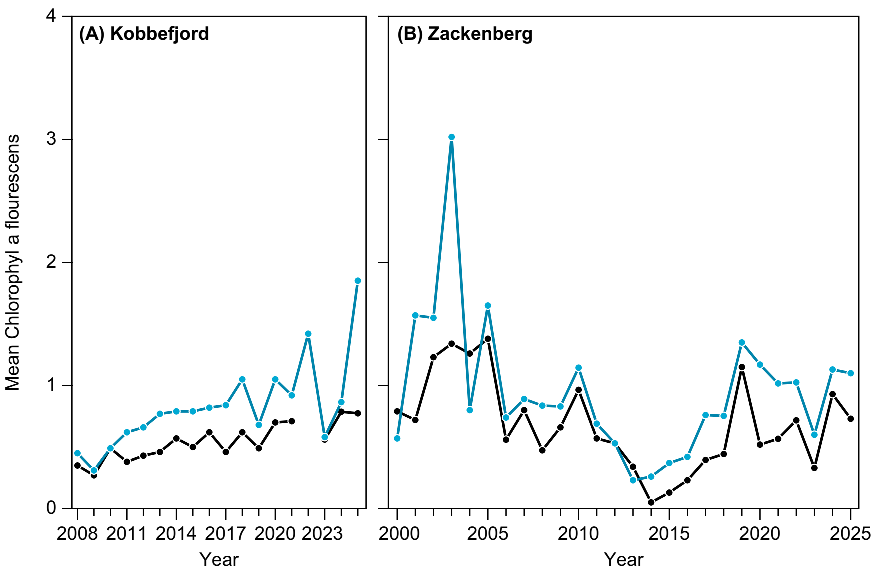

Figure 2. Chlorophyll fluorescence is a measure of productivity in the limnic ecosystem. The graphs show inter-annual variation in chlorophyll fluorescence in lakes at Kobbefjord and Zackenberg 1996-2025. Blue lines indicate lakes with fish, black lines lakes without fish. Note that due to the late onset of the 2020 season at Zackenberg dictated by the covid-situation, only one measurement was conducted in July. In 2022, one lake in Kobbefjord could not be sampled due to logistical constraints.

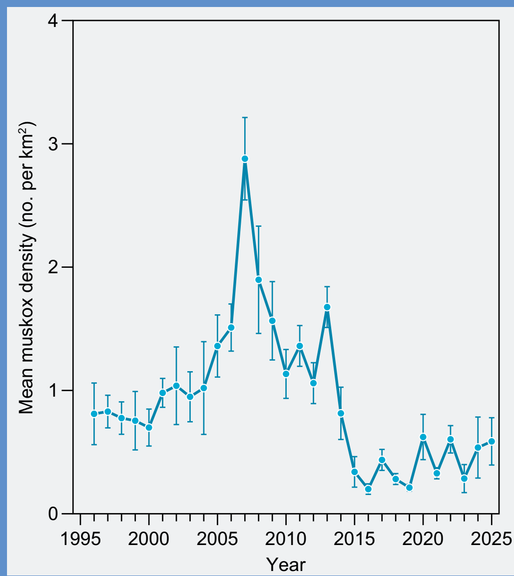

Figure 3. Inter-annual variation in muskox population dynamics (July and August) at Zackenberg 1996-2025.

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GEM MARINEBASIS

Photo: Thomas Juul-Pedersen.

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

Monitored parameters:

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

Photo: Henry Henson.

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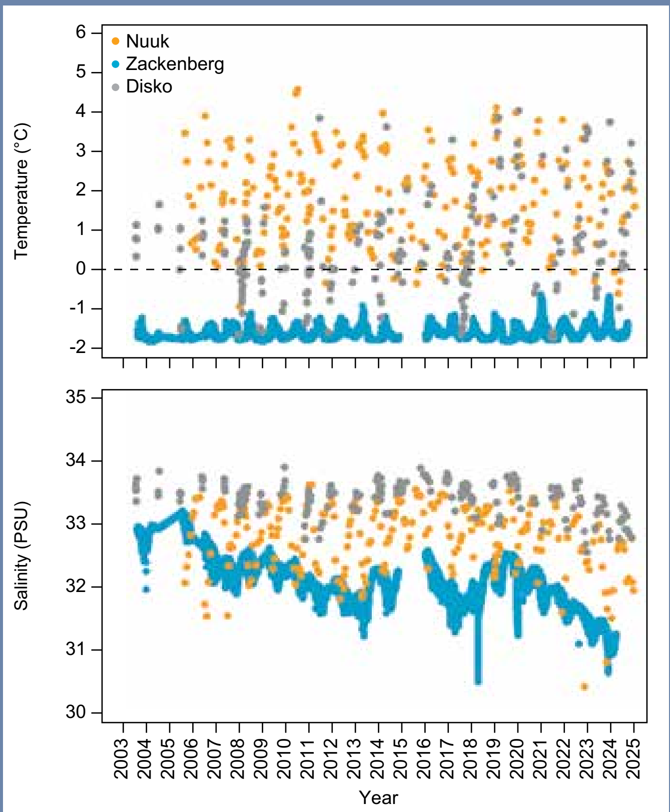

Figure 1. Water temperature and salinity at the permanent monitoring stations in Nuuk, Zackenberg and Disko. The time series from Nuuk and Disko represents one depth (63 m) selected from a monthly profile covering the entire water column. The time series from Zackenberg represents an autonomous mooring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

Photo: Mie Winding.

Photo: Mie Winding.

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GEM GLACIOBASIS

The GlacioBasis program focuses on monitoring the mass and energy balance of peripheral Arctic glaciers at the three Greenland Ecosystem Monitoring (GEM) locations. The program provides in situ observations of essential climate variables, as identified by AMAP, IPCC, WMO-GCW, and WGMS. These observations help quantify the processes governing glacier mass balance and assess the impacts of Arctic glacier melt on future sea-level rise, freshwater inputs into fjord systems, and fjord ecosystems.

Globally, glacier ice loss is a significant contributor to sea-level rise, accounting for 25–30 % of the observed increase (Zemp et al., 2019). Greenland peripheral glaciers are the second-largest contributors to this global loss. The three GlacioBasis monitoring sites represent half of Greenland's existing glacier monitoring locations, underscoring their critical role in addressing the sparse distribution of such data across the region.

GlacioBasis monitors three key glaciers: Qassinnguit Sermiat at the Kobbefjord/Nuuk site, Lyngmarksbræen at the Disko site, and A.P. Olsen Ice Cap at the Zackenberg site.

The monitoring program combines permanent infrastructure with regular field surveys and remote sensing. Automatic ablation and weather stations transmit data hourly throughout the year, while a network of stakes, time-lapse cameras, and annual field campaigns provide additional in-situ measurements, complemented by satellite-derived glacier inventories capturing broader spatial changes. Ice ablation – the loss of ice through surface melting, measured as surface lowering – is shown in Figure 1, and point surface mass balance from the main stake network in Figure 2. Since ice at these measurement sites is in a state of continuous net loss, year-to-year variation primarily reflects the intensity of each melt season relative to the long-term mean. In the most recent season, A.P. Olsen Ice Cap experienced below-average melt due to a slow start to the melt season, while Qassinnguit Sermiat saw above-average melt driven by an earlier-than-usual onset – also evident in the point mass balance data in Figure 2.

Monitored parameters:

Automatic ablation and weather stations:

- Temperature
- Humidity
- Radiation
- Pressure
- Wind speed and direction
- Ice temperature down to 10 m
- Ice surface lowering/ice ablation

Field surveys and permanent installations

- Snow depth surveys using UAVs, probes and snow radar.
- Snow water equivalent
- Surface elevation change (UAV)
- Winter, Summer, Annual net surface mass balance (stake method)
- Timelapse camera
- Glacier outlines and inventory

The terminus of Chamberlin glacier. Photo: Michele Citterio.

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: Alexandra Messerli, ame@asiaq.gl

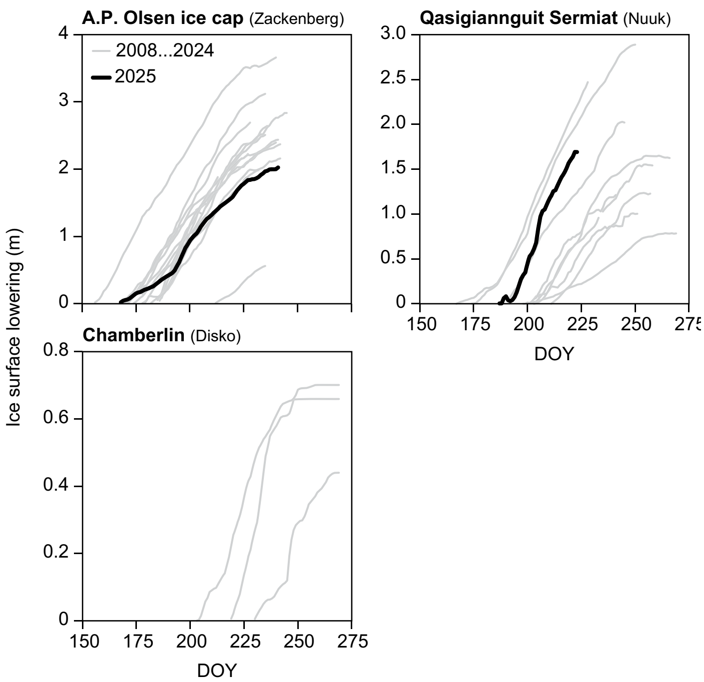


Figure 1. Ice surface lowering, directly convertible to ice melt, from GlacioBasis automatic ablation and weather stations in the ablation zone of the monitored glaciers at the three GEM sites in 2025 (black) vs. earlier years (gray).

Measuring the height and location of an ablation stake on a cold day on A.P. Olsen Ice Cap. Photo: Signe Hillerup Larsen.

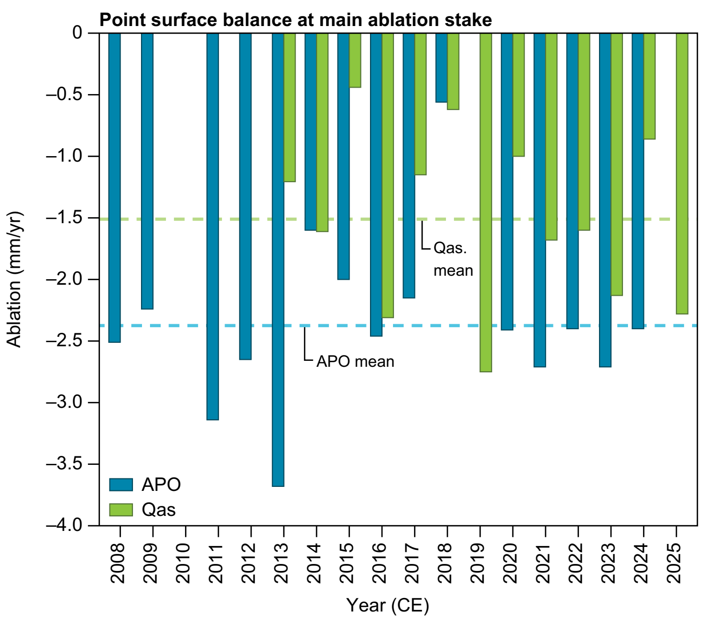
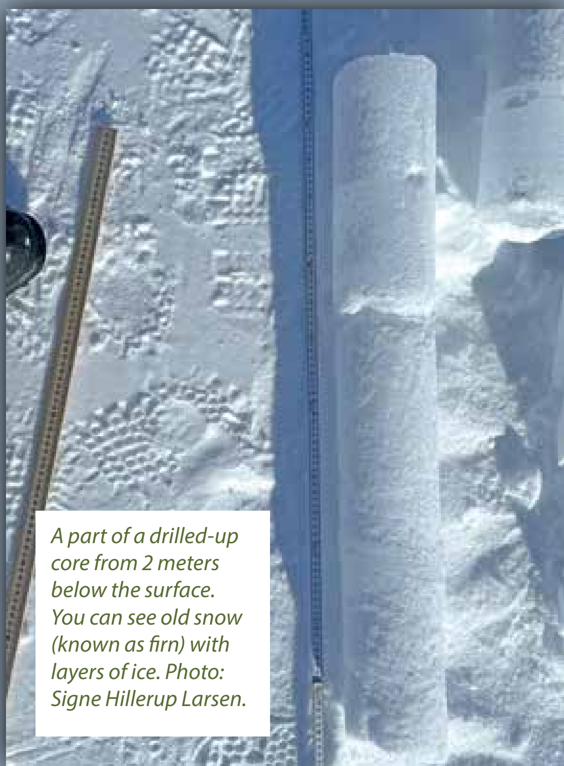


Figure 2. Point surface balance at the main stakes at Qassingguit Sermiat (Qas.) and A.P. Olsen Ice Cap (APO).



A part of a drilled-up core from 2 meters below the surface. You can see old snow (known as firn) with layers of ice. Photo: Signe Hillerup Larsen.

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GEM REMOTE SENSING PROGRAMME

Increased accessibility of select GEM remote sensing products

Ecosystem modelling and remote sensing are key tools for understanding changes and making forecasts for remote and highly heterogeneous arctic landscapes. Since 2022, GEM has implemented several remote sensing and modelling products across the three science thematic structures aligned with the GEM 2022-2026 strategy (see Fig. 1) for use by national/international stakeholders and researchers.

The GEM initiative of providing specifically developed and calibrated remotely sensed products and model runs for Arctic Greenland is moving into a new phase aiming at increased user accessibility. This is an important step towards the remote sensing and modelling initiative being able to bridge across both the established Basis-programs and the three thematic themes from the current GEM strategy.

Monitored and modeled products in 2025

Product

1. Satellite-based cloud cover
2. Downscaled 2 m monthly air temperature grids
3. Skin and sea surface temperature from satellite
4. Snow depth (snow water equivalent) model
5. High-resolution snow cover (over land and sea ice) and albedo
6. Carbon, water, energy cycles modelling
7. **Enhanced high-resolution land-cover classification**
8. Topographic wetness index (TWI)
9. Spectral and structural canopy diversity
10. Marine chlorophyll a
11. Coastal underwater light

Operational product

12. Satellite-based NDVI
13. Satellite-based land surface temperatures

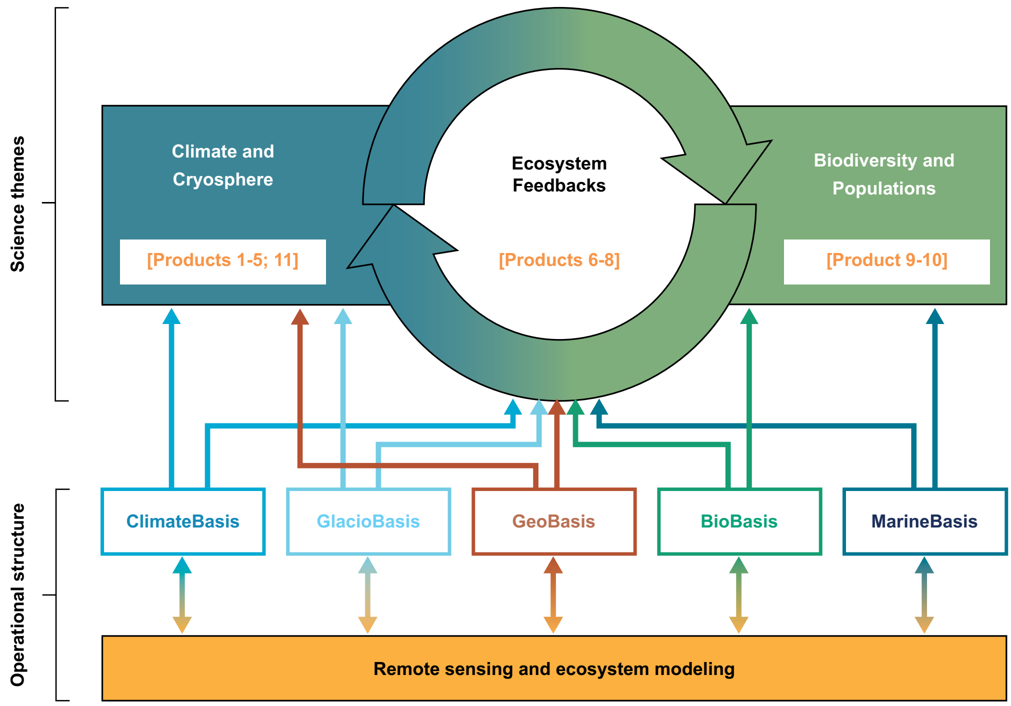

Figure 1. Overview of structure and interactions between the Remote sensing and ecosystem modeling initiative and the other operational Basis-programs.

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AND MODELING DESCRIPTION

2025 update of Product 7: Advancing Vegetation Mapping in Zackenberg – The Veg(M)app Initiative

The Challenge

Vegetation classification maps are essential for upscaling ecosystem processes, particularly for estimating greenhouse gas (CO_2 and CH_4) fluxes across a landscape. However, these products often carry significant, non-trivial uncertainties. The choice of map can dictate whether a region's carbon sink or source dynamics are heavily under- or overestimated.

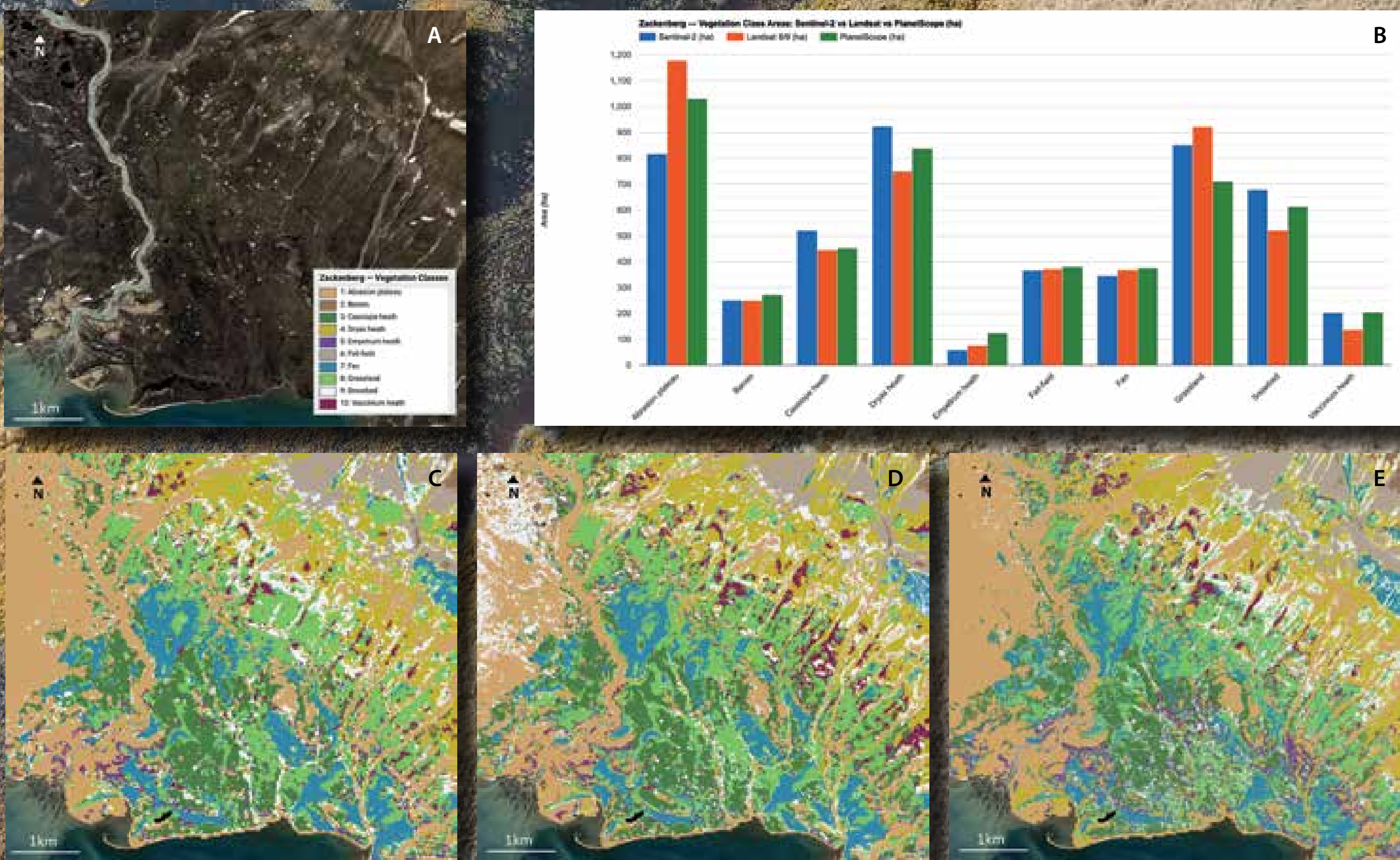
Recent Advancements

Following successful implementations in Kobbefjord last years, the Veg(M)app initiative has expanded its focus to Zackenberg. To better understand the ecological implications of map selection, we aimed to improve existing vegetation maps by evaluating how different satellite sensor resolutions impact the final classification.

Using Google Earth Engine, we integrated ground-truthing data (Stewart et al., 2015; Figure A) with three distinct remote sensing products: Landsat 8/9 (30m resolution), Sentinel-2 (10m resolution), and PlanetScope (~3m resolution) (Figures B, C, D).

Key Insights

Our comparative framework reveals how critical spatial resolution is. As shown in Figure E, the total estimated area (in hectares) for specific vegetation classes fluctuates dramatically depending on the sensor used. For example, the estimated coverage of "Grasslands", "Abrasion plateau", and "Dryas heath" varies significantly between Landsat, Sentinel-2, and PlanetScope, directly impacting the accuracy of subsequent carbon upscaling models.



Greenland Ecosystem Monitoring

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

www.g-e-m.dk

ClimateBasis Programme

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

GeoBasis Programme

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

BioBasis Programme

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

MarineBasis Programme

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

GlacioBasis Programme

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

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

AARHUS UNIVERSITY

GEUS

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Greenland Institute of Natural Resources

DTU Technical University of Denmark

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